Biologist in a Box

Final Report

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Team 20
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Executive Summary

In order to better study the relationship between the chewing rate of mammals and their body mass, Professor Geoffrey Gerstner, Ph.D, of the University of Michigan School of Dentistry tasked us to design and build an apparatus that would film free roaming mammals chewing and simultaneously record their body mass. It is possible that general biological principles or unifying theories may emerge from this research by finding the underlying reasons that mammals have such rhythmical chewing patterns.

Our sponsor made it clear that the design should be sturdy and stable, environmentally friendly, and weatherproof. Additionally he wanted the data recordings to be accurate. The engineering specifications set ensures that the design would be structurally stable, be large enough to accommodate the test subjects, and have waterproofing ratings high enough that any components would not be damaged in rain or humid environments. Accuracy limits were 10% on mass readings and used a high speed camera to capture fast chewing rates.

Final Design and Prototype

The final design has been established as one which is scalable; its ultimate size and many of the components are not specified due to its adaptability for different animal sizes. At its core, it consists of a scale (load cell) and a rotating camera boom actuated by a DC motor. It accommodates mammals the size of squirrels. There will also be a central DAQ to facilitate signal transfers and reception. Our design allows for test subjects to feel free and uninhibited as there is no enclosure. The boom system allows for view point changes as needed. The load cell was the most accurate system in measuring body mass.

Fabrication Plan & Cost

Each system is manufactured independently of each other, giving some flexibility in the process. For instance, making the enclosure does not depend on how far along the platform structure is. Once the structure, boom and enclosure are fabricated, they can be assembled together. The overall structure including the enclosure cost about $350 in materials. The electronic components added about an additional $400.

Results and Design Critique

The prototype's electronic subsystem works and the camera enclosure is somewhat waterproof, although not up to our desired specification. There were many issues during the manufacturing process and improvisations on certain parts were necessary to complete the prototype on time. This resulted in slight differences in dimensions and tolerances between the theoretical design and the actual product, making certain assemblies more difficult or impossible in accordance with the theoretical design. There were also some vendor issues that resulted in either late parts or undelivered parts.

If given the chance again, there would be key changes in the boom and camera enclosure, two areas that were not up to par in the current prototype. There would have to be a different method of countering the moment caused by the camera enclosure possibly through the use of a suspension wire. There would also have to be change to fully ensure that the enclosure is practically waterproof against any weather. The lack of vertical translation for the camera would also be remedied as well.

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1. Project Background

This unique project will be used to observe and collect data from mammals in their natural environment. The sponsor for this project is Professor Geoffrey Gerstner from the University of Michigan School of Dentistry - Department of Biologic and Materials Sciences. One of our sponsor's main areas of research involves studying the relationship between chewing rate and body mass in mammals, with a secondary focus on jaw kinematics. It is generally agreed upon that chewing rates scale inversely to mass, but there is still debate over the constants and exponents describing the true relationship. The value of this research is that accurately describing this relationship, something which is not often achieved, could provide insight into more general biological principles or unifying theories [9].

Figure 1. Squirrel, one of our major potential test subjects.

Since this research is quite unique, there is not much data available on the subject, thus Professor Gerstner does the data collection himself. He has done most of his work in zoos, which has both its advantages and disadvantages. One advantage is that one can get the mass of the animals fairly easily since all of the animals are in captivity. Another advantage is that a wide range of species can be observed in one place, but on the other hand, the number of animals in each species is limited.

Our sponsor has also conducted many observations on wild animals. He wishes to continue his research without having to restrain or capture animals in any way. The main issue that our sponsor has run into while observing wild animals is the difficulty of obtaining accurate readings while keeping the animal unrestrained. Using just a digital scale and a handheld camera, he has attempted to film rodents that were eating while on the scale. Although he was able to obtain some data regarding the mass and chewing rates of the rodents he was observing, his results were not of the quality that he desired. Therefore, he has asked us to develop an apparatus that will film the chewing of a mammal and simultaneously record its weight. The apparatus that we will be developing will accommodate small to medium-sized mammals and will not trap them. The apparatus will be designed so that it is easy to scale up the size to accommodate larger mammals. Later stages of the apparatus will record jaw kinematics in 3D and will have a marking system to better track the jaw. These later stages will also measure head, tongue, and jaw length.

The purpose of this project is to develop a full design, and construct a prototype of the device that will assist our sponsor with his research in developing a mathematical relationship between chewing rate and body mass in mammals.

1.1 Literary Review

The novelty of the research our sponsor is conducting means that there are relatively few resources other than our sponsor on the specific subject matter at hand, the observation of chewing rates in the wild, and the relationship between body mass and chewing rate in mammals. Therefore, we relied heavily on him for background information on the relationship and, to a lesser extent, observation and the environments that we will be designing for. For instance, our sponsor told us he would eventually be taking the apparatus to the desert; thus, we had to make sure that our final design would be stable on very dry ground. We also collaborated with him to determine the project requirements and their weights relative to each other.

We were able to find resources for our engineering specifications as well as potential challenges we could expect to encounter. Regarding issues related to the camera, we looked at professional-level cameras and accessories as examples to gather information on specifications such as resolution for video, range of frame rates, ranges of angles and motion (i.e when mounted on tripods), and waterproofing methods and ratings.

To better understand our potential test subjects, we looked to various field guides for mammals as well as field experts who conduct research on mammal behavior. In doing so, we were able to find information on their diet, natural habitation, average body masses, body length, and period of activity. In a related matter, we also looked to wildlife photographers and conversationalists in order to better understand what it is like filming and photographing animals in the wild and for any technological innovations that could assist us. In addition to researching mammal behavior, we conducted some field testing of our own in order to get an idea of the challenges associated with observing animals in the wild; we filmed squirrels eating around campus.

Lastly, we researched state and federal laws regarding wildlife and the environment in order to be confident that neither the apparatus nor any part of the project would be in violation of the law.

2. Design Guidelines and Considerations

This section outlines our original set of requirements and guidelines which we established together with our sponsor. The content of this section served as the main driver behind all decisions we made for the duration of our work.

2.1 Customer Requirements and Engineering Specifications

Our established customer requirements along with their relative weights are listed in Table 1. Table 2 lists the engineering specifications we derived from these requirements. Each customer requirement is explained in more detail and related to engineering specifications following

Table 2.

Table 1. Customer requirements and relative weights

Primary "essential" requirements		Additional requirements	
10	Equipment protection	6	Adaptability
9	Weight readings accuracy	6	Manufacturability
9	Camera angle reliability	6	Animal size range
8	Recording quality	4	Remote indication of activity
8	Scalability	4	Cost
8	Sturdiness / stability	2	Portability
7	Controlled remotely	1	User-friendliness

Table 2. Engineering specifications and target values/ranges

Impulse required to tip (applied at a height of 0.3 m)	>= 50 kg·m/s
Camera actuated degrees of freedom	>= 2
Camera manual degrees of freedom	>= 1
Camera frame rate	>= 30 fps
Camera resolution	>= 720p at 30 fps
Camera optical zoom	>= 2x
Temperature Range	-10ºC < T < 55ºC
Camera distance from edge of platform	>= 0.3 m
Weight measurement resolution	<= 5.0 g
Maximum weight accommodation	>= 15 kg
Platform surface area	>= 0.49 m^2
Camera enclosure IP rating	>= 55
Camera enclosure allowable impulse	>= 50 kg·m/s
Camera battery life (recording)	>= 2 hrs
Device battery life (moving)	>= 10 min
Percentage of functions (during collection) controlled remotely	100 %
Operator maximum distance	>= 15 m

Beginning with the first eight customer requirements, the "essential" requirements which must be addressed for the success of the project, we will discuss each requirement and how it is affected by related engineering specifications.

Equipment Protection: Most importantly, the equipment must be properly protected – an expensive digital video camera will be in use as well as electronics, and we would prefer to have everything else fail before the camera is damaged. To achieve good protection, we aim to maximize the IP rating of the camera's enclosure and the enclosure's strength. The IP rating is a system of codes which represent an enclosure's resistance to intrusion by various sizes of solids and levels of liquid. A rating of 55 represents resistance to dust and full protection from anything larger, and full protection from a jet of water [13]. The enclosure must also be able to withstand impact from natural hazards such as animal collisions and being struck by branches. We established that resistance to an impulse of 30 kg·m/s, the equivalent of a 10 kg raccoon (large) running at 3 m/s, is sufficient.

Weight Readings Accuracy: A high level of accuracy of the weight readings, in this case less than 10 % error, is essential for the data to be of any use, and thus is weighted highly. The maximum value was a requirement given to us by our sponsor. Along with the accuracy of the weight-measurement equipment we use, the maximum animal weight that we design for will also have great influence on this parameter. The greater the maximum weight we accommodate, the less accurate readings will be, especially when measuring much smaller animals.

Camera Angle Reliability: The camera's ability to film at the correct angle, which is straight at the animal's face, is equally important as the accuracy of the weight readings. Just as useful weight data requires high-accuracy measurements, the researcher's ability to measure chewing rate hinges on the camera's ability to film from a good angle. This is even more important for any desired tracking of the jaw's motion, which is a large part of the research at hand. The most influential factor on this requirement is the number of degrees of freedom of the camera's fixture. We established a minimum of two actuated and one manual degree of freedom for the final design.

Recording Quality: In addition to a good angle, the quality of the video must also be sufficient to distinguish points on the animal's jaw and to track the motion clearly. The resolution of the camera along with its frame rate will have the most effect on this requirement. Other important factors will be the camera's focal length, zoom capability, f-stop range, and its distance from the platform, which together will determine the camera's ability to focus on the animal's face and have it occupy as much of the shot as possible [5]. Values for these specifications were chosen based on observation of different quality recordings and experimentation with the camera.

Scalability: As the device is intended for future use with much larger animals, it should be designed such that it will be as simple as possible to scale up to much larger sizes. A design without enclosure will be much more easily scalable, which is one of the factors that aided or decision of proceeding with a no-enclosure design. Also, the weight measurement system will be the primary factor affecting how difficult the device will be to produce on a larger scale. Using a load cell offers the best scalability out of all methods we discussed, because load cells are made in a range of accuracies in sizes far exceeding any possible future needs.

Sturdiness / Stability: The device should be able to withstand the force of animals running into it without falling over or being damaged. The device being knocked over by animals was a common problem with previous implementations, causing wasted time and risk to the equipment. We have established the following measure as an engineering requirement: the minimum impulse required to tip the device over, applied at a height of 0.3 m from ground level. This specification has replaced two former ones, "Overall weight" and "Vertical position of center of gravity", as we believe it is a more concise measure of the devices ability to resist tipping. The minimum for this requirement will be 20 kg·m/s, the equivalent of a 10 kg (large) raccoon running at 5 m/s. Experiencing this great an impulse is a highly unlikely scenario, and the device tipping over from a collision of greater magnitude would likely cause no more than an inconvenience for the user.

Controlled Remotely: The operator should be able to control the device, for the duration of data collection, from a distance of at least 15 m. All of the operations outside of set-up and take-down should be able to be performed from this remote location. These operations comprise the movement of the camera within the two actuated degrees of freedom, starting and stopping recording, and turning the camera on or off. Operations such as replacing bait and adjusting the tilt of the camera will be performed manually.

Outside of essential requirements, we have established seven more lower-weighted requirements.

Adaptability: Along the same lines as scalability, when the device is adapted for use with larger animals, it will also be located in more remote environments. In this situation, battery power is a necessity, and a design which already incorporates battery power will require fewer changes to adapt for future use. We have established a minimum battery life of 10 minutes of motion for both parts of the camera actuation system as one of our engineering requirements. Also, the device may need to film in the dark in the future. Many mammals are nocturnal creatures, such as the raccoon (*Procyon lotor)*, and do their feeding at night [21]. It is possible that an infrared camera will be swapped in, so the camera should be mounted in such a way that it can easily be removed and replaced.

Manufacturability: The ease of manufacture is important to the customer for multiple reasons. If less common procedures are required to manufacture the device, it may take longer to build and develop. Simpler processes allow for faster prototyping and in some cases make scaling much easier. The material choices, degree of waterproofing, and amount of enclosure will all affect the manufacturability of the device. Our choice of a load cell as the weight measurement method was partially influenced by the fact that it will require minimal manufacturing to implement, especially compared to alternatives such as a hydraulic system or a spring scale. Manufacturing difficulties stemming from use of non-conventional processes and tolerance-sensitive parts will only get worse when the design is scaled up.

Animal Size Range: The animal size range that we design for should be as large as possible without detracting from more important factors. Many factors influence the size range the device will be able to accommodate, including the sensitivity and range of weight measurements, the physical size of the device, the maximum weight it can safely handle, and the range of motion of the camera. We chose to design for a maximum animal weight of 9 kg. The largest raccoons don’t weight more than 10 kg, and any larger animals will have difficulty fitting on the platform of the device [21]. The platform will have a surface area of at least 0.36 m^2 (0.6 m × 0.6 m), which will be more than enough space for a large squirrel.

Cost: Our sponsor indicated that although the $ 400 budget was reasonable to fulfill the primary requirements, he did not want cost to impede the fulfillment of any of these goals or further improvements. Many factors influence the cost, including the quality of the camera (resolution, frame rate), the degrees of freedom of the camera's mount, the weight measurement method, material choices, and the presence of a battery.

Portability: The device will need to be moved, but ease of moving the device was treated as more of a convenience, the pursuit of which we made sure did not interfere with any other requirements. We didn't expect any issues with the device being difficult to move, but acknowledged that the possibility that it would require two people. The inclusion of a battery in the final design improved the device's portability greatly over a design requiring an external power source.

User-friendliness: This was also established to not be of much issue at all, and while it was kept in mind it was treated as the lowest priority. The people using the device will likely only be researchers, and it was decided that it would not be a big deal if some learning is involved.

2.2 Customer Requirements not Applicable to the Prototype

Some customer requirements were initially established but later found to not be applicable to our prototype, due to the differences between it and the final design.

Remote Indication of Activity: In the final design, the operator will not be within sight range of the device, and may not be paying attention to the video feed at all times. The operator may also wish to turn off the camera between recordings in order to preserve battery power. For these reasons, the controlling software should alert the operator when the load cell signal reaches a certain threshold, indicating the presence of an animal. For the prototype, the operator will have to be present (within sight range) for the duration of data collection, and there should be no trouble noticing the presence of an animal. We did not give heed to this requirement when designing and building our prototype.

Detection Reliability: In a related manner, for the final design, it is important that the device reliably detects animals' presence, and minimizes false detections. The load cell will be used for detecting an animal's presence, and the reliability will mostly depend on how well the detection threshold is calibrated. We established 90 % as what we believe to be a reasonable target for correct detections. This measure is defined as the ratio of correct detections to total detections plus missed detections. This customer requirement, being tied in to the previous one, Remote Indication of Activity, was ignored during the designing and building of our prototype.

2.3 Previously Discussed Requirements, Later Removed

We had discussed the capability to mark the jaws on animals, and listed it as a customer requirement. We later decided, with our sponsor, that it is not important enough to warrant its difficulty at the moment and will not be implemented as of yet.

We removed "% Enclosure" from our original set of engineering specifications, as we settled on a no-enclosure design.

3. Concept Generation

When we began to come up with concepts for our project, we each generated a few full-device concepts. We soon decided on a different approach, noting that our device's functions could be broken down into distinct subsystems, and that these subsystems were generally independent of each other in operation. Using our previously generated ideas and brainstorming more, we developed concepts for each of the subsystems individually, being careful to cover all aspects of the device. The functional decomposition of our device was instrumental in defining these subsystems, the graphical representation of which is included in Appendix E. We concluded that the four primary subsystems which we would have to design were the camera enclosure, the platform, the weight measurement device, and the camera mounting and actuation system.

The camera enclosure serves the functions of holding the camera in place, protecting it from weather and animals, and performing camera control functions.

The platform must be stable and able to support the animal and possibly the food. Its main functions are to provide a surface for the animal to sit and eat on and to reliably transfer the weight of the animal to the weight measurement device.

The weight measurement system measures the weight of the animal and platform and sends a signal to the operating computer for storage and animal presence detection.

The camera mounting and control consists of the overall frame of the device and all parts involved in actuation of the camera. This subsystem is responsible for holding the device together and getting a good camera angle.

It is important to mention that a few decisions were made separately from the concept generation process which helped to preliminarily narrow the field. The following is the most notable example. Certain concepts for actuation could warrant the use of either vertical motion or tilting of the camera. After performing some field tests (filming squirrels that were chewing food) and discussing with our sponsor, we concluded that vertical motion was decidedly more valuable than tilting, as due to the jaw's position on some small mammals, it can be nearly impossible to see motion of the jaw from a vantage point above the animal's face. Therefore, tilting would prove to be virtually useless in these situations, while a vertically-moving camera could obtain a better angle, from below the animal's face.

3.1 Trivial Subsystems

During our concept selection (Section 4), we did not perform a full evaluation for every single concept which we generated. Discussion over certain aspects of the system produced clear answers, which we concluded were not worth debating during concept generation and selection. Concepts for these specific aspects were not included in this section, and will be discussed in Section 4.

4. Concept Selection

Our primary tool for concept selection was the Pugh chart. We put together one for each subsystem and used them to analyze and compare each set of concepts. We will discuss our criteria for each subsection and our results here; the full Pugh charts can be found in Appendix G.

4.1 Weight Measurement Subsystem

To compare our concepts for the weight measurement subsystem, we established the following set of criteria and weights, shown in Table 3. The accuracy of the measurements is the most important factor, because an inaccurate system would essentially render the whole device useless. The measurement range and resolution are of almost equally great importance as they determine the quality of data which can be obtained. The concepts we evaluated for this subsystem were as follows: a load cell, a hydraulics-based system, a spring-based system, and a standard digital readout scale.

Table 3. Criteria for weight measurement subsystem

5	Accuracy
4	Range
4	Resolution
3	Durability
3	Manufacturability
2	Ease of data recording
2	Cost

In our analysis, the load cell came out far ahead of any other concept, as it received the highest ratings for all criteria except for cost. The cost was recognized to be our major limiting factor when selecting a load cell to use, as they can easily cost thousands of dollars. Based on these results, we decided to proceed with a load cell as our weight measurement device.

4.2 Platform Subsystem

For the physical platform of the device, we established just three basic criteria, shown in Table 4. The stability criterion refers to the platform’s ability to transfer the weight of the animal to the load cell while transferring as little of the load as possible to its supports. This becomes an issue as the animal moves away from the center of the platform. This criterion was our most important concern because the platform transferring too much load to the supports would result in inaccurate results. We evaluated three basic concepts for this subsystem. They were the following: a circular platform supported in the center, a circular platform with four supports around the perimeter, and a rectangular platform with four supports at the corners.

Table 4. Criteria for platform subsystem

5	Stability
3	Weight
2	Manufacturability

The perimeter-supported circular platform and the rectangular platform ended up being very close, with the only difference being a better manufacturability rating for the rectangular platform. We decided to move forward with the rectangular platform.

4.3 Camera Actuation / Mounting Subsystem

We evaluated our concepts for camera actuation or mounting based on the criteria shown in Table 5. The freedom of the camera to get a good angle on the animal’s face is the most important factor here, as it is essentially the overall purpose of the camera actuation system. For this subsystem, we analyzed the following concepts: three boom-based systems with either vertical motion or tilt, a circular track with tilt, and arc-shaped track with vertical motion, a tripod with pan and tilt, and a stationary tripod.

Table 5. Criteria for camera actuation / mounting subsystem

5	Camera angle freedom	2	Power consumption
2	Durability	1	Cost
2	Manufacturability		

Our evaluation yielded a very tight distribution of scores for all concepts. The concept which scored the highest was a boom-based system with the camera outside of the supports and vertical motion. This concept only edged out the stationary tripod by score, but we believed the boom-based system to be a better choice and proceeded with it.

One of the other boom-based concepts was identical to the one we selected expect that it included actuated tilting for the camera rather than vertical motion. After observing squirrels’ chewing, we determined that it can be virtually impossible to see motion of the jaw if the camera is not low enough, so vertical motion for the camera was determined to be far more valuable than tilt.

4.4 Camera Enclosure Subsystem

Lastly, we evaluated three concepts for possible use as a camera enclosure. These concepts were: a full-enclosure box with transparent material in front of the lens, a partial-enclosure box which closes around the lens and leaves it exposed, and a flexible bag-like enclosure which would also include a transparent material in front of the lens. Our criteria for analyzing these concepts are shown in Table 6. The IP rating, which includes its ability to protect the camera from moisture, was a primary concern [13]. Protection of the camera and lens from physical harm are also very important. The enclosure’s impact on video quality, while not anticipated to be marked, is also a significant factor as a quality video recording is one of the primary needs of researchers who would be using this device.

Table 6. Criteria for camera enclosure subsystem

5	IP rating (waterproofing)	2	Adaptability for other cameras
4	Protection of camera from physical harm	2	Empty volume in enclosure

4	Protection of lens from physical harm
3	Impact on video quality
3	Manufacturability
2	Cost
1	Weight

The full-enclosure box came out ahead in our analysis, with its notable advantages over the second-place finisher, the partial-enclosure box, being lens protection and adaptability. We included the full-enclosure box in our final design.

4.5 Power Generation and Transmission

Our feasible options for power generation were limited; we settled on DC motors quickly, as they are relatively easiest to find, implement, and control. Ac motors were another viable option, but we decided that since the final design operates on DC power, DC motors meet the scalability requirement and minimize the amount of necessary electronics. Gears were selected over pulleys based on their simplicity to implement, load capacity, and inexpensiveness.

4.6 Camera Button Actuation

We quickly settled on solenoids as button-pushers, as push-type ones are perfectly suited for this application – they create a pushing force through a small area over a short range, and are easy to mount and control.

It is worth mentioning that the wiring and cable management were considered during our concept selection stage, and it was decided that it would be addressed at a later time and decisions would be based primarily on standards and safety.

5. The Final Design

In this section, the details of the generated concepts which were not previously addressed will be fleshed out, and the full system will come together.

The concept of our final design is somewhat unique in that its overall size is not specified. It is a design which can theoretically be adapted for any size of mammal, being restricted mainly by the load cell. Due to the scalable nature of our final design, we will not specify part dimensions or parameters of certain hardware, such as the motors and the load cell. Parameters such as these are dependent on the size of animal the device is being built for, and while they are not specified for our final design, they will be specified for our prototype in Section 8.

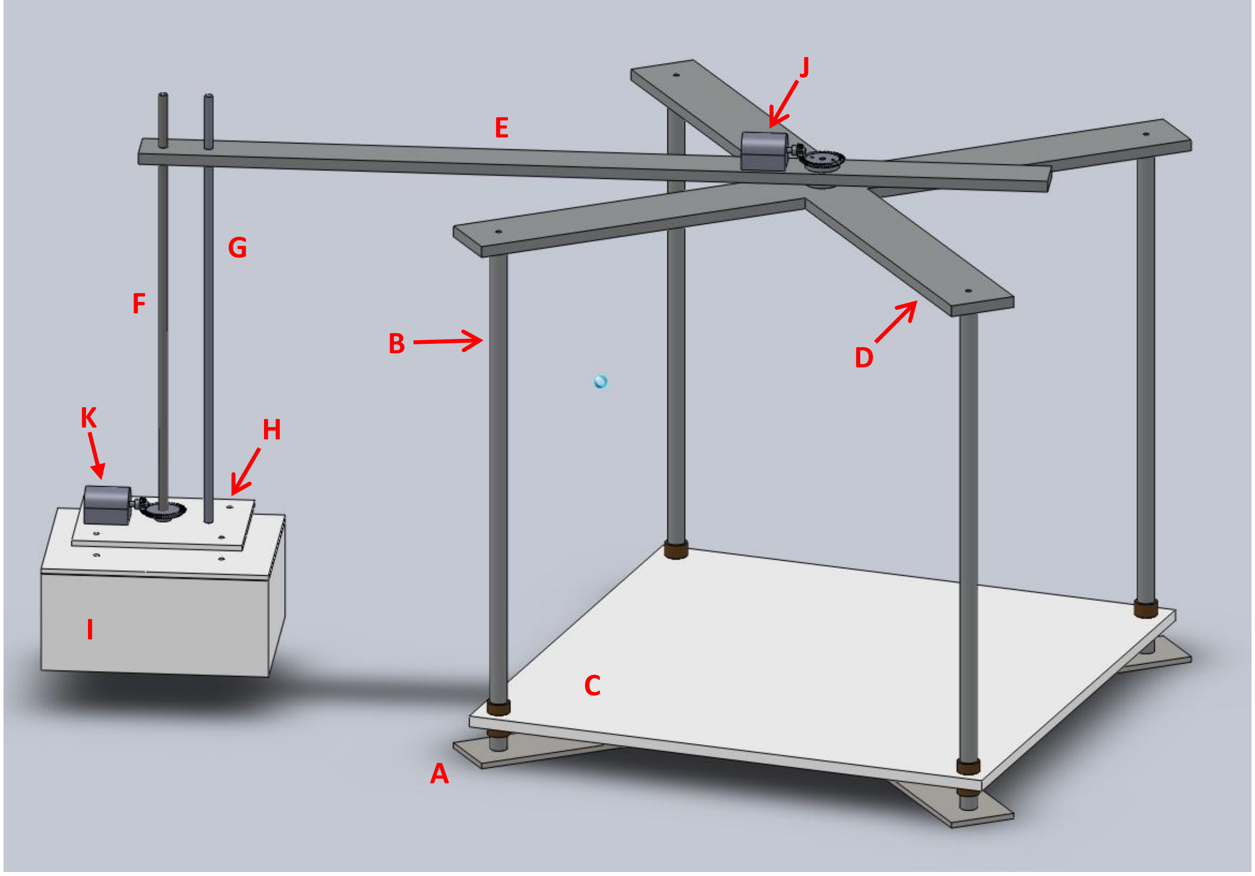


Figure 2. Screenshot of CAD model of full system

Table 7. Part terminology and corresponding labels in Figure 2

A	Base	G	Guide shaft
B	Column	H	Mounting plate
C	Platform	I	Camera enclosure
D	Support assembly	J	Boom motor
E	Boom	K	Leadscrew motor
F	Leadscrew		

Throughout this description of the final design, we will be introducing terminology which we will use to describe certain parts for the remainder of this report (listed above). When a new term is mentioned, its corresponding label from Figure 2 will be included in parentheses. Note that some of these "parts" are in reality manufactured from multiple actual parts, and are referenced by a single name in this report for the sake of clarity.

Beginning at the bottom, the "base" (A) consists of two long pieces of steel forming an X-shape. At each end of the base, one "column" (B) will be attached. Each column is secured to the base; for the prototype, they are press-fit into holes. Near the center on the base, one end of the load cell is securely mounted. The load cell is mounted off-center because it is cantilever-style, meaning it is essentially a horizontal beam with one end supported by a fixed structure (the base) and the other end bearing the load. The load cell is mounted in such a way that the load-bearing end sits directly under the center of the “platform” (C).

The platform is a single sheet of PVC, which the animal sits on when eating. At the center of the platform on the underside, there is a single point of contact, a sort of “nub,” which will rest on the end of the load cell. Just inside each corner of the platform, a sleeve bearing is press-fit into a circular hole. These bearings keep the platform oriented horizontally and allow it to slide vertically along the columns. With this configuration, the entire weight of the platform and its contents will, ideally, be borne by the load cell.

Spanning the distance between the top of the columns and the mounting point of the “boom” (E) is the “support assembly” (D). One longer piece runs between two opposite corners, and two shorter pieces are welded to that piece, forming an x-shape similar to that of the base. A sleeve bearing is press-fitted through the center of this assembly, and a gear is bolted onto the top of it. The boom will rotate around this bearing, and a gear attached to the “boom motor” (J) will mate with the one fixed to the beam assembly.

At one end of the boom, the “leadscrew” (F) is threaded through its mating nut, which is fixed in the boom. The leadscrew is held axially to the “mounting plate” (H), to which the “leadscrew motor” (K) is also mounted. The mounting plate is bolted to the top of the “camera enclosure” (I). A second, unthreaded shaft, the “guide shaft” (G) is fixed to the mounting plate and runs through a hole in the boom. The guide shaft prevents the enclosure from rotating when the leadscrew is actuated, constraining the entire assembly to vertical motion as the leadscrew turns.

The boom is counter-weighted appropriately based on the weight of the entire leadscrew-enclosure assembly. We estimated this weight prior to building the prototype (section 8), but decided to base our actual counterweight on what we measure once the camera enclosure/leadscrew assembly for the prototype is constructed.

5.1 Computer Control, Data Acquisition, Electronics

A computer is used to handle the control of all actuators and the recording of data from the load cell. A data acquisition card (DAQ) will be the hub of communications for the device. It will take the analog signal from the load cell, which will first be amplified by an instrumentation amplifier. The DAQ sends this signal digitally to the computer. The same card will, based on signals sent to it by the operator, supply signals to the H-bridges in order to control the solenoids and motors. Communication between the DAQ and the operating computer will be wireless, with the ideal method being 802.11(x) Wi-Fi. A circuit diagram of the overall system is included in Appendix H.

5.2 Camera Motion Actuation

The rotation of the boom is driven by a motor (at least in smaller-scale implementations, a standard DC motor). Fixing a beveled gear to the top of the center shaft and another to the motor shaft allows for the easiest installation, and only required the manufacture of a simple Lshaped mount for the motor. The boom motor is a high-torque, low speed motor. The leadscrew is turned by another motor, a faster, lower-torque one, also with power being transmitted through a set of beveled gears. Both motors are driven by appropriate controllers (for the case of standard DC motors, H-bridges), which take digital PWM and direction signals, supplied by the DAQ. In larger-scale implementations of the final design, the motors may be replaced by a different type of motor (brushless DC, AC), and it is important to note that the motor controllers would change in these situations.

5.3 Camera Control

The final design includes electronic camera control (sending signals directly to the camera to control recording and other functions), but the camera must support this kind of control in order to implement it. The camera we will be using for the prototype does not, and thus we have devised an alternative, though not ideal, method for controlling key functions of the camera. Our sponsor stated that powering on/off the camera and starting/stopping recording should be controlled remotely. The way we allowed these buttons to be pressed was by mounting two push-type solenoids to the top of the camera enclosure, such that their plungers rested on top of the respective buttons. The solenoids are driven by a dual h-bridge, which takes a 5V and 12V inputs and two digital signals and switches power to the solenoids.

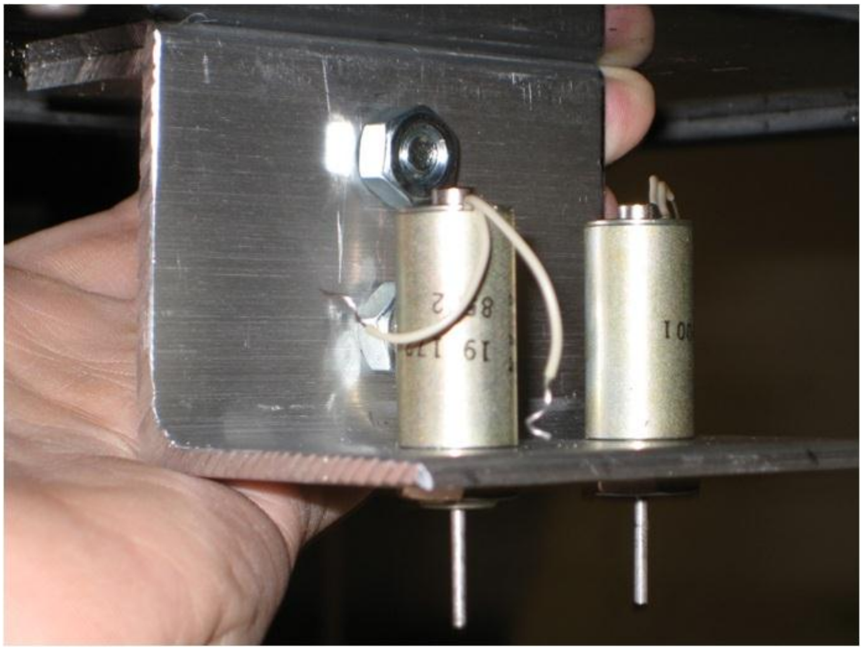


Figure 3. Photo of solenoids in their mounting bracket

5.4 Wiring and Cable Management

All wires are be properly shielded at for all lengths outside of an enclosure. Lengths of wire run through conduits fastened to the appropriate parts. The main electronics enclosure, containing the DAQ, power regulation and distribution, and all H-bridges, is fixed to the support assembly in order for the fewest number of wires to have to run to the rotating boom. One group of cables runs from the main enclosure, across the underside of the support assembly, and up through the bore of the center shaft and the gear affixed to it. Here, the two wires supplying power to the boom motor branch off and enter that motor's enclosure. The remaining wires, a ground wire, two supply wires for the solenoids, and two supply wires for the leadscrew motor, run to the end of the boom, off the end, and to the camera enclosure. The motor wires run into the motor enclosure, while the rest run into the camera enclosure to the solenoids. Another group of wires, comprising the signal wires from the instrumentation amplifier and supply power for the amplifier and the load cell, will run from the main enclosure, down one of the columns, beneath the platform (but on top of the base) to the load cell electronics box, which contains its instrumentation amplifier and all associated connections. The load cell electronics box is mounted on top of the base.

5.5 Motor Protection

Both motors are protected from weather by simple enclosure boxes, which leave openings only for wires and the output shaft. It is not as important that these boxes are completely weather-proof, as there is much less risk associated with damaging a motor than with the camera.

5.6 Camera Enclosure

The enclosure is as described in Section 4.4. The top plate and mounting plate assembly fasten to the rest of the enclosure using simple latches, allowing for easy access to the camera inside while still maintaining a tight seal when closed.

6. System Modeling

In order to aid with the selection of certain parameters and parts, we created a model of the system using MATLAB/Simulink and SimMechanics, which allows integration of physical bodies and motion constraints with Simulink systems. The model includes the key physical components of the system with estimated masses and inertia tensors where appropriate, and all of the necessary constraints to mimic the operation of the design.

Basic representations of both motors are included, which apply torque to the system based on the applied voltage and key parameters (no-load current, resistance, inductance, torque and EMF constants). Although we will be using PWM to control the motors in practice, we used average voltage control for the model, as simulating with PWM takes unreasonably long. Also represented are estimated efficiencies of each gear system, efficiency of the leadscrew, frictional losses in the motors, and friction between the boom and the support assembly.

All parameters that were uncertain to us were estimated conservatively, i.e. greater masses, greater friction, lower efficiencies than we would expect. Screenshots of the model are included in Appendix J for reference, along with our selected parameters.

Using this model, we were able to simulate the effects of various candidates for motors, gear assemblies, and leadscrews. This functionality was key in making decisions about motors and gear ratios. This model and results from our simulations will be referenced and discussed in section 8, Design Parameter Analysis.

7. Design Parameter Analysis

In this section, we will discuss how we selected the specific parameters to use for our prototype, which is a scaled-down and, in some aspects, limited-functionality version of our final design

7.1 Base

The hole diameters were designed for an interference fit with the columns as this part will act as the base for the overall frame. As stated above, the distance between holes was made so that the distance from the center of the support beam would both maximize the space for the test subject and be structurally stable from any forces on the support beam. The “cross” shape reduces the total mass compared with having a complete plate, without sacrificing the stability of the part.

The base needed to be heavy in order to keep the device’s center of gravity as low as possible. It does not attach to any moving parts and therefore we considered corrosion resistance to be less important; this decision was revisited, as mentioned in Section 11.2. We drilled holes in the pieces and welded them, so they had to be machinable and weldable.

Using CES, we looked for material that had a minimum density of 200 lb/ft^3 and a maximum price of $ 1/lb. The materials that CES came up with were different steel alloys, zinc alloys, and pure lead. A graph of price verses density can be found in Appendix I.

We decided to use A36 mild steel, because it is readily available to us in the machine shop and is cheap, heavy steel. It also gives us good stiffness, which is important because we want to minimize deformation within the frame. Material specifications for A36 steel are in Appendix I.

7.2 Columns and Support Assembly

The columns needed to be long enough so that the test subject would not bump into the top frame while eating, regardless of its position (on hind legs or on all fours). The only important considerations here were that the columns needed to be of equal length.

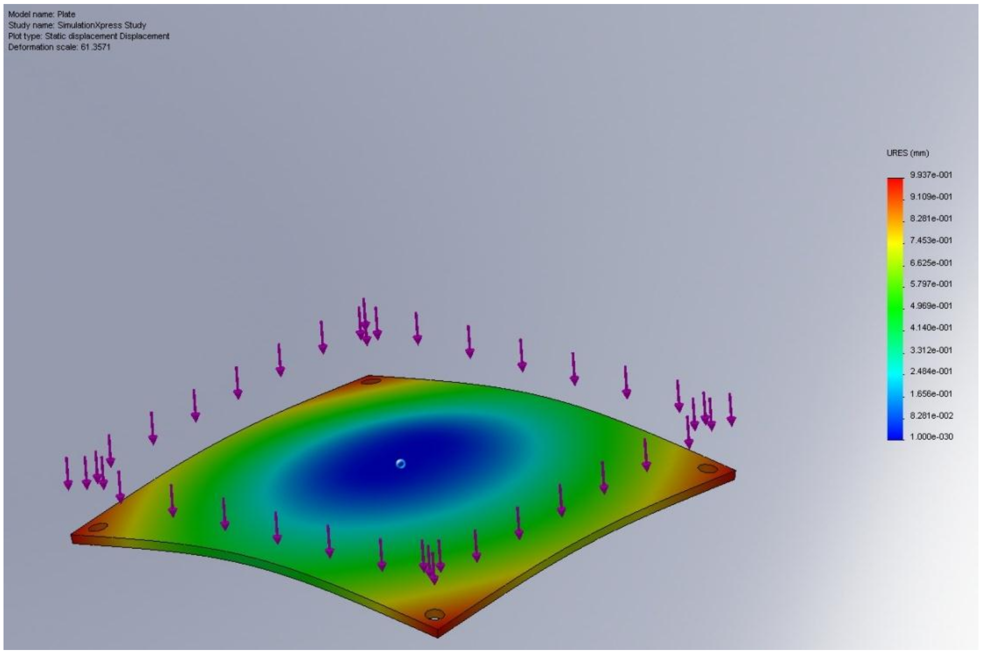
We designed the support assembly using the same parameters as the base. The only differences were in thickness and the addition of the hole for the center shaft. We needed a thicker part in comparison with the bottom frame as we needed to be sure of a stable fit with the center shaft as well as for the columns. The center shaft hole was dimensioned for an interference fit with the center shaft as we want the shaft and gear to remain stationary. The holes for the tops of the columns were dimensioned for an interference fit as we wanted good structural stability.

For these parts we decided to use 6061–T6511 aluminum. Relative to other aluminum alloys, 6061 has good corrosion resistance, good machinability, and good strength. Aluminum is a lighter material than the steel we will use in the base, which helps keep the center of gravity low. Aluminum is also corrosion-resistant, which is important as these parts will be exposed to the elements. Material specifications for 6061 aluminum are in Appendix I.

7.3 Platform

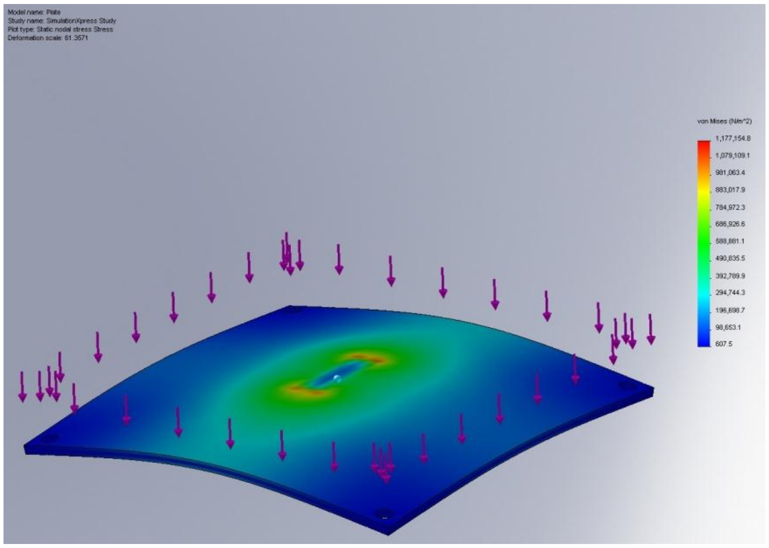
When designing for the platform, we mainly considered the largest animal size we would have to accommodate as well as the manufacturability of the part. We decided on a square shape for the plate because it will require less manufacturing time than any shape with contours, and the symmetry will allow for a relatively consistent view of the platform regardless of the angular position of the camera. The current side dimension allows for comfortable accommodation of a any animals up to the size of a large squirrel, while keeping the camera at a reasonable distance for it to both be in focus and have an appropriately-sized picture of the animal.

Our main issue with the thickness of the plate was getting enough elastic deformation without yielding for a range of weights (representing the weight range of the mammal species we are testing for) so that the load cell could record a reading. This was done mostly through use of linear statics tool of SolidWorks Simulation. An example simulation using the mass of a very large raccoon (mass of 15 kg) is shown in Figures 4 and 5.



Model name: Plate
Study name: SimulationXpress Study
Plot type: Static displacement Displacement
Deformation scale: 61.3571

Figure 4. Screenshot of a SolidWorks static deformation simulation for the platform



Model name: Plate
Study name: SimulationXpress Study
Plot type: Static nodal stress Stress
Deformation scale: 61.3571

Figure 5. Screenshot of a SolidWorks static stress simulation for the platform

The maximum displacement is about 1 mm at the hole and most of the stresses (up to ~ 1 MPa) will occur near the area where the platform rests on the load cell.

The hole diameters were designed for a press fit with the sleeve bearings as we wanted to prevent any bending or lateral sliding of the support beams. The inner diameter of the sleeves were chosen for a small clearance with the support beams as we wanted to be able to easily move the platform vertically along the support beams, while minimizing the sleeves' ability to tilt away from vertical. The holes are placed close to the corners of the platform to maximize the available platform space, while leaving enough material between them and the edges to maintain structural soundness and facilitate machining.

The platform should be able to deform slightly when loaded. A stiff platform, supported in the center and loaded at the edge, will tend to tip and could cause unwanted friction at the bearings. The platform must also be lightweight so that the smallest, most precise load cell as possible can be used. It will be exposed to the elements and must interface with the frame supports with minimal friction and therefore must not corrode or rust. We drilled holes for the supports in the platform, so the material had to be machinable. Using CES we set the minimum yield strength, tensile strength, and compressive strength to 5 ksi each. We set the minimum fracture toughness to 2 ksi·in$^{1/2}$ and a maximum density of 100 lb/ft^3. We made sure that it had good machinability and had excellent durability against water. The final constraint was that the material was less than $ 1/lb.

The materials that CES came up with were Acrylonitrile butadiene styrene (ABS), Polyethylene terephthalate (PET), Polypropylene (PP), and Polyvinylchloride (tpPVC). A graph of tensile strength versus density for these materials can be found in Appendix I.

For the platform, we decided to use PVC, as it is readily available to us in the machine shop and is a light material that is strong enough for our purposes. Material specifications for PVC are in Appendix I.

The platform was one area for which in building our prototype, we strayed from our plan. This will be discussed in Section 8.

7.4 Boom

The main considerations for the boom cross-section were displacements due to bending moments caused by the loading (in addition to the weight of the part) and manufacturability. We decided on a rectangular cross-section as most vendors sell long pieces in that shape, and the absence of any contours will give us an easier time creating the hole for the transmission shaft/gear as well as mounting the motor to the boom. The center hole diameter was chosen for a clearance fit with the center shaft for unrestricted rotation. The diameter of the hole for the leadscrew nut was, naturally, based on the leadscrew nut's outer diameter. The length of the boom was based on how far from the platform the camera would have to be to get a good recording while having clearance with the support beams.

We looked at materials with a high modulus of elasticity to minimalize the deflection of the boom. Due to the relatively small magnitude of the loads, yielding was not a major concern. As with the plate, we used SolidWorks Simulation to predict the approximate deflection caused by the loads and the stresses near the center hole. The results of the analysis are shown in Figures 6 and 7.

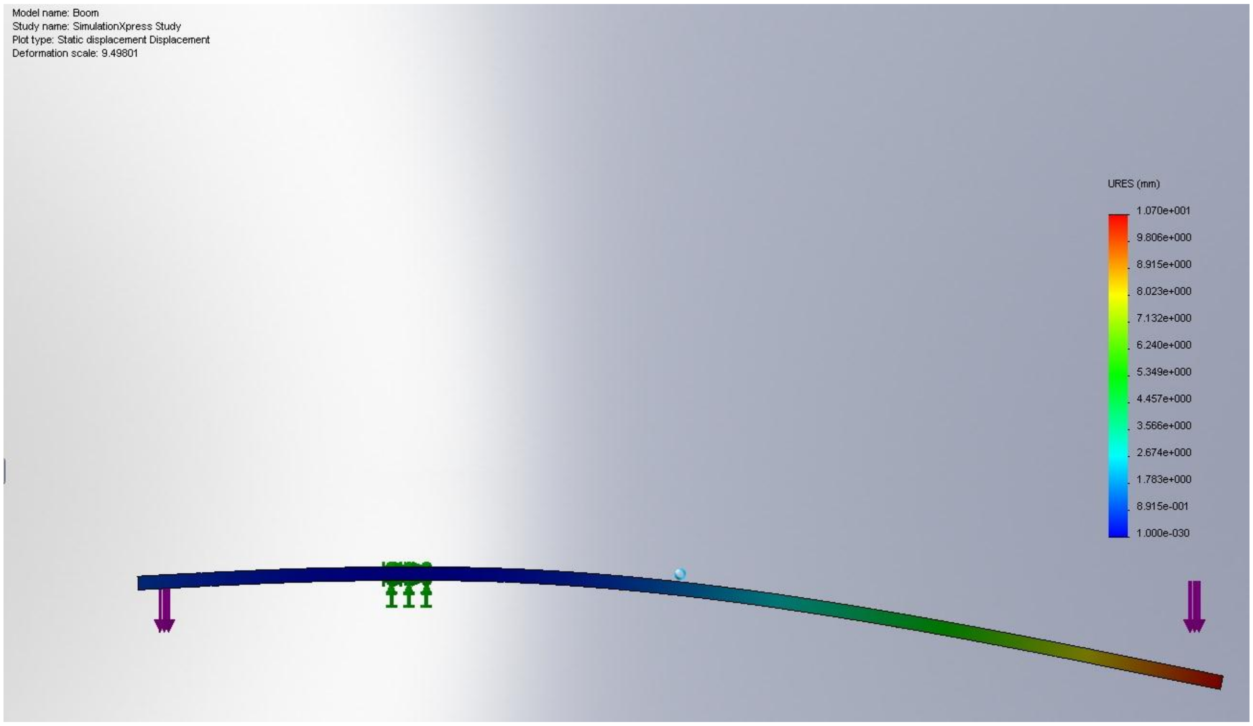
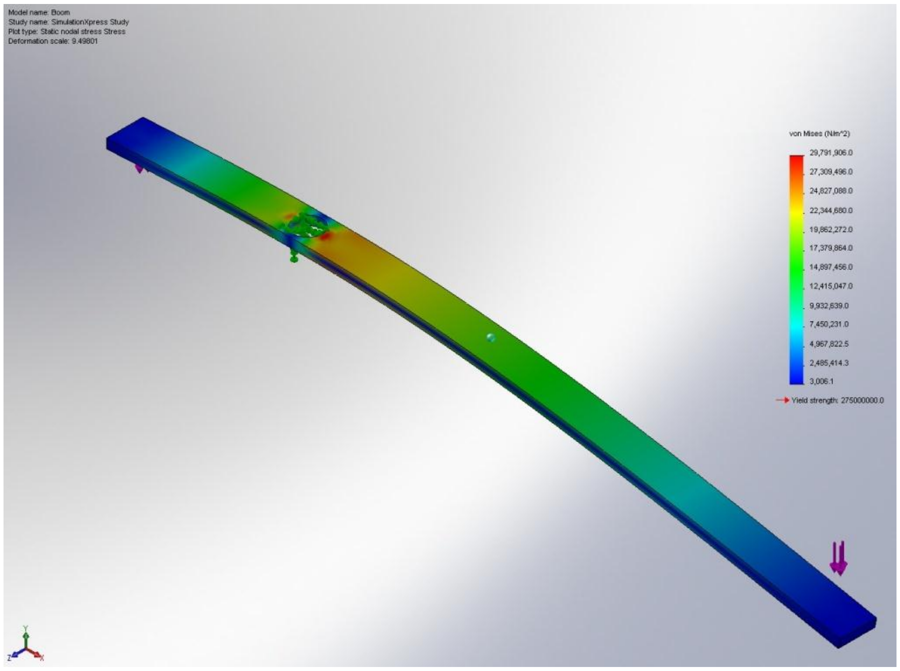

Model name: Boom
Study name: SimulationXpress Study
Plot type: Static displacement Displacement
Deformation scale: 9.49801

Figure 6. Screenshot of SolidWorks static deformation simulation for the boom



Model name: Boom
Study name: SimulationXpress Study
Plot type: Static nodal stress Stress
Deformation scale: 9.49801

Figure 7. Screenshot of SolidWorks static stress simulation for the boom

The simulation showed a maximum displacement of about 1 cm at tip of the boom, and a maximum stress of about 30 MPa near the center hole.

Our other important considerations were corrosion resistance, since the part will be almost fully exposed, and cost. We decided to use 6061–T6511 aluminum for the boom. It will offer corrosion resistance, a relatively light weight, and a satisfactory stiffness to keep deflection to an acceptable level. Material specifications for 6061 aluminum are in Appendix I.

7.5 Camera Enclosure

Manufacturability played a large role in our choice of a box-shaped enclosure. This shape will allow us to assemble the enclosure plate by plate. The total volume is based on the approximate volume of the camera and includes extra room for the camera actuator solenoids. The thickness of the plates is based on calculations for the ability to withstand an impact, while trying to also minimize weight.

The two main material properties we looked when deciding what material to use were the density, yield strength, and fracture toughness. We needed an acceptable yield strength to withstand any impacts the enclosure might encounter (such as an animal running into it). As mentioned above, we also looked to minimize the weight of the enclosure, in order to minimize deflection of the boom and to reduce the friction between the boom and the center shaft.

Using CES we set the minimum yield strength, tensile strength, and compressive strength to 1 ksi each. We set the minimum fracture toughness to 2 ksi·in$^{1/2}$ and a maximum density of 100 lb/ft^3.

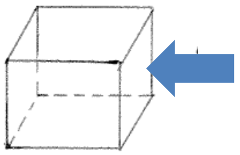
CES came up with many materials that we could use for the camera box. The families of materials that CES came up with were natural materials, polymers composites and metals. A graph of fracture toughness verses density for these materials can be found in Appendix I.

We are using PVC for the top and bottom of the box and polycarbonate for the sides. PVC is harder and stronger than polycarbonate, but polycarbonate is lighter and transparent. Both of these polymers have the same fracture toughness. Both materials will not corrode, which is important as proper protection of the camera depends on their integrity. Material specifications for polycarbonate are in Appendix I.

7.5.1 Enclosure Box Impulse Analysis

The purpose of the enclosures is to protect all sensitive electrical equipment and power transmission system (including gears and bearings) from physical damage as well as moisture damage. We would model impact forces on areas the size of the body parts of our test subjects to see if there is any chance of the enclosure yielding or fracturing.

The camera enclosure should be strong enough to withstand and absorb all the shocks caused on it. When an animal collides with the box, it transfers its momentum to the box as an impulse, as shown in Figure 8. The camera enclosure should be designed to be strong enough to dissipate this energy without taking damage.



$$J = m_{animal} \cdot \Delta V_{animal}$$

Figure 8. Camera enclosure. *J* is the impulse applied to the enclosure, m_{animal} is the mass of an animal, and ΔV_{animal} is the change in velocity of the animal. In this case, we assume that the animal comes to a stop, so ΔV_{animal} is the animal's velocity when it strikes.

The system will collect data from a range of mammals from chipmunks to raccoons. A raccoon is the heaviest in the range and the chipmunk is the lightest. Raccoons (*procyon lotor*) can weight, in extreme cases, up to 15.9 kg, and their top speed on ground is about 6.71 m/s [23]. A chipmunk (*tamias striatus*) weighs up to about 0.113 kg and the top speed of a chipmunk is about 9.39 m/s [7]. A squirrel (*sciuridae*) weighs up to 1.00 kg and can run as fast as 7.15 m/s [26]. Equation 1 describes the impulse that an animal can cause, where *J* is the impulse, m_{animal} is the mass of the animal, and ΔV_{animal} is the change in the animal's velocity at the moment of collision. In this case, it is assumed that the animal comes to a stop when it collides with the camera enclosure. Therefore, the change in velocity will be zero minus the animal's maximum velocity which gives the animal's maximum velocity in magnitude. Heavier animals tend to have lower maximum speeds and lighter animals tend to have higher maximum speeds.

$$J = m_{animal} \cdot \Delta V_{animal} \text{ Eq. 1}$$

Using Equation 1, the maximum impulse that each species of animal can cause is shown below.

$$J_{chipmunk} = m_{chipmunk} \cdot \Delta V_{chipmunk} = (0.113\ kg) \times \left(9.39\frac{m}{s}\right) = 1.06\ kg \cdot m/s$$

$$J_{squirrel} = m_{squirrel} \cdot \Delta V_{squirrel} = (1.00\ kg) \times \left(7.15\frac{m}{s}\right) = 7.15\ kg \cdot m/s$$

$$J_{raccoon} = m_{raccoon} \cdot \Delta V_{raccoon} = (15.9\ kg) \times \left(6.71\frac{m}{s}\right) = 107\ kg \cdot m/s$$

The weight of the animals which could strike the device can be as light as 0.113 kg but can also be as heavy as 15.9 kg. However, the maximum speeds of animals vary a little compared to the maximum weights of the animals. Since the masses of animals differ a lot more than the maximum speeds of the animals and since a raccoon is the heaviest animal within the range, it is reasonable to say that the maximum impulse will be that of a very heavy raccoon, or about 107 kg·m/s. It is not expected that all, or even most, of this momentum will be transferred to the enclosure in the event of a collision. A good portion of the momentum will remain with the animal itself, and likely most of the energy from the collision will be dissipated in other parts of the device, namely the leadscrew, guide shaft, and boom.

7.6 Boom Actuation and Power Transmission

The choice of motors and power transmission is directly related to the overall size of the system, as along with increasing size comes increased mass of parts and increased torque required to move them.

Our primary aid in selecting parameters for actuation and power transmission for our prototype was our MATLAB model. After trying a few different motors and gear ratios in our simulation, we settled on a high-torque DC gear motor, shown in Figure 9. At no-load, the motor draws a current of 800 mA and spins at 100 RPM. At stall, the motor produces a torque of 3.43 N·m.

Figure 9. Boom motor

The power from the motor is transmitted through a set of gears with a 1:4 ratio in order to further increase the torque and reduce the speed to a workable level.

We simulated the motion of the boom by plugging this motor into the model and applying a half-power (6 V) to it, starting with the system at rest. Shown in Figure 10 are the results.

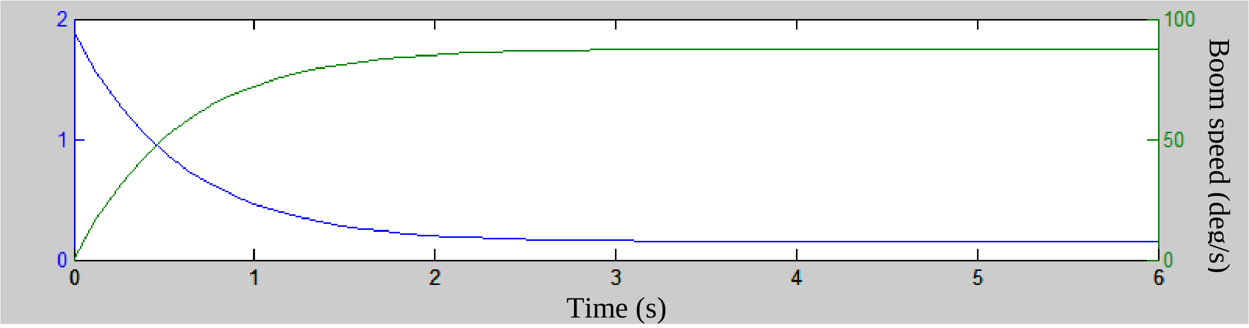


Figure 10. Simulation results with boom motor at half-power

It should be noted that at half power, the motor draws a maximum of less than 2 A. The boom reaches a speed of about a quarter of a rotation per second at this power, which is an ideal speed for normal operation. For our prototype, we found the combination of the aforementioned motor and a 4:1 gear ratio to yield the best trade-off between a low current draw, a reasonable operating speed, and sufficient torque.

One concern that we have regarding this motor is the strength of its gearbox. The combination of the motor's very high gear ratio (1:250) and the great inertia of the moving boom could possibly lead to broken gears, depending on their strength. As we had trouble finding specifications for the motor's gearbox, we were left to test the strength of the gearbox ourselves, taking some solace in the fact that the motor is relatively inexpensive to replace.

7.6.1 Wind Analysis and Resulting Torque

We expect that the greatest torque on the motor's gearbox will be caused by gusts of wind striking the enclosure box. The force exerted by wind on a flat surface is described by Equation 2, where F_{wind} is the force caused by blowing wind, ρ_{air} is the density of air, Q_{air} is the volumetric flow rate of air, and V_{air} is the velocity of air [6].

$$F_{wind} = \rho_{air} \cdot Q_{air} \cdot V_{air} \quad \text{Eq. 2}$$

$$Q_{air} = A_c \cdot V_{air} \quad \text{Eq. 3}$$

The maximum speed of wind occurs when the wind velocity is the highest which is January [2, 7]. In order to know the air density, ρ_{air}, the temperature is needed. The recorded lowest temperature in January is -30 ºC [7] and the corresponding air density is 1.438 kg/m^3 [1]. The average highest wind speed, V_{air}, in January is 6 m/s [2]. The volumetric flow rate of air, Q_{air}, can be obtained by multiplying the cross sectional area of the corresponding part of the system with the wind speed as shown in Equation 3 above, where A_c is the cross sectional area of the part of the system where the wind blows onto. In this case, the cross sectional area of interest is that of the camera enclosure.

$$F_{wind} = \rho_{air} \cdot A_c \cdot V_{air}^2 = \left(1.438\ \frac{kg}{m^3}\right) \times (0.0290\ m^2) \times \left(6\ \frac{m}{s}\right)^2 = 1.50\ N \quad \text{Eq. 4}$$

The calculation of the force by wind is shown above in Eq. 4. The calculation of wind force is done for the worst case scenario where the wind force is the greatest. In the worst case, the surrounding temperature is the lowest, which makes air density, ρ_{air}, the thickest. Also, the cross sectional area, A_c, considered here is the cross sectional area of the camera enclosure which is the biggest area where the wind will blow on. The worst case wind speed, V_{air}, is the fastest wind speed which occurs in January according to the record [2, 7].

Therefore, the moment caused by the wind can be obtained by using the moment Eq. 5, where M_{wind} is the moment caused by wind and h is the distance from the center of the gear mounted on the beam to the end of the beam where is the camera enclosure is attached.

$$M_{wind} = F_{wind} \cdot h = (1.50\ N) \times (0.762\ m) = 1.14\ N \cdot m \quad \text{Eq. 5}$$

This calculation on the moment caused by wind is also for the worst case where the variable h is the longest. The moment obtained from Eq. 5 above is 1.14 N·m which is substantial but likely not problematic amount. This torque being applied quickly could still cause issues, however, and we recognize the fact that the gearbox is at risk and we currently lack a robust solution to the problem.

7.7 Leadscrew Actuation and Power Transmission

The torque and speed required to move the camera enclosure vertically depends mainly on the mass of the enclosure and the efficiency of the leadscrew. For the prototype, the main driving factor was this mass, as the leadscrew efficiencies did not vary greatly among our considered options. This mass is mainly based on the construction of the camera enclosure, the camera choice, and the length and size of the leadscrew. A longer leadscrew may be required for larger implementations, and a wider leadscrew may be necessary to support greater loads.

We also used the MATLAB model to find an ideal system of actuation for the leadscrew for our prototype. We first selected our leadscrew based on availability, cost, and ease of integration with our project, and settled on one with a lead of 0.1 inches.

Based on the speed of the motor we estimated would be necessary (5000 RPM after gearing), our motor selection was much more limited this time. We sampled various motors and gear ratios in the model and settled on a 12 V DC brushless motor with a no-load speed of 15,000 RPM and a stall torque of 0.56 N·m. This, in combination with a 2:1 gear ratio and the leadscrew mentioned above, produced acceptable simulation results.

Below are shown the results of a simulation run using these parameters, with the system starting at rest and 2.4 V applied to the motor.

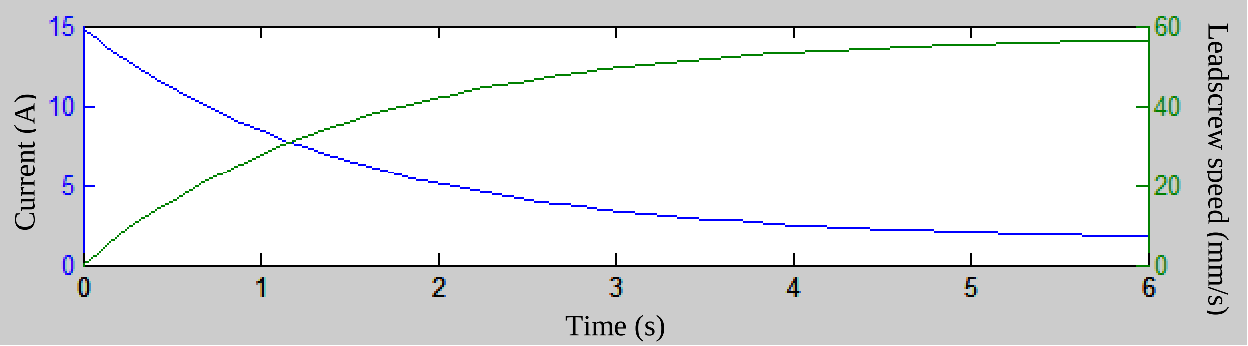


Figure 11. Simulation results with leadscrew motor at 1/5 power

At 1/5 power, the leadscrew reaches a (simulated) translational speed of 4 cm/s, sufficient for normal operation, by about 2 seconds. By that time, the current, which started at around 15 A, is under 5 A and continues to decrease as the leadscrew gains speed. This configuration was decided to be ideal, as it appeared to provide plenty of torque and speed to the leadscrew, and while it would be the largest power draw in the system, it was not predicted to draw enough to be an issue.

Leadscrew actuation another major areas in which the construction of our prototype differed from our plan; this will be discussed in Section 8.

7.8 Load Cell

The choice of load cell in the Final Design depends almost entirely on the maximum animal mass the system is being designed for. The load cell must be able to support the mass of the platform plus the mass of the largest animal which could fit on the platform. Even if the system is only intended for certain animals, there is no way to know what sort of animal might happen upon the device; this is why it’s important to design for any animal that could possibly fit.

With our prototype, we determined that the heaviest animal we need to design for is a raccoon. We estimated this to be the heaviest animal which could fit on the device. Raccoons can weigh up to 10 kg and our platform (including bearings) will weigh around 3.3 kg, so we decided that our load cell should be able to safely handle 14 kg. We originally selected a load cell which can measure up to 10 kg and has a safe-load capacity of 15 kg. It would cut it close, but we didn’t expect to encounter any raccoons weighing over 10 kg – that in itself is an extreme case. After discussing this choice with our sponsor, we went with a smaller-scale load cell, measuring up to 6 kg and supporting up to 9 kg. Our sponsor stated that he did not expect that heavy animals stepping on the device to be a problem, and that the better resolution would be worth the change.

The load cell we have chosen claims an accuracy of 0.02 % full range, translating to a measurement accuracy of 1.2 g. This resolution is not final for our purposes, however, as the resolution of our data acquisition device factors in as well, as discussed in Section 7.9.

7.9 Electronics and Signal Transmission

The DAQ must have at least one analog input and must be able to control 4 H-bridges with digital signals. The DAQ we selected for our prototype does not support PWM generation, so PWM is generated in a separate circuit. Therefore, in our prototype design, the DAQ uses four digital outputs; two control the solenoid H-bridges and two send direction signals to the motor H-bridges. It also uses two analog outputs to send voltages to the PWM circuit for comparison (illustrated in Appendix H). The single analog input handles the signal from the load cell and amplifier.

The last parameter of concern for the DAQ was the resolution of the analog inputs. With the output of the load cell properly amplified so that the output range of the load cell matches the input range of the DAQ, the lesser of the two resolutions of the DAQ and the load cell will theoretically be the limiting one. The DAQ used in our prototype has an analog input resolution of 12 bits, or 4096 discreet values. This means that the DAQ supports an accuracy of 2.44 g; this will be the best-case resolution at which we can measure mass.

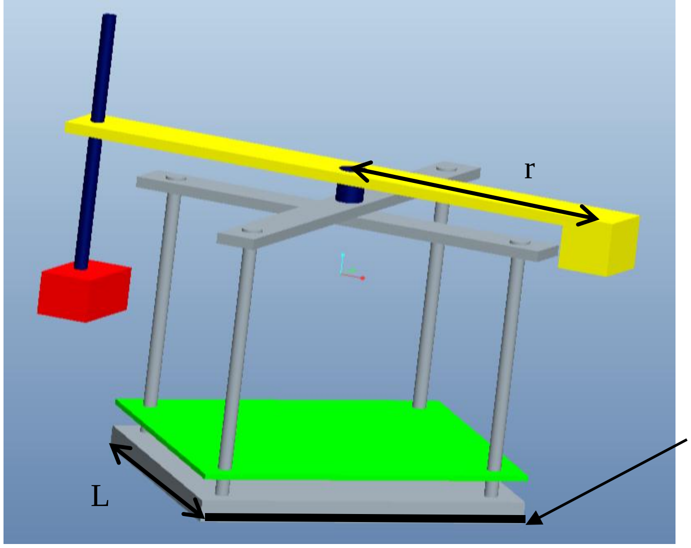
As mentioned earlier, the output of the load cell must be amplified so that its range matches the input range of the DAQ. Our DAQ has an input range of 0 - 10 V and our load cell outputs voltages of 0 - 24 mV when excited with 12 V, so the load cell output should ideally be amplified 417 times. We actually amplified the signal about 450 times, essentially discarding part of the top end of the load cell's measurement range in favor of better resolution. When choosing an instrumentation amplifier, we only had to make sure that it could handle an input voltage of 12 V and that it could produce a gain of at least 500. These requirements were easy to meet.

In our selection of the H-bridges, the parameter to which we paid the most attention was the maximum current outputs they could produce. For our boom motor, we needed an output current of at least 2 A. For the leadscrew motor, we determined needed an output current of at least 5 A continuous. We had little trouble finding H-bridges which met these requirements.

In the Final Design, the communication between the DAQ and the computer will be wireless, and control of the camera will be performed electronically. For our prototype, the communication is hard-wired. The DAQ we chose has a USB connection, which we planned to convert to serial (RS-232 or RS-485, depending on the desired distance) to run to the computer. USB's range is very limited – about 16 ft per cable – but RS-232 and RS-485 connections offer longer distances – 50 ft and upwards of 500 ft, respectively. This is another area in which our prototype differed from our plan (Section 8).

7.10 Tipping Analysis

Another aspect of the system that we analyzed was the moments that can be caused when an animal runs into the system. There are two types of possible moments that can be caused. The first case is the case in which an animal runs into the camera enclosure. The moment caused by the animal is Eq. 6, where M_{animal} is the moment of the animal, m_{animal} is the mass of the animal, a_{animal} is the horizontal acceleration of the animal at the time it collides with the enclosure and h is the vertical distance from the point where the animal hits the enclosure to the ground.



Axis about which the system rotates when tipping

Figure 12. Select dimensions labeled on full system.

$$M_{animal} = m_{animal} \cdot a_{animal} \cdot h \text{ Eq. 6}$$

Calculation for the moment of animal is shown in Eq. 7. Since raccoon is the heaviest animal in the range, the mass of raccoon is used in the calculation. Since acceleration of animals is hard to obtain, we decided to look for the maximum acceleration allowed by putting the acceleration as *x* and then later seeing if an animal can accelerate faster the maximum acceleration.

$$M_{animal} = (15.9\ kg) \times \left(x\ \frac{m}{s^2}\right) \times (0.610\ m) = (9.70 \cdot x)\ N \cdot m \text{ Eq. 7}$$

The moment of the camera enclosure can be expressed as Eq. 8, where M_{camera} is the moment of the camera enclosure, m_{total} is the total mass of the system, g is the gravitational constant, and r is the distance from the center of the camera beam to the end of the beam. In this case, the moment of the camera enclosure should be equal in magnitude and opposite in direction to the moment caused by the animal in order for the system to stand still without tipping over.

$$M_{camera} = m_{total} \cdot g \cdot r \text{ Eq. 8}$$

The moment of camera enclosure is calculated in Eq. 9, which is 170 N·m.

$$M_{camera} = (22.7\ kg) \times \left(9.81 \frac{m}{s^2}\right) \times (0.762\ m) = 170\ N \cdot m \text{ Eq. 9}$$

The second case is when an animal runs into one of the supports in the four corners of the platform. The moment caused by the animal is the same as Eq. 6 in the previous case except that the h denotes the vertical distance from the point on the support where the animal hits to the ground. The moment of the total system is expressed as Eq. 10, where M_{total} is the moment of the total system and L is the length of a side on the platform.

$$M_{total} = m_{total} \cdot g \cdot L \text{ Eq. 10}$$

The moment of the total system about the axis marked in Figure 12 is calculated in Eq. 11, which is 136 N·m.

$$M_{total} = (22.7\, kg) \times \left(9.81 \frac{m}{s^2}\right) \times (0.610\, m) = 136\, N \cdot m \text{ Eq. 11}$$

M_{total} should also be equal in magnitude and opposite in direction to the moment caused by the animal so that the whole system doesn't tip over. Since M_{total} is smaller in value than M_{camera}, M_{total} is the maximum value of M_{animal}. Hence, in order to obtain the value of x in Eq. 7 above, Eq. 7 and Eq. 11 above are compared as Eq. 12.

$$(9.70 \cdot x) N \cdot m = 136\, N \cdot m \text{ Eq. 12}$$

$$x = \frac{136}{9.70} = 14.0 \frac{m}{s^2}$$

The allowable maximum acceleration for an animal is 14.0 m/s^2 as obtained above. Considering that a cheetah, the world's fastest land mammal, accelerates at 8.89 m/s^2 [6], this value of x is far greater than the acceleration most animals in our range can have.

8. The Prototype

Figure 13. Photo of prototype, without wiring installed

Many of the details of the prototype have been described in Section 8; here, we will review the key aspects, differences from the prototype plan, and differences from the Final Design.

The prototype is designed to accommodate animals as large as squirrels. The size of this prototype is likely close to the smallest implementation that will ever be made. The platform is be a 2 ft-by-2 ft square, with a column height of 2 ft, giving the even the largest of squirrels a comfortable amount of space.

Due to issues with the shipment of our platform piece, we ended up making our own platform out of materials readily available to us. The new platform consisted of two sheets of sheet aluminum with pieces of PVC between them for added rigidity. After testing the implementation, we quickly decided that the sleeve bearing interface with the columns was a terrible plan. We instead widened the holes in the platform so that there was plenty of clearance between the platform and the columns, and fixed the platform securely to the load cell at the center. This design could have issues with applying a moment to the load cell if the animal sits near the edge of the platform, but is a decidedly better method than our original conception, as it eliminates any frictional effects on the weight measurements.

The load cell can measure up to 6 kg. It can safely handle up to 9 kg, enough to accommodate just about any animal expected to possibly stand on the platform, and can measure with an accuracy of 1.2 g.

The data from the load cell is amplified and sent to a DAQ. The resolution of the DAQ is 12 bits, meaning the accuracy of the load cell measurements its limited to about 1.46 g. According to a source with related experience, the true resolution, factoring in electrical noise and other real-life factors, was predicted to be around 5 g. One aspect of the prototype design which was not implemented due to limited time was the serial communication. As it stands, the DAQ will have to interface with the computer over USB only, leaving us with a maximum distance of 5 m. This can readily be improved even on the prototype, however, as USB is widely supported and there are many possible methods of extending the communication range.

While our final design calls for battery power, after discussion with our sponsor and in the interest of time, we decided not to implement batteries for our prototype – it currently runs off of an externally supplied 15 V DC. Adapting the device to run off of batteries would be relatively simple, though – a battery pack which supplies 14.7 V with a protection circuit board would be perfect and simple to include.

The most significant deviation from our prototype plan that we made was scrapping the leadscrew actuation system. With our limited knowledge of motors, we ended up with one which we couldn't use, and after further issues with getting the correct leadscrew nut, we decided in the interest of time to not implement leadscrew actuation. The leadscrew can still be turned manually to adjust the height of the camera box. The exclusion of this system simplified electronics significantly, leaving us with one less motor to control, a significantly lower maximum current draw, and a reduced camera enclosure assembly weight, all of which factored into our decision to do so.

The center shaft was not, as in the plan, press fit into the support assembly, but rather was welded to the assembly as an undesirable but quick solution to an over-bored hole problem. This caused further issues which will be discussed in Section 11.3.

8.1 Validation Potential

An important issue to address regarding the prototype is how well it can possibly validate the final design; that is, based on the magnitude of the differences between the prototype and the final design, how well does success of each function of the prototype translate to validation of the final design?

8.1.1 Camera actuation subsystem

The method of actuation that we incorporated, namely the rotating boom and leadscrew, is certainly scalable to a certain extent. Considering an implementation of the final design which would accommodate cattle-sized animals, an appropriately sized boom would definitely be feasible, and although it would require a powerful motor and a good bearing, it's not outside the realm of possibility.

Leadscrew actuation should remain effective as the device is scaled up. The lead of the screw would have to be increased to obtain a reasonable speed in operation, but the efficiency of leadscrews tends to increase with the lead. So, while a larger motor would still be required to drive it, the leadscrew would actually become a more efficient system in a larger version of the device.

Unfortunately, as we are not implementing leadscrew actuation for our prototype, we cannot validate this system at this time. However, we can and have confirmed that the leadscrew can support the weight of the camera enclosure without slipping, and that the enclosure does indeed move vertically as the leadscrew turns.

We believe that the prototype can definitely validate the boom part of the actuation subsystem, but it is unable to fully validate the leadscrew part.

8.1.2 Platform subsystem

We can't foresee any problematic differences between our prototype-sized platform and a full-scale platform. Since removing the bearing interface between the platform and the columns, there isn't much to the platform subsystem; its only major role is to transmit any weight it bears to the weight measurement system beneath it. As long as the full-scale platform is made of a sufficiently rigid material, there is no reason that it shouldn't function just as well as our prototype platform.

8.1.3 Camera enclosure subsystem

There are no major differences between the enclosure of the prototype and that of the final design. Possible differences would be a different shape to accommodate a different camera, a slightly larger size, and different material, all of which are minor and none of which should have an effect on the fulfillment of the customer requirements.

The camera control subsystem (button-pushing solenoids) would not be present on the final design, which calls for camera control using a direct signal from the operator. Technically, this aspect of the final design can't be validated by our prototype, but we also see this system being straightforward to implement on the final design, as long as an appropriate camera is chosen.

The success of our prototype camera enclosure subsystem would indeed validate the design, outside of the camera control subsystem.

8.1.4 Weight measurement subsystem

Load cells are made in capacities and accuracies exceeding the possible demands of the final design. As long as a load cell is selected which can resist the large moments created by a larger platform, it should function just as well as the one in our prototype does. The biggest issue with scaling up the design would be the increased cost of the load cell. Outside of cost concerns, though, the performance of the load cell in the final design can be accurately represented by the performance of the one in our prototype.

8.1.5 Electronics

There would be a few differences in the electrical components of a full-scale device. Firstly, as the motors would be larger and more powerful, the wiring would have to be a larger gauge in order to handle the larger current draws. The controllers for these motors will also have to be larger in order to handle the current increases. The amplification of the load cell signal may also have to be handled slightly differently depending on the load cell in use. None of these differences are expected to affect the electronics' ability to perform their function, though, so we believe that the prototype is sufficient to validate the electronics systems of the final design, excluding camera control.

9. Fabrication Plan

In this section we will discuss our original plans for machining and assembly and the differences between the plans and our execution.

9.1 Machining

To determine our machining speeds, we used Equation 13, where V (ft/min) is the feed rate and D (in) is the diameter of the tool.

$$RPM = \frac{12V}{\pi D} \quad \text{Eq. 13}$$

All interference fits mentioned had 0.002 – 0.003" of interference, providing an optimal level of sturdiness while allowing easy manufacture.

9.1.1 Base

The base is made with two rectangular steel bars 3 in wide and 0.25 in thick. One has a 3 in long section cut out exactly in the middle using a bandsaw. After smoothing the ends of the cut, the two halves are welded to the uncut bar to form an “X” shape. Holes are then drilled for the columns using a size U drill running at 300 RPM. The welded parts should be positioned as accurately as possible to line up with the center of the long piece. These holes will be used as references to make the holes in the platform and support assembly. These holes are later reamed to produce the smallest possible interference fit with the columns.

9.1.2 Platform

The PVC platform is made from a PVC plate with a thickness of 0.5 in. The holes for the sleeve bearings are drilled with 63/64 in sized drill at 450 RPM.

In reality, we made our platform out of sheet aluminum and pieces of PVC sheet, as mentioned earlier. Two pieces of aluminum were first cut at 2 ft x 2 ft, and four holes of 1.25” diameter were drilled at the corners based on the position of the holes in the base. PVC pieces were laid on the middle of the first sheet in an X-shape for rigidity. After an attempt to complete the platform with sleeve bearings at the corners, we realized that the bearings caused far too much friction, and decided to scrap them completely. Instead, extra PVC pieces were placed along the four edges of the platform for further support, and the whole assembly was glued together much like a sandwich (with sheet aluminum as the bread and PVC as the contents.) Holes for two screws, the positions of which were transcribed by hand from the mounted load cell, were drilled in the center of the platform in order to allow it to be screwed into the load cell.

9.1.3 Columns

The ¾ in aluminum support beams are cut to length using a band.

In reality, the shaft diameters were too great to fit into the mating holes in the base and support assembly. This problem could be solved if we had a properly sized ream to widen the holes, however we did not and instead sanded down the ends of the columns on a lathe until they were appropriately sized for a slight interference fit.

9.1.3 Support Assembly

The initial fabrication of this part is the same as the base plate expect for the fact that the material will be 6061 aluminum alloy and will have dimensions of 2 in x 0.5 in. The holes for the columns are drilled at just under 0.5 in and reamed to produce an interference fit. The center hole is drilled using a bit just under 1.5 in. The hole is then bored to a size which will create an interference fit with the center shaft. A final hole is drilled for a setscrew and tapped, the size of which depend on the size of set screw being used.

When building this part, we decided not to cut the 2 in section out of one piece and instead welded the two pieces one on top of the other to form the same X-shape. The holes for the columns were drilled prior to welding, using the base a template. The pieces were lined up against the base and ensured to be orthogonal before welding them together. The differences in height among the ends of the support assembly also meant that we had to cut two of the columns shorter by 0.5 in, which we did using a band saw at ~300 fpm.

Since the center shaft ended up being welded into this part, the setscrew was not necessary and was not included.

9.1.4 Boom

The large 1.5" hole is face-milled at 2000 RPM. The hole for the leadscrew nut is drilled using a size C drill at 3000 RPM. The hole for the guide shaft is drilled using a size E drill at the same speed.

9.1.5 Center Shaft

The shaft about which the boom rotates is made from a 1.5 in diameter solid aluminum cylinder. The two threaded holes for mounting the gear are drilled at 3000 RPM using a size 32 drill and then tapped manually. The center hole is drilled using a ½ in drill at 3000 RPM.

9.1.6 Enclosure Box

Polycarbonate sheets 3/16 in thick are cut using a band saw and then milled into the appropriate dimensions for the four side faces of the enclosure using an appropriately sized end mill running at 1800 RPM.

The ¼ in-thick PVC for the bottom portion of the enclosure is initially cut using a band saw and then properly dimensioned appropriate size end mill running at 1800 RPM. The hole for the camera mounting screw is drilled with a size D drill at 1800 RPM and then tapped manually.

For the top plate, the initial process is the same as the bottom plate. After the part is properly dimensioned, the five 0.25 in holes are drilled with a size C drill at 1800 RPM and then tapped manually.

For the mounting plate, the process will be exactly like the process of the top plate only with an additional hole of diameter 0.375 which is drilled using a size U drill at 1800 RPM. The holes for the bolts holding the mounting plate to the top plate are drilled using the top plate as a template.

In execution, we decided to produce four additional rectangular box-shaped pieces of PVC to sit in the four bottom corners of the enclosure box. These blocks need only to be at least 1 in in each dimension and to be squared off.

9.2 Assembly

This section describes the steps involved in assembling the various parts of the device.

9.2.1 Enclosure Box

The enclosure is composed of six different plates, four polycarbonate, two PVC. The two PVC plates will be the top and bottom of the enclosure. Figure 14 gives a visual guide of the assembly process. The four blocks are glued to the bottom plate at their appropriate positions, using the polycarbonate pieces as guides to space the blocks out from the edges of the plate. They are then screwed to the bottom plate from beneath. The four polycarbonate pieces (walls) are then glued to on the base and screwed in at the square sections. At this point, all edges of the enclosure are sealed with epoxy. The camera mounting bolt is screwed into the bottom plate with a small neoprene piece used as a sealing washer.

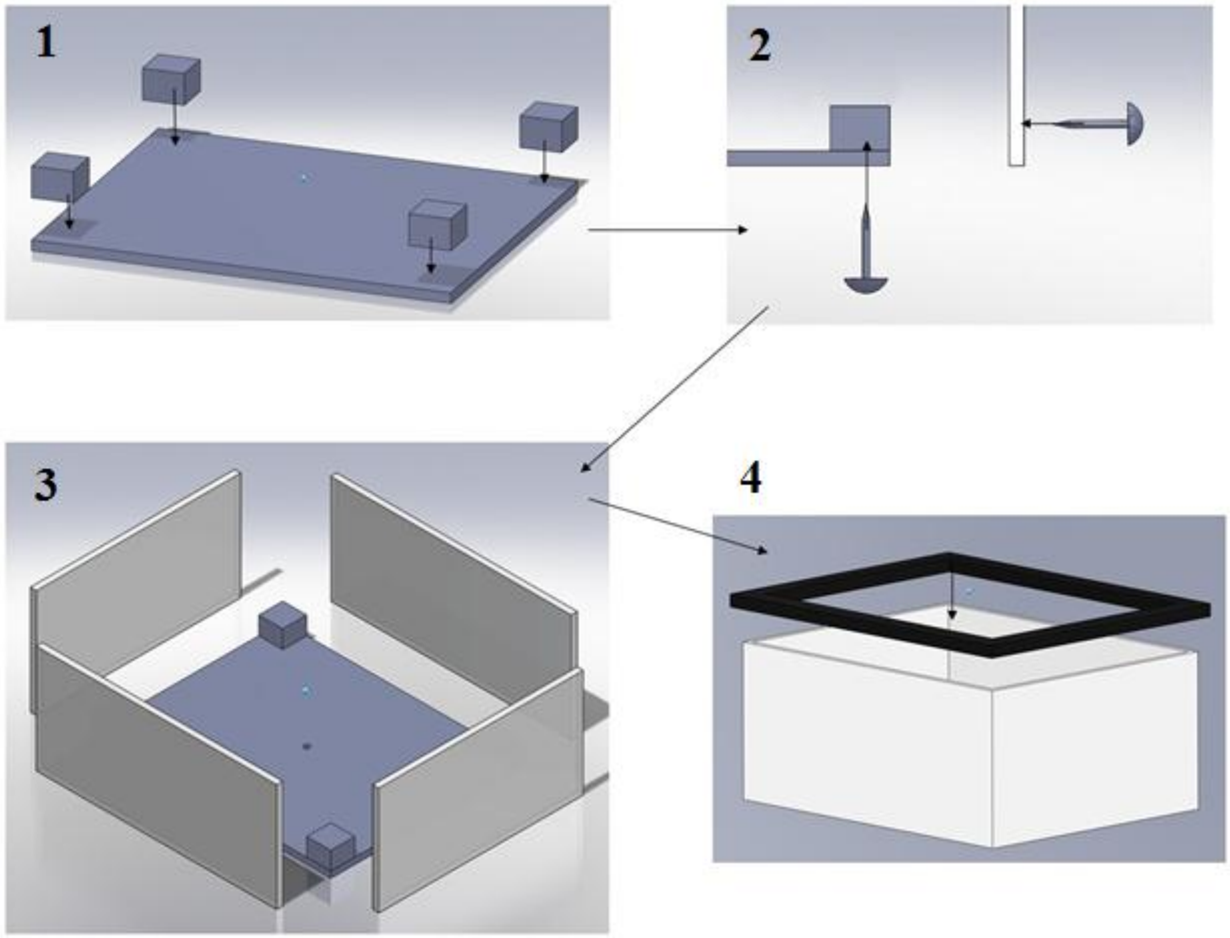


Figure 14. Steps for enclosure box assembly

The neoprene liner is glued to the underside of the top plate. The four bolts are driven up through the top plate, leaving their ends exposed to fasten to the mounting plate. An exploded view of the top plate assembly is shown in Figure 15.

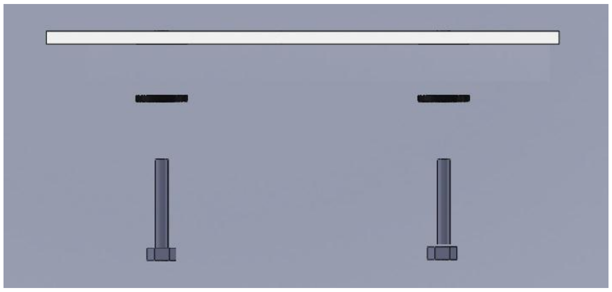


Figure 15. Top plate, exploded view

10.2.2 Frame

An exploded view of the frame can be seen in Figure 16. The four columns are press fitted into the steel base. The four sleeve bearings are press fitted into the four holes in the PVC platform.

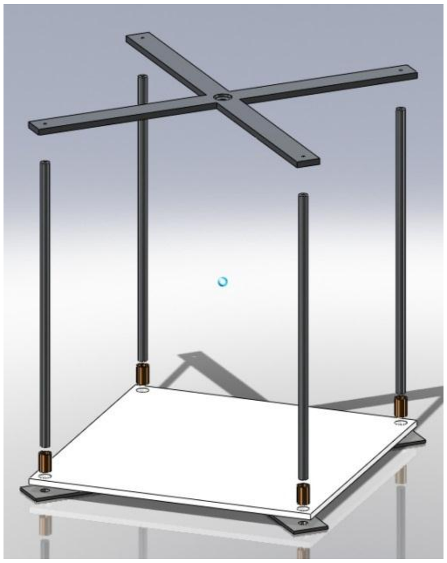


Figure 16. Exploded view of frame-platform assembly

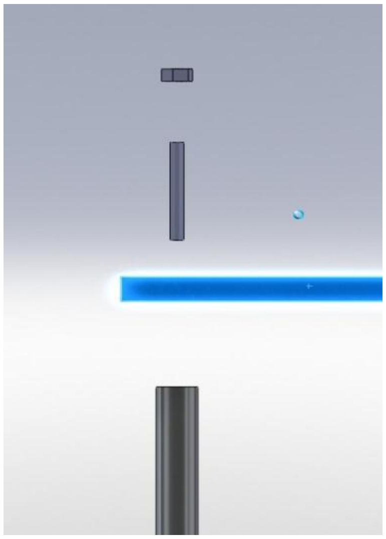


Figure 17. Exploded view of the column-support assembly interface

Here is a point where we deviated from our original plan; as mentioned earlier, the sleeve bearings were not used in the end, so that the platform does not come in contact with the columns at all. We have adopted this change for our final design as we believe it to be a better method.

The support assembly is press-fitted onto the tops of the four columns and will be fastened to them with a bolt and nut. Figure 17 shows a detailed view of the latter assembly.

The gear-shaft assembly is shown in Figure 18. To mount the gear to the shaft, two screws will be put through the gear and screwed into the threaded holes of the shaft. The assembly is then press-fitted into the center bore hole in the support assembly, as shown in Figure 18, and secured with a setscrew (not present in the prototype due to the weld).

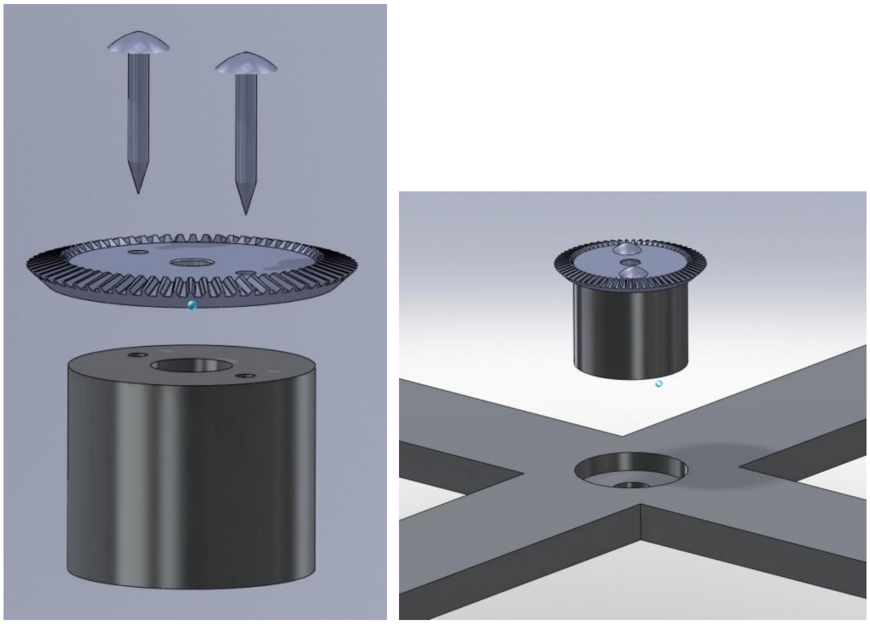


Figure 18. Center shaft and gear assembly

10.2.3 Boom, Leadscrew, and Mounting Plate

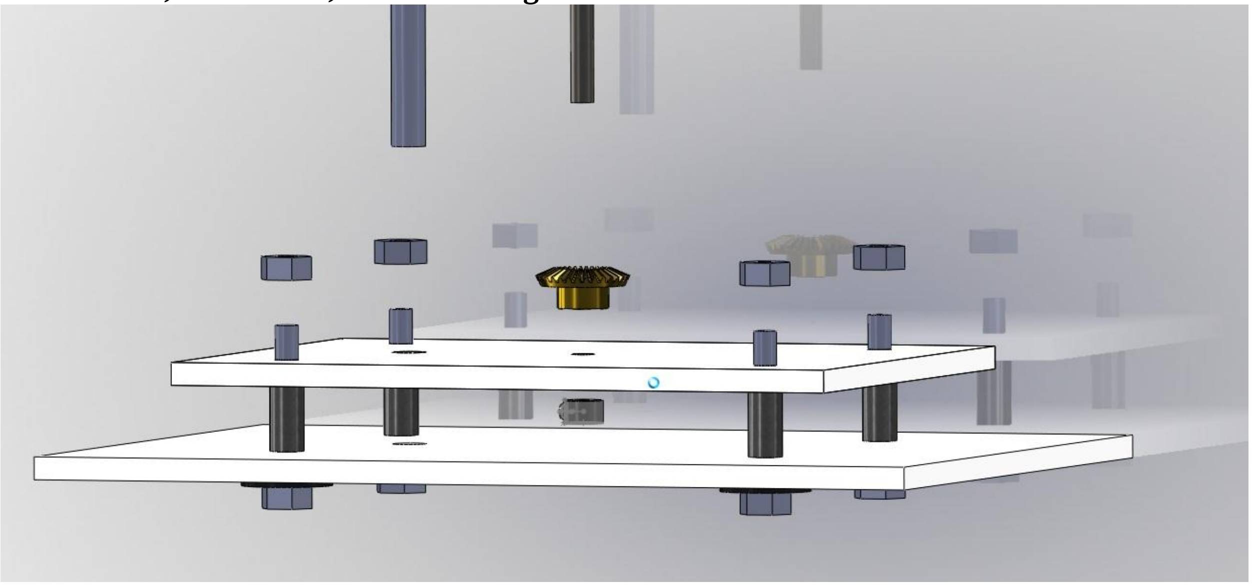


Figure 19. Partially-exploded view of mounting plate assembly

Figure 19 above shows how the mounting plate is fastened to the top plate of the enclosure. The guide shaft is put through the mounting plate and then press-fitted to the top plate. The leadscrew is fitted through the gear and secured with a key. A collar is then tightened around the bottom of the leadscrew to prevent it from separating from the mounting plate. The mounting plate is then laid over the four bolts and fastened down with nuts. The entire system is mounted to the boom by positioning the stabilizing rod and leadscrew to the two holes in the boom, shown in Figure 20, and then threading the leadscrew into its nut. Finally, a collar is placed around the top of the leadscrew to keep it from separating from the boom.

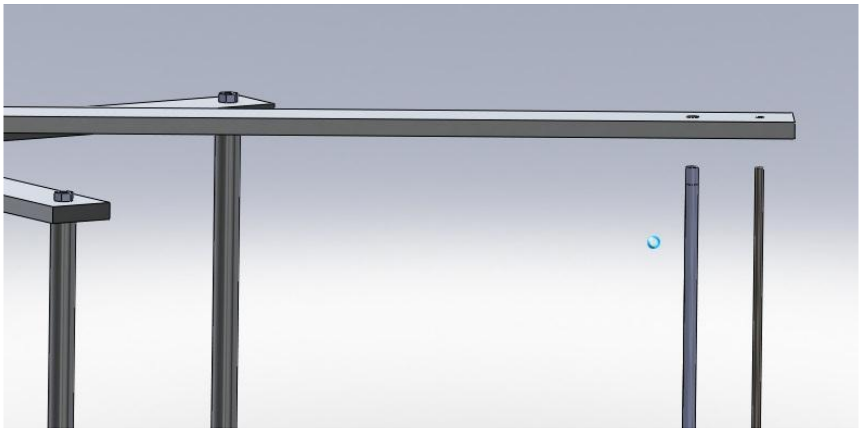


Figure 20. Boom-leadscrew-guide interface

10. Validation

Unfortunately, our prototype is not completed at the time of this report, and as such we have not yet been able to evaluate the system as a whole. We have been, however, able to validate specific subsystems of the device to a good extent.

10.1 Electronics and Load Cell

The electronics systems were successfully validated for the most part. The 12 V, 3 A voltage regulator circuit we put together performs perfectly, producing an output voltage of 11.99 V. The PWM generation circuit produced beautiful pulses (shown in Figure 21), the width of which were variable from 0 to 100% by the adjustment an input voltage. Sending this signal to the h-bridge along with a digital direction signal from the DAQ drove the motor and controlled its speed and direction as expected. Control of the solenoids using digital signals and H-bridges also functioned flawlessly.

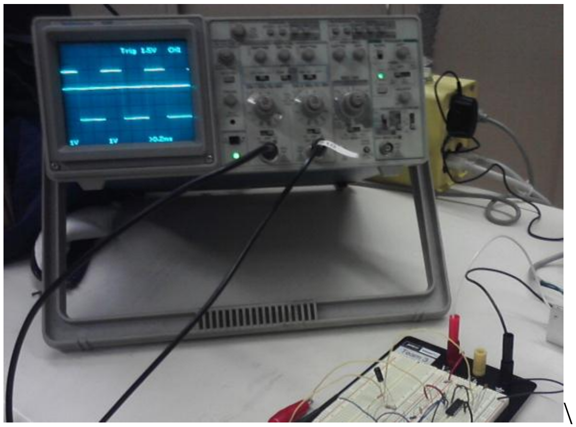


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Figure 21. Demonstration of pulse generation

We were able to validate the functionality of the load cell, although not over the range we had originally intended. The platform which we put together last-minute ended up being heavier than we wanted the platform to be, and ended up consuming most of the range of the load cell by itself. Thus we were only able to test the load cell over a small range (< 1kg) until it reached its maximum measurement capacity. The instrumentation amplifier worked as expected, producing a gain within 1% of what we attempted to set it at (450).

We could not devise an acceptable method for validating the accuracy of the load cell, without having access to some precise and closely-weighted calibration weights and some extra time. We will attempt to further validate the load cell as we complete the prototype, using calibration weights to analyze the variation of the output from the ideal linear model.

10.2 Camera Enclosure

We were successful in the performing validation testing for the camera enclosure. Using a relatively high pressured nozzle, we sprayed the enclosure from several angles for about 3-5 minutes. The result was that it did not a meet the requirement for a level 5 rating on the IP waterproofing scale (resistance to a jet of water). We moved down the rating level testing and performed heavy splash testing, for a level 4 IP rating. The enclosure was successful in this test. We believe that the leakage from the water jet test was due to small gaps resulting from poor manufacturing quality (typical of inexperienced manufacturers). Although the prototype enclosure failed the level 5 test, we believe that if made correctly the design would be successful. Our prototype was able to validate that the final design meets the requirement of equipment protection, as the device should not even encounter any jets of water in operation.

10.3 Camera and Camera Control

We were able to test the camera-related specifications (frame rate, focal length, optical zoom, battery life, resolution) by simply using the camera; all aspects that investigated met the manufacturer specifications, and thus the requirement of good recording quality.

We were also able to successfully validate the camera actuation system (the solenoids). This was done by simple observation of the camera as the solenoids were actuated. The system succeeded in turning the camera on/off and starting/stopping recording. This satisfies the requirement of the device being controlled remotely.

10.4 Camera Motion Actuation

We were able to partially validate the rotating boom part of the camera actuation system. Due to unplanned changed to the manufacturing of our prototype, the interface between the center shaft and the boom ended up being a rough, unsymmetrical, and poorly-toleranced one, resulting in excessive friction and a struggling boom motor. Although we are in the process of replacing this joint, we were still able to validate the concept. By lubricating the joint, we were able to produce the motion we desired, at a speed suitable for operation, and as such we believe this concept to be validated. It is clear that if we reduce the friction at the joint, it will function smoothly. Our success in controlling this system along with the solenoids means fulfillment of the remote control requirement.

As we did not implement leadscrew actuation for our prototype, we could not validate this part of the actuation system. Although we did not meet our engineering specification of 2 actuated degrees of freedom, we hold that the prototype still meets the customer requirement of camera angle reliability. The simple tests we performed by filming squirrels chewing in the wild confirmed that an acceptable camera angle for viewing chewing is obtained as long as the camera is centered at or below the jaw and the jaw is fully in the shot. By positioning the camera at the right height (centered ~4 in above the platform), an acceptable camera angle is reliably obtained for any animal in the size range of interest for the prototype.

This success unfortunately cannot be translated to the final design, however, as the circumstances could be very different with a larger-scale device. We were not able to fully validate that our final design meets the camera angle reliability requirement due to our lack of vertical actuation.

10.5 Scalability, Adaptability, Manufacturability

It is difficult to test the scalability of our design; the best we can do is examine all the aspects of the device and predict the difficulties associated with scaling them, something which we have addressed in Section 2. Based on our analysis, we believe the device to satisfy the scalability requirement.

Adaptability refers to the ease of replacement of certain parts, namely the camera and the load cell. The camera can easily be swapped out in our prototype. Although the solenoid configuration would differ with the camera, the final design does not include that system, so the adaptability of the final design is not affected by it. The load cell is relatively easy to swap out, also. It can be removed by simply unscrewing four screws and removing some wires from terminals. Installing another one is just as easy, simply follow this process in reverse!

The device was confirmed to be relatively easy to manufacture. No non-traditional processes were used, and with the exclusion of the platform sleeve bearings, tolerances are only important for the press fits and a in a few other small-scale instances (hole separations of < 2 in, etc.) Although we would change a few things from our original plan, everything was doable by inexperienced builders, leading us to hold that the manufacturability requirement was satisfied.

10.6 Validation of Various Other Aspects

We were able to validate that the platform successfully transfers the weight it bears to what lies beneath it (the load cell). The platform does not deflect considerably when weight it applied, so it meets our stability requirement.

The portability requirement is satisfied, as two people were able to carry the device without trouble.

Due to limited time and resources, we were not able to test the operating temperature range for our electronics.

Although we have not yet been able to validate the stability of the device as a whole as we had no means of applying a precisely controlled force, but we believe that the design meets the stability requirement, as it requires a force much greater than a raccoon-sized animal could produce in order to tip over.

11. Discussion

Although we were satisfied with the overall concept of the design, there were a number of issues that came to light during the assembly of the prototype. There were many important lessons learned and a few things which we would have done differently if we had the chance. One thing that we learned is that we may have been too ambitious when planning our project and setting requirements; the device ended up taking much longer and involving much more work to build than we expected, leaving us with insufficient time to complete every aspect of it.

11.1 Boom Bending

One unanticipated issue was the moment that the weight of the enclosure and the boom itself created at the boom's middle section. Our initial design called for a simple counterweight at the other end of the boom; however, the effects of the boom bending due to its loading were more detrimental with the addition of the center plate. A better solution which would be used in the future is a suspension-bridge type system – a rod would extend straight up along the axis of rotation of the boom, from which load-bearing wires would be stretched to the ends of the boom. This configuration would allow distribution of the load while controlling the bending of the boom.

11.2 Platform Issues

Other issues arose due to unexpected delays with getting parts shipped to us. After struggling for a while with the vendor supplying our PVC sheet for the platform, we ended up making our own platform, as described in Section 8. This platform was not as desirable as the PVC one, as it is much less rigid and much heavier than the original would have been. Its extra weight had additional negative impact on the device by consuming most of the range of the load cell.

Although we changed our platform design significantly along the way (namely removing the sleeve bearings), we agreed that the final design without the bearings is a better one than our original concept anyway, and it should be used in the future.

11.3 Manufacturing Issues

We also had some problems with manufacturing arising mainly from our inexperience. We recognize that the base and the support assembly should not have been welded, as this causes warping and is a method that is bound to, and did, result in poor tolerances. The poor tolerances created by welding these parts made press fitting the whole frame together difficult, and contributed to the failure of our sleeve bearing system for the platform. Instead, the two pieces for each part should have been bolted together, allowing for much better tolerances and no warping.

The center shaft should also not have been welded to the support assembly, although this was not our original intention; this action was the result of a miscommunication. This weld caused some big issues, as the boom was intended to rest on the flat area which was suddenly occupied by a large uneven weld. In an attempt to grind down the weld, the center shaft was also ground a bit, creating a rough interface between the boom and the center shaft and adding friction. To account for the weld bead, we also decided to fit a plate over top of the weld in order to give the boom a flat surface to rest on, which caused additional friction between the boom and the center shaft. In an ideal situation, the center shaft would simply be press-fitted about halfway into the support assembly. Also, we recognize that a bearing should be used at this interface, something which we are currently working on implementing for the prototype in order to fix our problem.

11.4 Camera Enclosure

Additionally, the method used assemble the enclosure will have to be relooked at as it did not meet our IP rating validation. The forces from the latches that held the cover down to the body also exerted strong horizontal forces that put unwanted stress on the adhesive that held the sides in place. Although we believe that if manufactured with better tolerances our method would be successful, there are alternatives which would also give better results. A redesign of the way the cover closes on the enclosure could be beneficial, such as a slight press fit with an extrusion out of the bottom surface covered with neoprene on the sides. A better adhesive should also be used to hold the sides together.

11.5 Other Points of Interest

A combination of more vendor issues and our lack of knowledge about motors led us to decide to scrap the vertical actuation part of the device for our prototype, as described in Section 8.1.1.

Due to time constraints, we have also yet to enclose the boom motor to protect it from weather. We will use a simple plastic box to enclose it, leaving openings for wires and the motor shaft.

While originally we weren’t concerned about corrosion on the base, in the future this should be better accounted-for. We didn’t believe it to be an issue because the base doesn’t involve any moving parts, but later decided that any parts exposed to the elements should be corrosion-resistant, no matter what they are used for, for the sake of safety and integrity.

12. Conclusion

Our team was tasked with designing and manufacturing a device that would assist Dr. Geoffrey Gerstner in his research in developing a link between a mammal’s body mass and its chewing rate. The final design is a scalable one without a specified size, while our prototype was built with a platform of 4 ft^2, comfortably accommodating animals up to the size of large squirrels. Attached to the boom is a high speed video camera with its own enclosure to protect it from the environment. This system is intended to translate vertically, although due to many issues it does not in our prototype. Controlling the camera and actuation of the camera is done by a nearby operator for the prototype, and a remote operator (over wireless transmission) for the final design.

Our team met many unexpected difficulties during the manufacturing process. Due to these issues and limited time, we were forced to improvise for many aspects of fabrication plan in order to finish the prototype on schedule. As a result, we were forced to omit certain aspects of the design for the prototype. Rushed manufacturing causes many issues and resulted in the boom and the camera enclosure not performing up to our expectations. We were also beset by issues regarding vendor punctuality and reliability; in one case, we never received an ordered part and were forced to create our own to replace it.

With all of the issues that we encountered, we were not left with enough time to fully validate our prototype. We were able to validate individual subsystems, such as the electronic components and systems, the solenoid camera control system, and camera enclosure. We learned many things along the way, including that welding should be avoided when tolerances are important, and that the boom needs to be better supported in order to prevent an unacceptable amount of bending. In the end, although we were not completely satisfied with the prototype considering the amount of work that was put into it, it does indeed provide a proof of concept and in the process of making it we learned many invaluable lessons.

13. Acknowledgements

Firstly, we would like to thank Dr. Geoffrey Gerstner, for sponsoring the project and giving us the opportunity to work on such a unique idea. We'd like to thank him for his continuing support, accommodation, and helpfulness throughout the process, and also for allowing us to use one of his cameras for most of the project duration. We'd also like to thank Dr. Grant Kruger, without whom we would have never been able to figure out so much of the project. Especially regarding the electronics, Dr. Kruger's advice, patience, and willingness to spend his own time helping us were an enormous help in planning the design and building the prototype, and he always had our best interest in mind.

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Appendix A. Bill of Materials

Part	Vendor	#	Part #	Price	Tax + Shipping	Total
.75" Extruded Aluminum Rods (6061-T6511), 48" cut	Online Metals	2		15.36	12.63	27.99
.5"x2" Extruded Aluminum Bars (6061-T6511), 36" cut	Online Metals	2		29.36		29.36
.5"x2" Extruded Aluminum Bars (6061-T6511), 48" cut	Online Metals	1		17.4		17.4
3/8" thick neoprene sheet	Drillspot	1		10.47	6.92	17.39
Bronze Sleeve Bearing for 1.5" shaft	McMaster	1	6391K311	1.72	4.36	6.08
Bronze Sleeve Bearing for .75" shaft	McMaster	4	9368T78	18.08		18.08
Collar for 3/8" shaft	McMaster	1	6435K13	1.85		1.85
1.5 Aluminum Shaft (6061), 12" cut	McMaster	1	8974K181	11.29	4.39	15.68
3/8" Anodized Alumninum Rod	McMaster	1	6750K153	12.08	4.39	16.47
Plastic Spacers, 1" cut, .26" ID	McMaster	20	92825A135	8.88		8.88
.25" leadscrew	Haydonkerk Engineering	1	LSSSSR-025-0100-FY24	72	8.83	80.83
Leadscrew nut	Haydonkerk Engineering	1	BFWFNR-025-0100-BZ00	13		13
Bevel Gear (Gear), 1.5" PD	Stock Drive Products	1	A 1B 3-Y24036	14.52	11.66	26.18
Bevel Gear (Pinion)	Stock Drive Products	1	A 1B 3-Y24018	11.53		11.53
Bevel Gear (Gear), 1" PD	Stock Drive Products	2	A 1B 3-Y32032A	29.04	11.66	40.7
Bevel Gear (Pinion)	Stock Drive Products	2	A 1B 3-Y32016	22.58		22.58
DAQ	Measurement Computing	1	USB-1208LS	129		147.29
Load cell	Omega	1	LCAE-6kg	151		159
H-bridge	RobotSimple	1	Pololu 18V15	38.95		45.59
Solenoid	AllElectronics	2	SOL-102	2.75		12.5
Motor	Robokitsworld	1	RKI-1419	28.12		36.12
						754.5

Appendix B. Changes From the Final Design

Appendix C. Design Analysis Assignment

Section C.1 Material Selection

1. Base: The function of the base is to provide support and stability to the design as well as hold the load cell in place.

The objective is that it is heavy enough so that the design will not easily tip over. The other objective is that it will not fail due to yield or fracture.

The constraints for the material selection were:
>200 lb/cu. Ft
<1 $/lb
> 10^7 psi for Young's modulus
> 10^6 psi for shear modulus
>10 ksi*in^0.5 fracture toughness

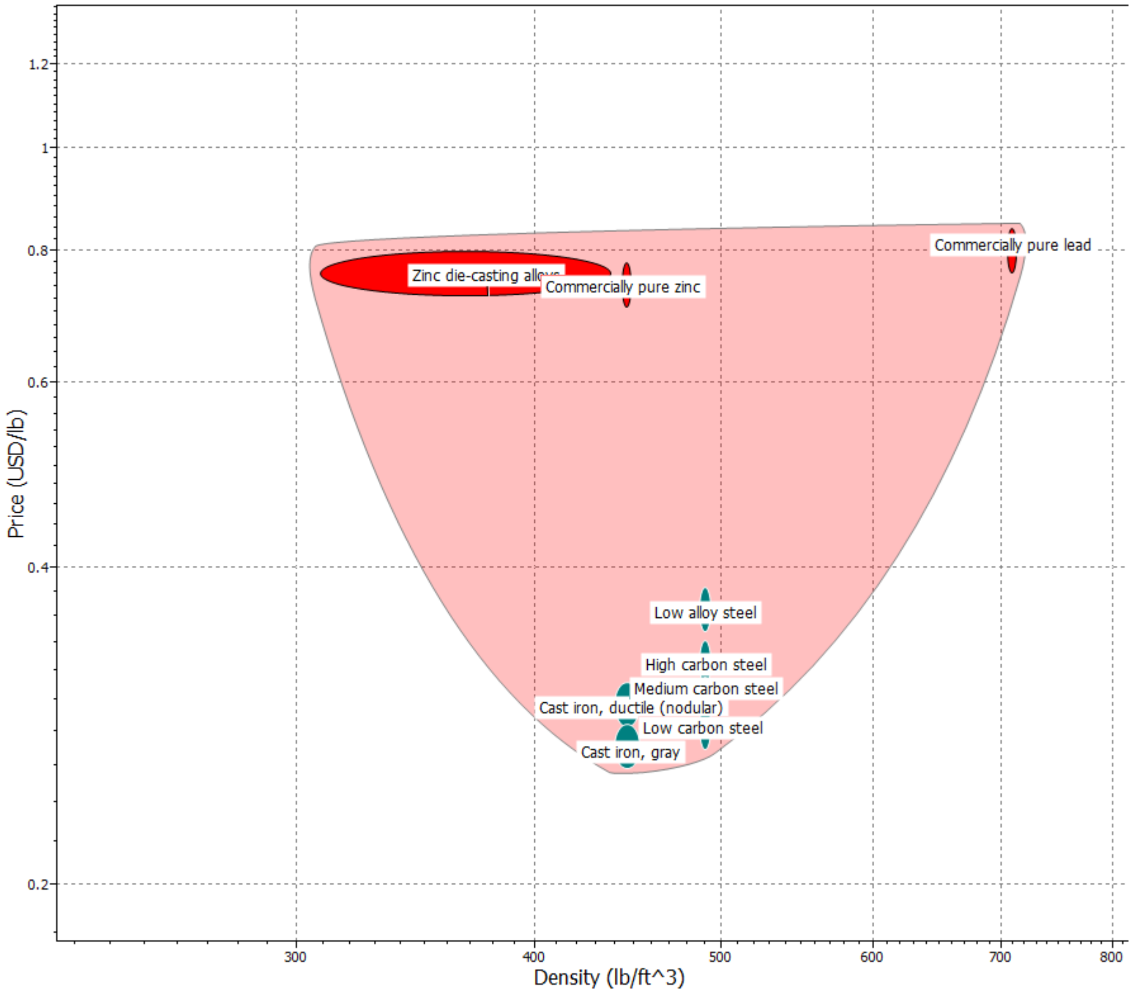


Figure C.1. CES plot for possible materials for the base

The materials that met our constraints were steel, cast iron, zinc, and lead.
We chose the mild steel because of its availability. It was both the cheapest online and was available for ME 450 use in the machine shop. It met all of the criteria listed above and was both machinable and weldable.

2. Camera box (side): The functions of the sides of the camera box are to provide protection to the camera without obstructing the view.
The objective is that it is strong enough to protect the camera from animals and clear enough so as not to obstruct the camera view.

The constraints for the material selection were:
<100 lb/cu. Ft
>1 ksi for yield, tensile, and compressive strength
>2 ksi*in^0.5 fracture toughness
Transparent

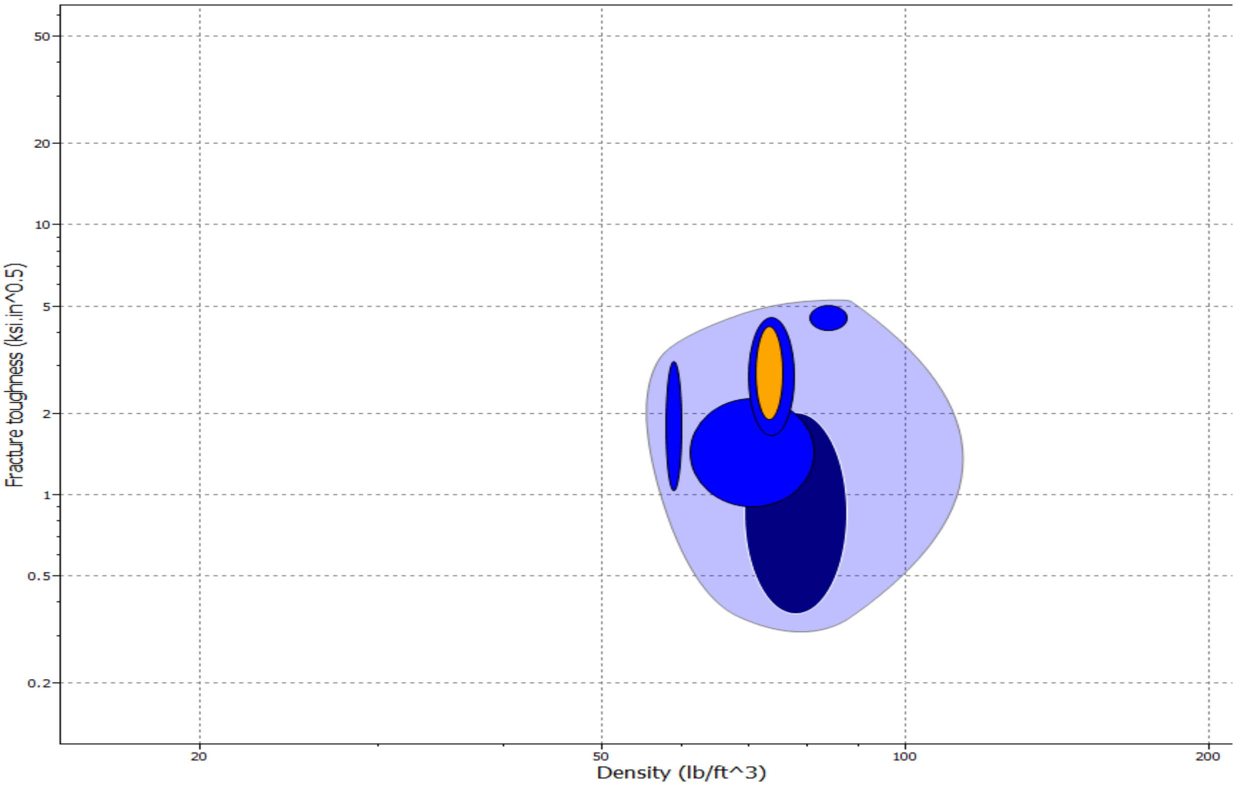


Figure C.2. CES plot of possible materials for camera enclosure walls

The materials that met our constraints were polycarbonate, PET, polyurethane, ionomer cellulose polymers and epoxies.

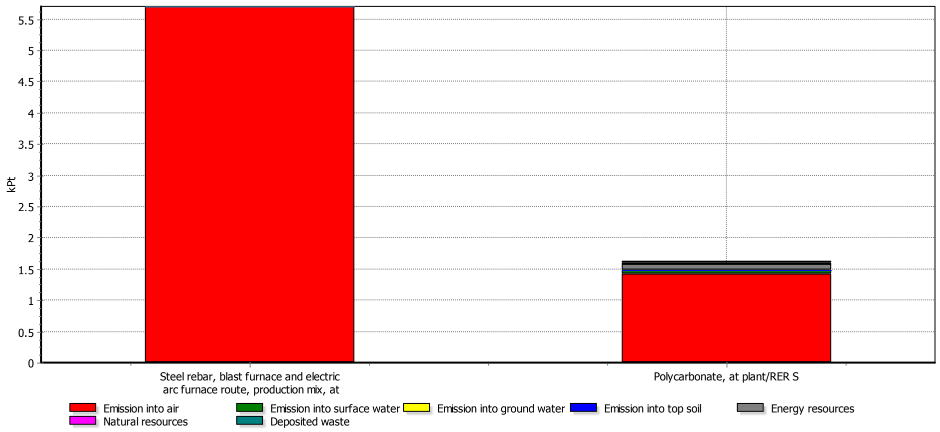
We chose the polycarbonate because we had a large sheet of scrap given to us and it had the best optical properties. It also met all of our constraints listed above.

Section C.2 Environmental Performance

Steel = 8.215 kg
Polycarbonate = 0.297 kg

Category	Steel	PC
air emissions	5700	1420
water emissions	0	56
raw material	3	112
solid waste	0	41.9
total score	5703	1630

Table C.1. Total emissions based on category



Comparing 8.21 kg 'Steel rebar, blast furnace and electric arc furnace route, production mix, at plant GLO S' with 0.297 kg 'Polycarbonate, at plant/RER S';
Method: Ecological Scarcity 2006 V1.05 / Ecological scarcity 2006 / Single score

Figure C.3. Plot of total emissions

The steel had more emissions than the PC did mostly because it weighs almost 28 times more than the PC. If we used the same amount of both materials, the steel would have much lower emissions.

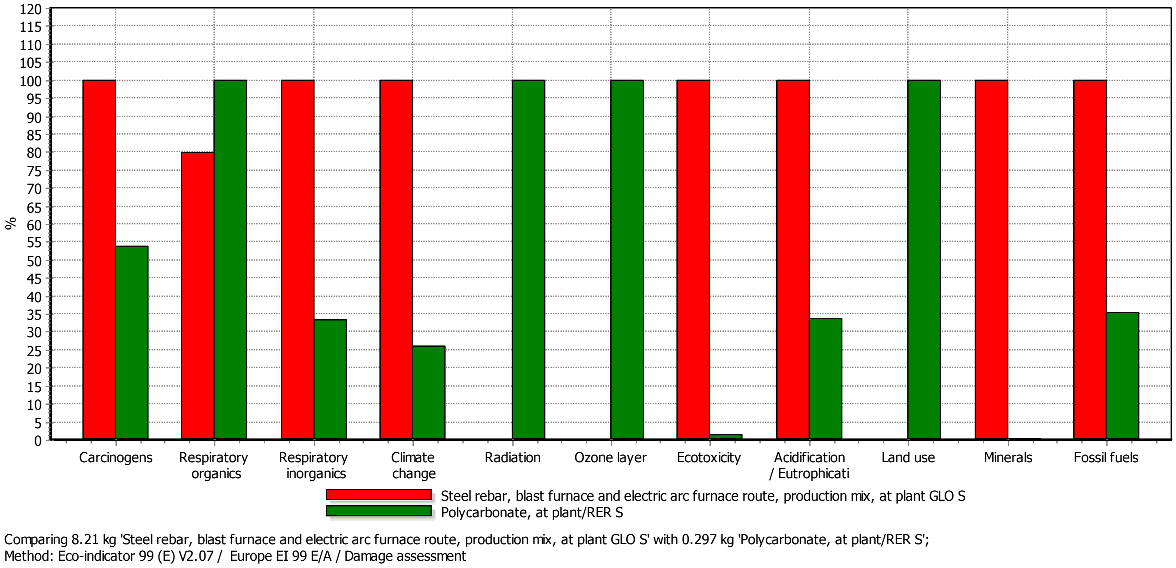


Figure C.4. Relative impact on various sources

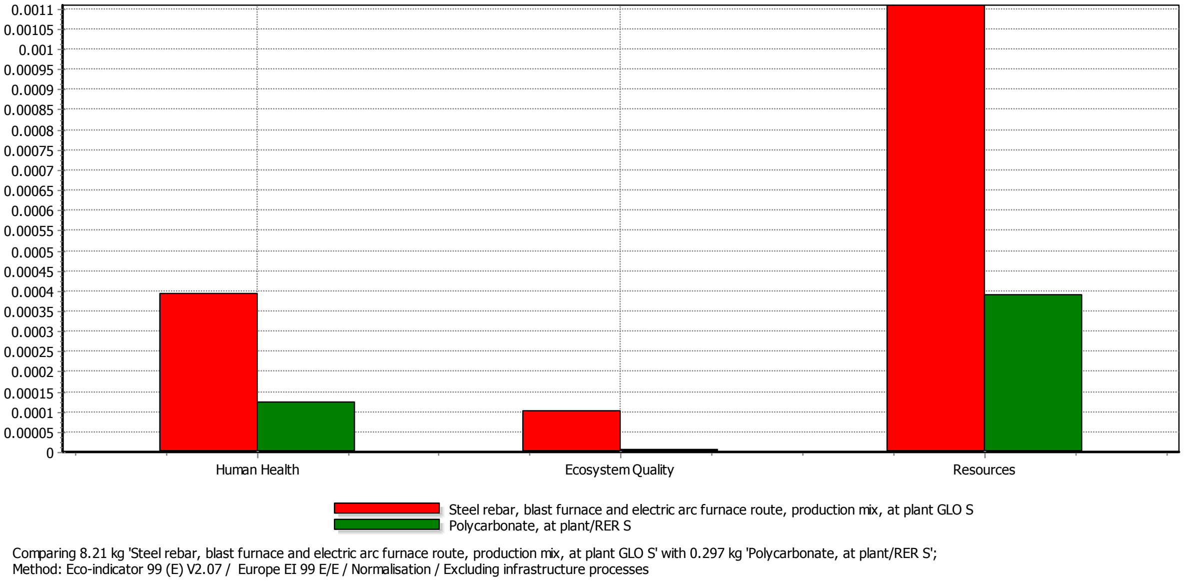
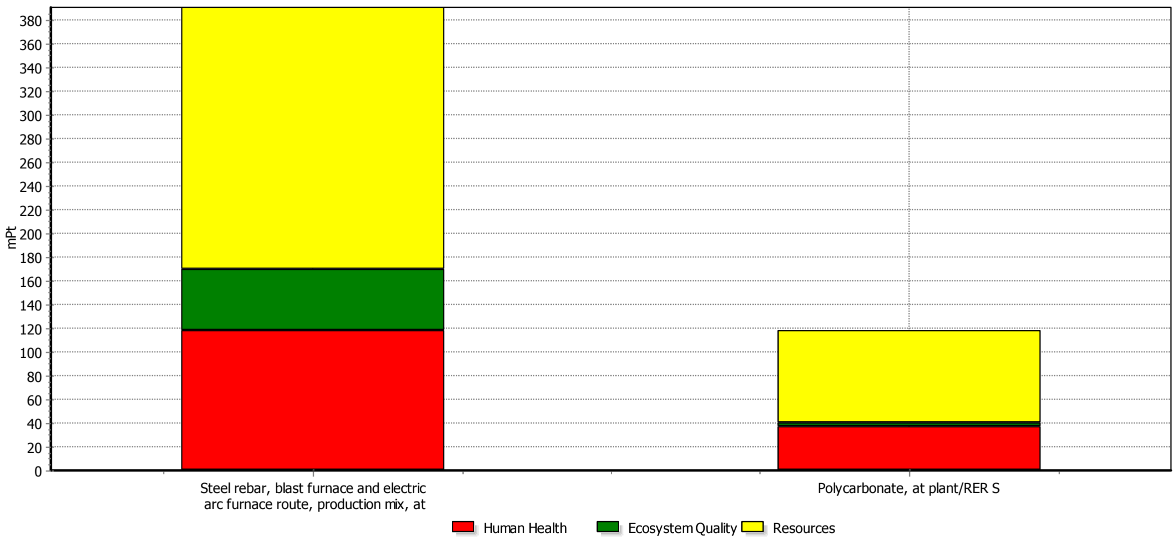


Figure C.5. Normalized score for impact on health, the environment, and natural resources



Comparing 8.21 kg 'Steel rebar, blast furnace and electric arc furnace route, production mix, at plant GLO S' with 0.297 kg 'Polycarbonate, at plant/RER S';
Method: Eco-indicator 99 (E) V2.07 / Europe EI 99 E/E / Single score / Excluding infrastructure processes

Figure C.6. Single score comparison

The material choice that had a larger impact on the environment was the steel base. The reason that it had a larger impact was because it was a much larger part of our design. If we used as much polycarbonate as steel, the polycarbonate would have had a larger environmental impact. As you can see from the relative impact graph, steel has a larger impact on carcinogens, respiratory inorganics, climate change, acidification, minerals, and fossil fuels. Polycarbonate has a larger impact on respirator organics, radiation, land use, and ozone layer. The meta-category that is most important to consider in choosing the materials is resources, because it has a much larger point value impact than human health or ecosystem quality as seen in the normalized score graph. While human health is the most important category, it is not impacted nearly as much as resources and is therefore less important to consider. When the whole lifecycle is considered, polycarbonate becomes slightly more environmentally friendly, most likely due to its recyclability. When comparing to other materials that we could have selected, these were relatively good choices. The mild steel that we used has a smaller score than the zinc that we could have used instead. Polycarbonate was not as good environmentally as other clear plastics or glass. We would still choose polycarbonate because of its strength and because it is not brittle like glass.

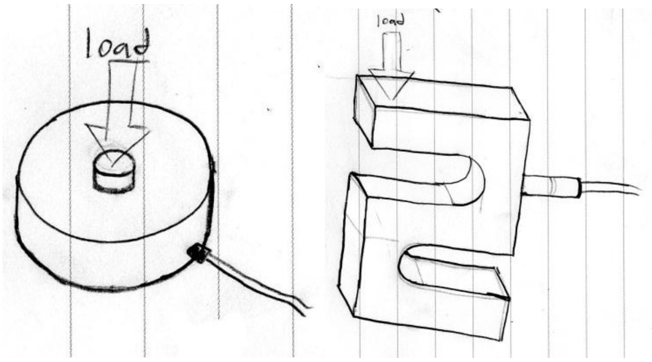
Section C.3 Manufacturing Process Selection

Our real world production would be relatively low, around 25-50 assuming the current scale. Larger scale versions of our project for larger mammals would be in less need to the cumbersome nature of it and the cost. Our sponsor has stated that this area of research is in relatively little demand, and that he often needs to put it on hold sometimes to acquire more funding/grants. The only real possibility of larger volumes (50-100) is if our design became fully wireless over long distances (greater than 1 mile) and one could place them like current camera traps and have them send data wireless to a central “command post”. The only other interest group would be wildlife photographers and videographers, but they rely on their own control to capture their desired shot, so they would not actually have an interest in this project.

If one assumes the best case scenario with a production volume of 100, there would be ~2400 in^3 of polycarbonate and ~7500 in^3 of steel produced for the “mass” production of our project. The best way to produce the steel would be to simply extrude it through a die. The steel part of our project is simple in geometry and can be made from two bars. Rolling steel can produce a high volume annually, and since our demands are relatively low, there should be no problem. Additionally, there is not a high need for it to have high corrosion resistant, just enough so that the overall structure would not be hampered. One could simply clean the rolled steel and then galvanize it. The best method of fabricating the polycarbonate would be to use the regular method and try to minimalize the phosgene use.

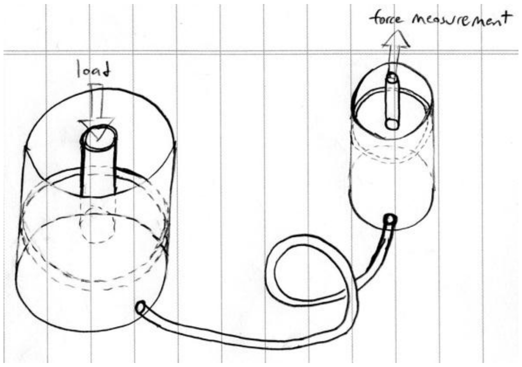
Appendix D. Generated Concepts

D.1 Weight Measurement Subsystem



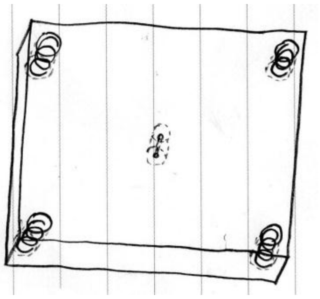
Load cell

This concept is simply a pre-fabricated strain-gauge based load cell upon which the platform would rest. The load cell would output data in real time which could be recorded.



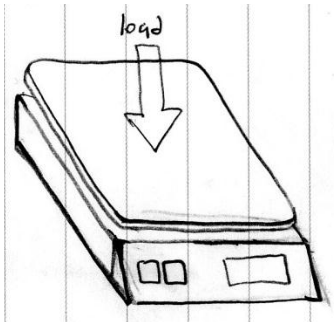
Hydraulic system

A hydraulic weight measurement system would consist of two fluid filled cylinders. There will be one cylinder under the platform in which the fluid is depressed when the animal steps on the platform. When this happens the fluid is transferred into the second cylinder and applied to a mass or spring. This concept was not fully developed as it was quickly determined to be very hard to manufacture.



Spring scale

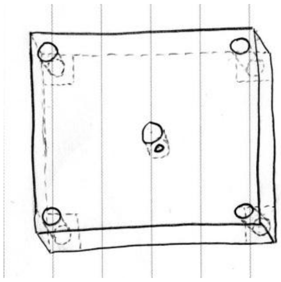
This system would use a number of springs to support the platform. The displacement of the platform would be measured by a transducer to determine force. The signal from the transducer would be recorded over time to determine the animal’s weight.



Standard digital readout scale

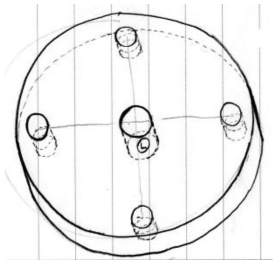
This concept would use a standard scale with a digital readout. Data from the scale would not be recorded, but the camera could film the display to record the animal’s weight.

D.2 Platform Subsystem



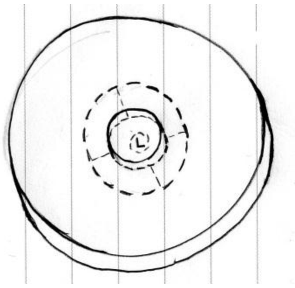
Rectangle corner supported

This platform would be a rectangular shape, supported by columns at each corner which run through the platform. It would move freely on the supports and rest on the weight measurement device in the center.



Circle perimeter supported

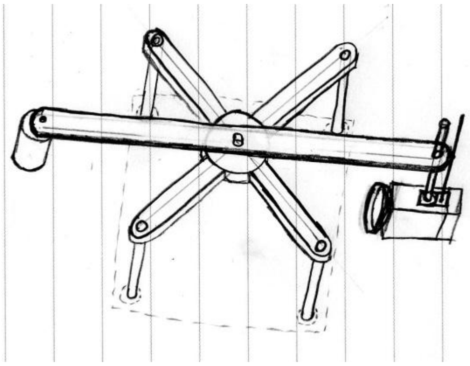
The platform would be circular, supported by columns at four points along the perimeter of the shape. It would move freely on the supports and rest on the weight measurement device in the center.



Circle side supported

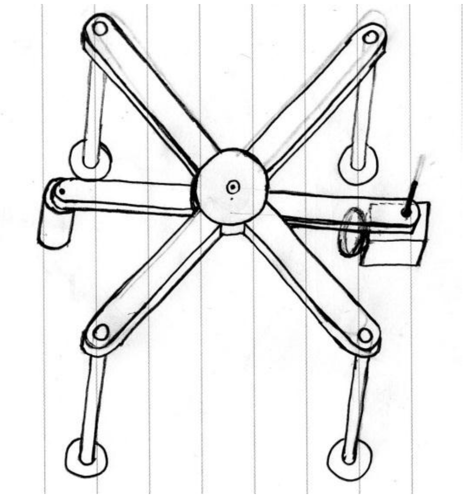
The platform would be circular, supported by a ring in the center. It would move freely on its support right and would rest on the weight measurement device in the center.

D.3 Camera Mounting and Actuation Subsystem



External boom-based design with vertical motion

For this concept, the camera is mounted on a boom which swings it around the platform. The camera's circle of motion is outside of the support columns. The camera can also move vertically with respect to the boom.

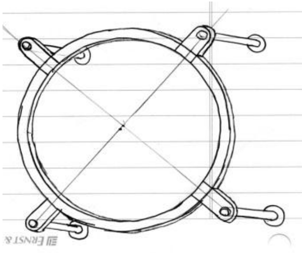


Internal boom-based system with vertical motion

This concept is similar to the previous one, except that the boom is located under the supporting frame, and the camera moves inside of the support columns.

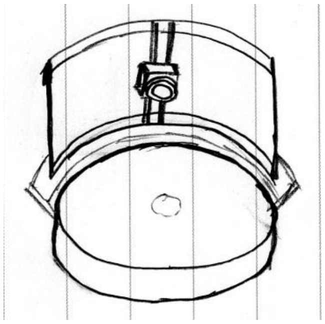
Internal boom-based system with tilt

Identical to the previous concept, except that the camera is able to tilt up and down instead of move vertically.



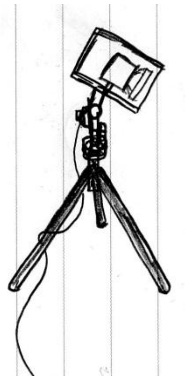
Circular track with tilt

The camera would travel in a circle around the platform and would be able to tilt up and down.



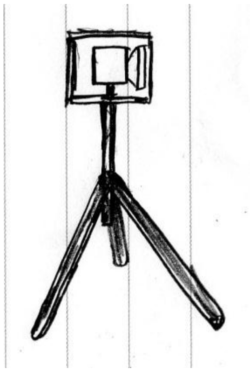
Arc-shaped track with vertical motion

In this concept, the camera would travel vertically on a track, and that track would travel back and forth along an arc-shaped wall.



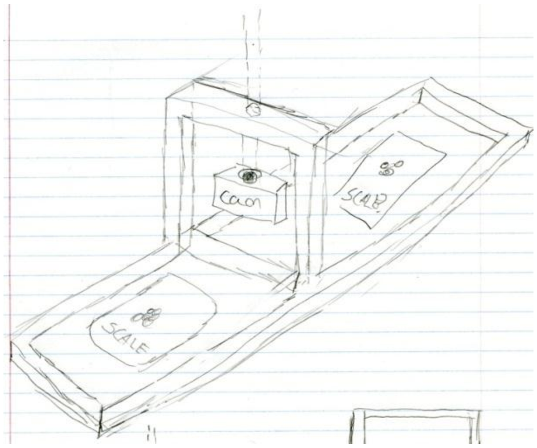
Actuated tripod

The camera would be mounted on a tripod which allows tilting and panning motions.



Stationary Tripod

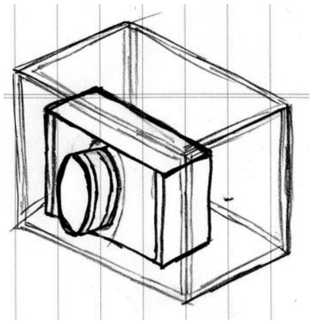
The camera would be mounted on a tripod which is completely stationary.



Dual-platform center-mounted camera

In this design there would be two scales with the camera placed in-between the scales. This would be a stable structure as the long frame would be averse to tipping, and the symmetry would give options on capturing the video.

D.3 Camera Enclosure Subsystem

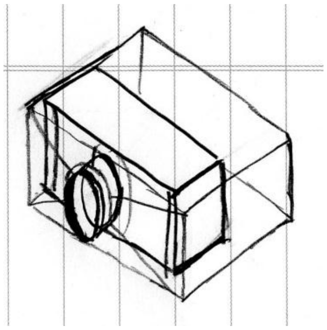


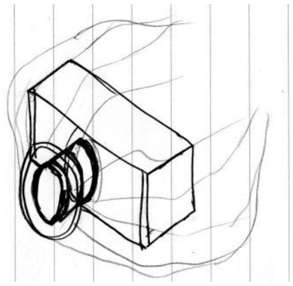
Fully enclosed box

This enclosure would be a fully-sealed rectangular box. The camera would be mounted to the bottom and the front wall would be transparent.

Exposed lens box

This design is much like the fully enclosed, however instead of having a transparent front; it has a hole for the lens to fit in; the box would close around the lens, leaving it exposed.



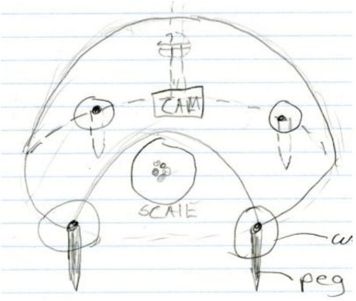


Bag or flexible enclosure

There are many bags that professional photographers use to protect their equipment. This would be a plastic bag or flexible material that covers the whole camera, with a transparent disk in front of the lens.

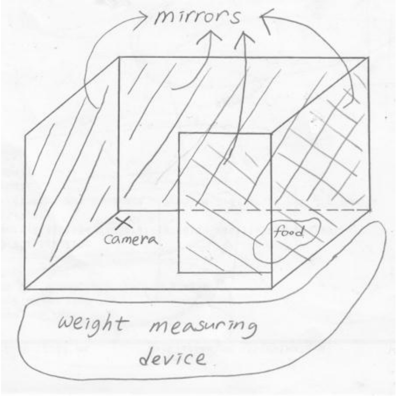
D.5 Device Enclosure Subsystem

Note: Since DR1, we decided to proceed with an enclosure-less design, so these concepts were not included in our evaluation and selection process.



Wire mesh dome enclosure

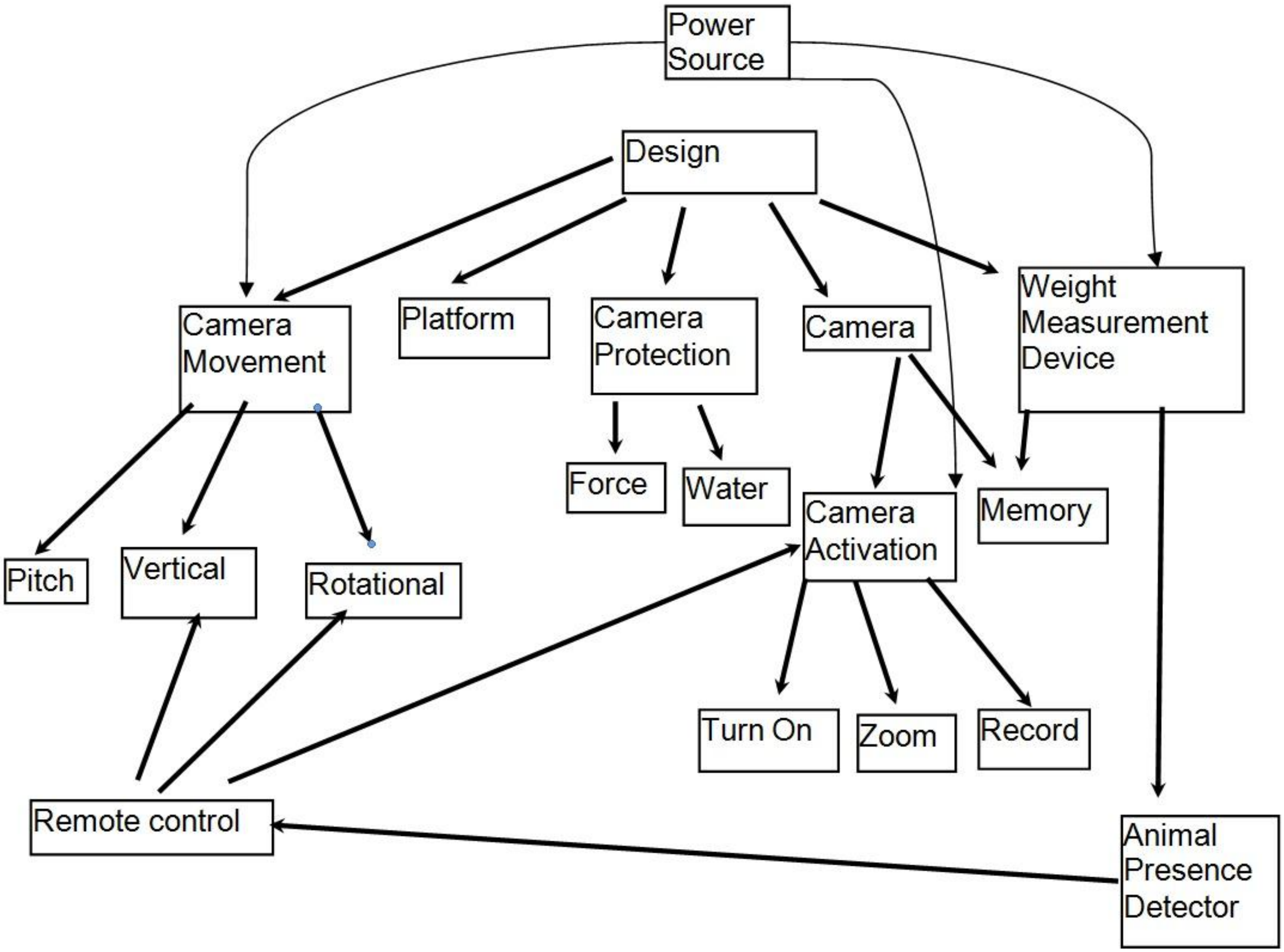
In this design there would be an enclosure made up of a wire mesh and four pegs weighted down into the surface. There would be a hole at the top to mount the camera, and the scale would be in the center. In essence, this would look like a “safe haven” and would be camouflaged to attract test subjects.



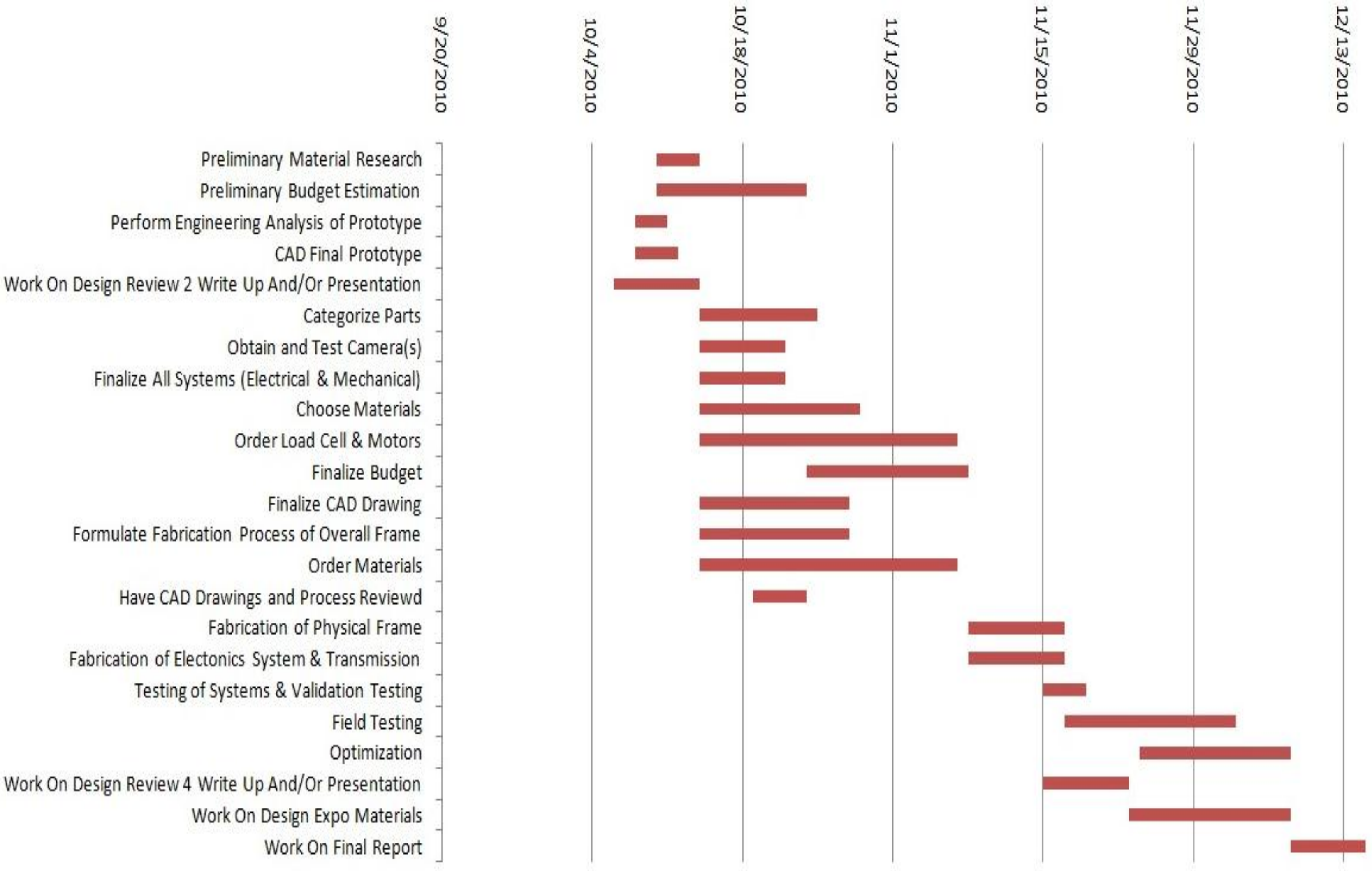
Mirror-lined box

This enclosure concept would consist of three full walls and one partial wall, which would be entirely lined with mirrors on the inside, to help ensure a good camera angle.

Appendix E. Functional Decomposition



Appendix F. Gantt Chart



Appendix G. Pugh Charts

Here are shown the charts behind our concept selection process. Each criterion represents a subsystem-specific implementation of a customer requirement, and is assigned a relative weight from 1-5. We chose criteria based on what we foresaw the significant differences between the concepts to be; thing which were not expected to differ between concepts were not included as criteria. The concepts we evaluated are listed across the top of each chart.

G.1 Weight Measurement Subsystem

Concept A: Load cell-based system
Concept B: Hydraulics-based system
Concept C: Spring scale
Concept D: Standard digital-readout scale

Table D.1 Weight measurement subsystem Pugh chart

Criterion / Weight		A	B	C	D
Resolution	4	2	0	-1	-2
Accuracy	5	2	-2	-1	0
Range	4	2	1	0	-1
Ease of data recording	2	2	0	0	1
Durability	3	2	-1	1	0
Manufacturability	3	2	-2	0	2
Cost	2	-2	-1	1	0
Scores		38	-17	-4	-4

G.2 Platform Subsystem

Concept A: Center-supported disk
Concept B: 4-Point perimeter-supported disk
Concept C: 4-Point corner-supported rectangle

Table D.2 Platform subsystem Pugh chart

Criterion / Weight		A	B	C
Stability	5	0	2	2
Weight	3	0	0	0
Manufacturability	2	-1	0	1
Scores		-2	10	12

G.3 Camera Actuation Subsystem

Concept A: Boom with camera inside supports, vertical motion
Concept B: Boom with camera outside supports, vertical motion
Concept C: Boom with camera outside supports, tilt
Concept D: Circular track, tilt
Concept E: Arc-shaped track, vertical motion
Concept F: Tripod, tilt and pan
Concept G: Tripod, stationary

Table D.3 Camera actuation subsystem Pugh chart

Criterion / Weight		A	B	C	D	E	F	G
Camera angle freedom	5	2	2	1	1	1	-2	-2
Power consumption	2	-1	-1	-1	-1	-1	0	1
Durability	2	1	-1	-1	1	0	1	2
Manufacturability	2	-2	-1	-1	-2	-2	1	2
Cost	1	-1	-1	-1	-1	-1	1	2
Scores		5	3	-2	0	-2	-5	2

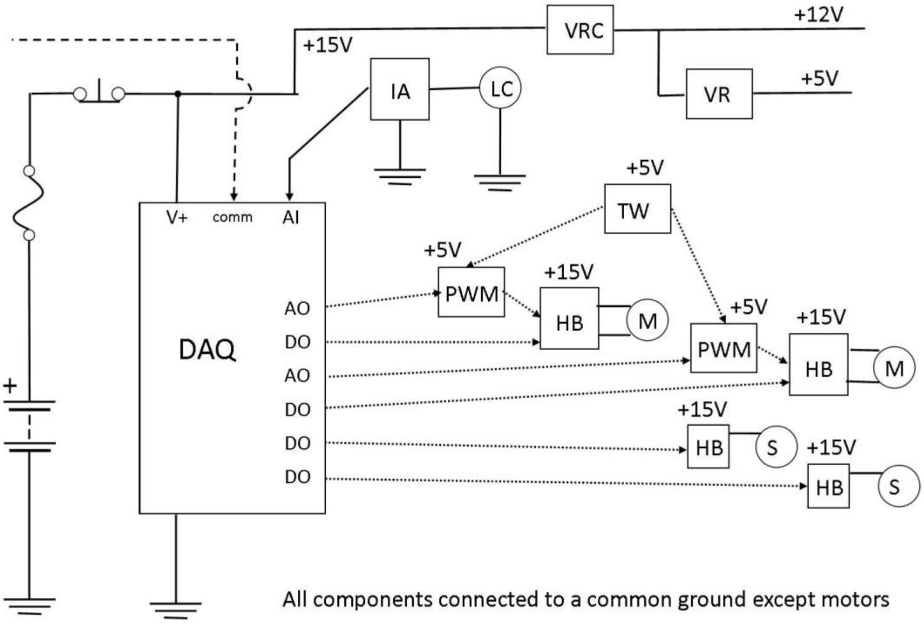
G.4 Camera Enclosure Subsystem

Concept A: Full-enclosure box
Concept B: Exposed-lens box with filter or other lens protection
Concept C: Bag

Table D.4 Camera enclosure subsystem Pugh chart

Criterion / Weight		A	B	C
Waterproofing	5	2	1	2
Protection from physical harm	4	2	2	-2
Lens protection	4	2	-1	0
Impact on picture quality	3	-1	2	-1
Manufacturability	3	2	1	0
Empty volume in enclosure	2	-2	-1	1
Adaptability for other cameras	2	2	0	1
Cost	2	0	0	2
Weight	1	-1	-1	2
Scores		28	15	9

Appendix H. Electronics Diagrams



All components connected to a common ground except motors

Figure H.1. Diagram of overall electronics system for prototype (note that one of two motors is non-existent in the actual prototype)

DAQ = Data acquisition card, AI = Analog input, DO = Digital output,
IA = Instrumentation amplifier, LC = Load cell, HB = H-bridge, M = Motor, S = Solenoid,
PWM = Pulse width modulation signal generator, TW = Triangle wave generator,
VR = Voltage regulator, VRC = Voltage regulation circuit

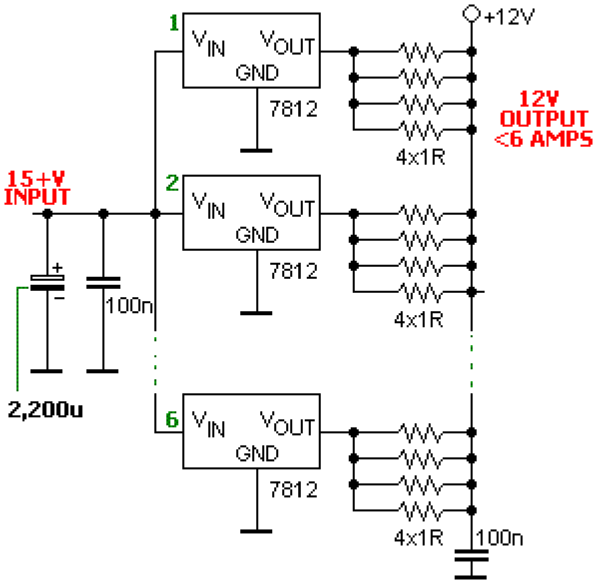


Figure H.2. Voltage regulation circuit diagram. Implemented with three IC's for a total output of 3 A.
Source: http://www.reuk.co.uk/High-Current-Voltage-Regulation.htm

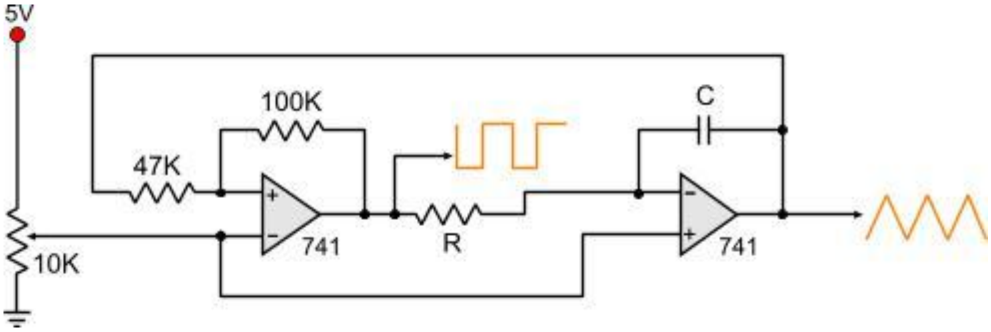


Figure H.3. Triangle wave generator circuit diagram.
Source: http://pcbheaven.com/circuitpages/Triangle_Wave_Generator/

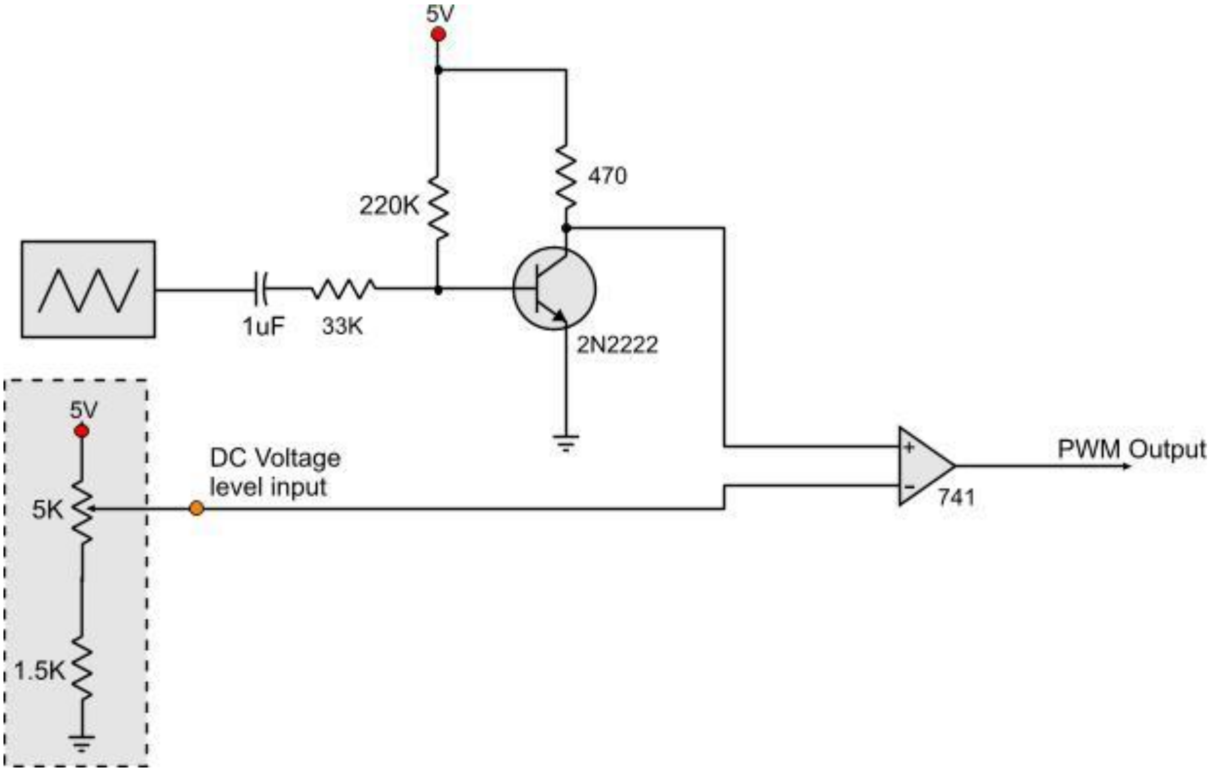
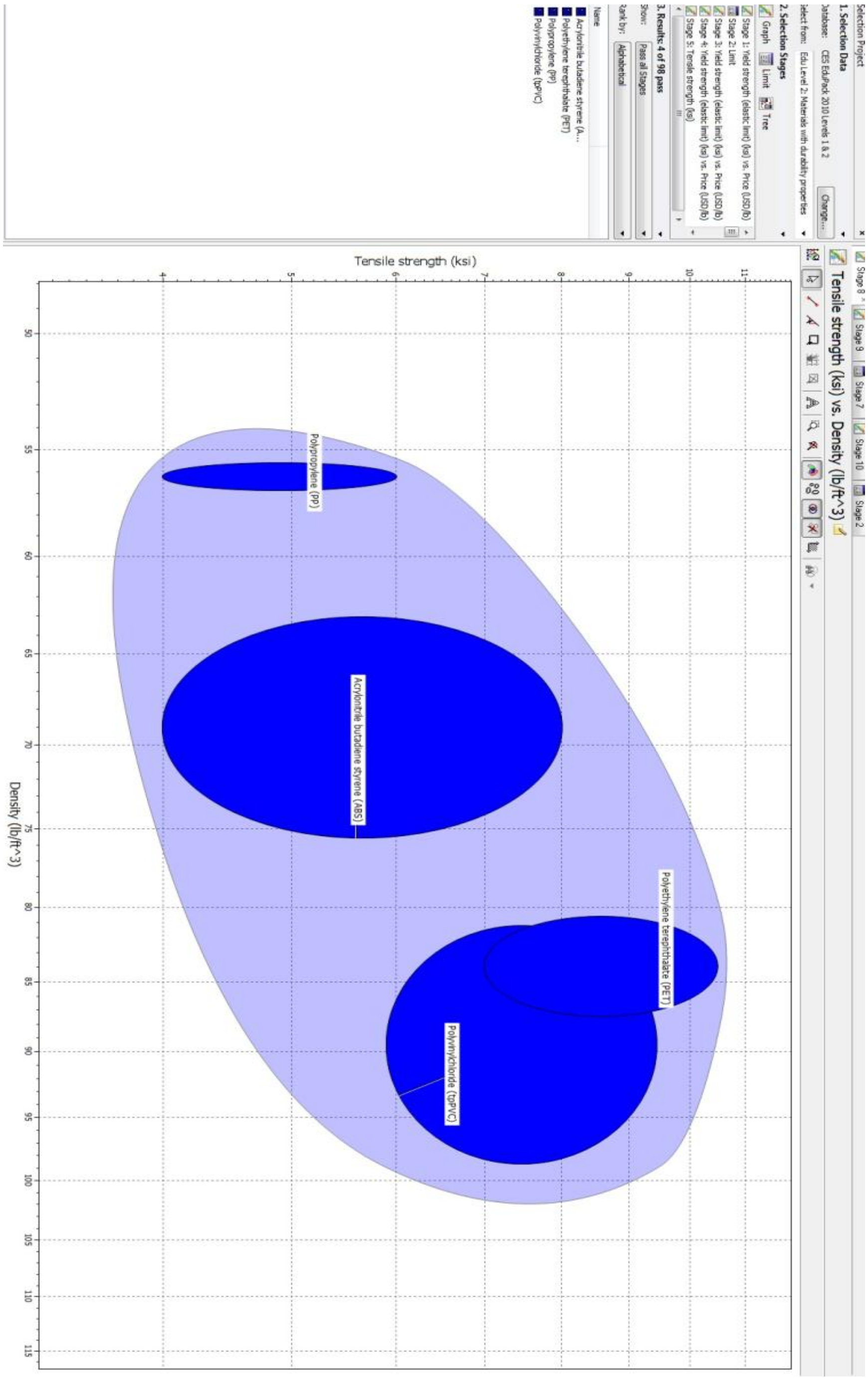


Figure H.4. PWM generator circuit. Box with triangle wave represents triangle wave generator circuit. Input voltage comes directly from a DAQ analog output.
Source: http://pcbheaven.com/circuitpages/Voltage_Controlled_PWM_Generator/

Appendix I. Material Selection Charts



Selection Project

1. Selection Data

Database: CES EduPack 2010 Levels 1 & 2

Select from: Edu Level 2: Materials with durability properties

2. Selection Stages

- Stage 1: Yield strength (elastic limit) (ksi) vs. Price (USD/lb)
- Stage 2: Limit
- Stage 3: Yield strength (elastic limit) (ksi) vs. Price (USD/lb)
- Stage 4: Yield strength (elastic limit) (ksi) vs. Price (USD/lb)
- Stage 5: Tensile strength (ksi)

3. Results: 4 of 98 pass

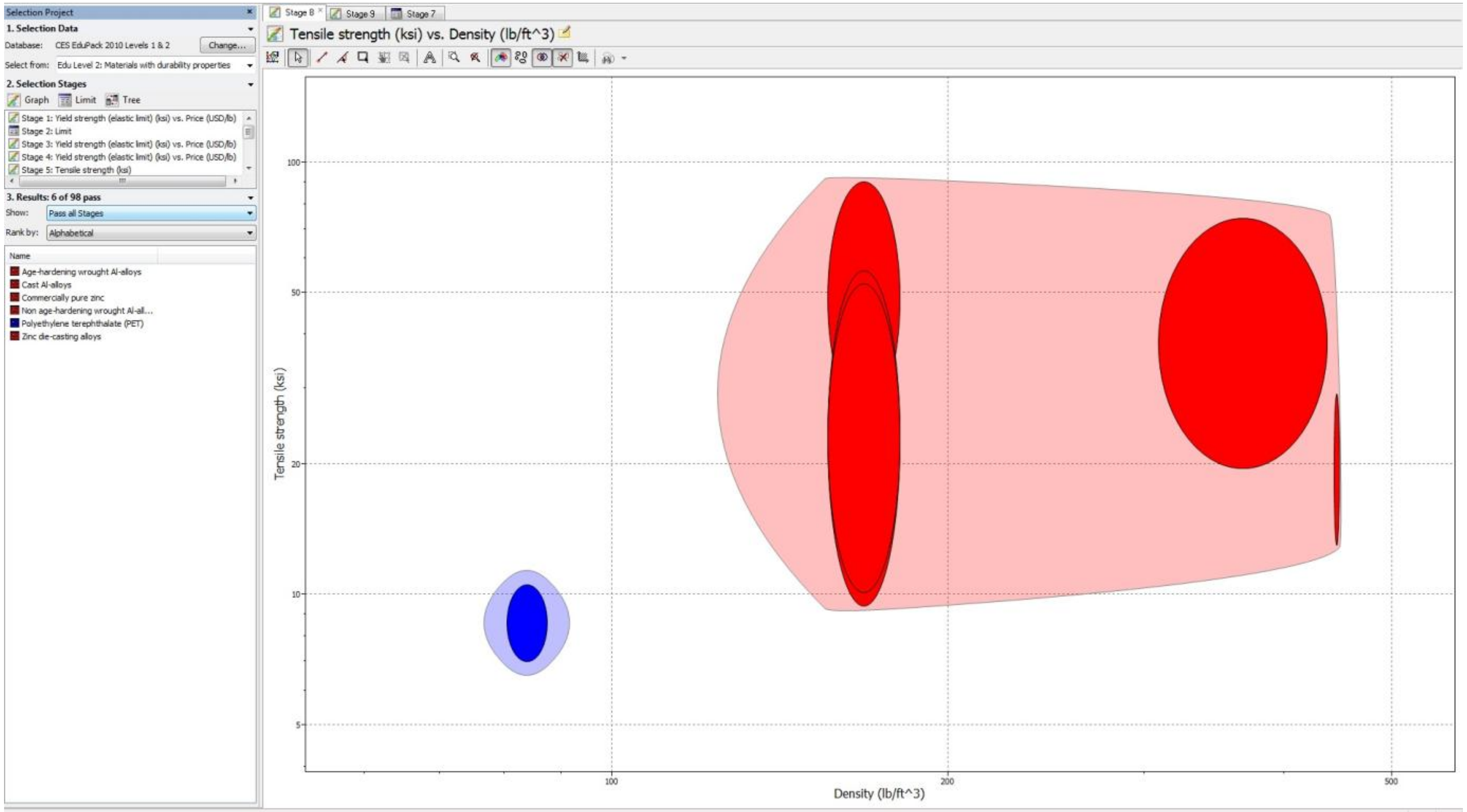
Show: Pass all Stages

Rank by: Alphabetical

Name
- Acrylonitrile butadiene styrene (A...
- Polyethylene terephthalate (PET)
- Polypropylene (PP)
- Polyvinylchloride (tpPVC)

Tensile strength (ksi) vs. Density (lb/ft^3)

Figure I.1. Tensile Strength vs. Density



1. Selection Data

Database: CES EduPack 2010 Levels 1 & 2

Select from: Edu Level 2: Materials with durability properties

2. Selection Stages

- Stage 1: Yield strength (elastic limit) (ksi) vs. Price (USD/lb)
- Stage 2: Limit
- Stage 3: Yield strength (elastic limit) (ksi) vs. Price (USD/lb)
- Stage 4: Yield strength (elastic limit) (ksi) vs. Price (USD/lb)
- Stage 5: Tensile strength (ksi)

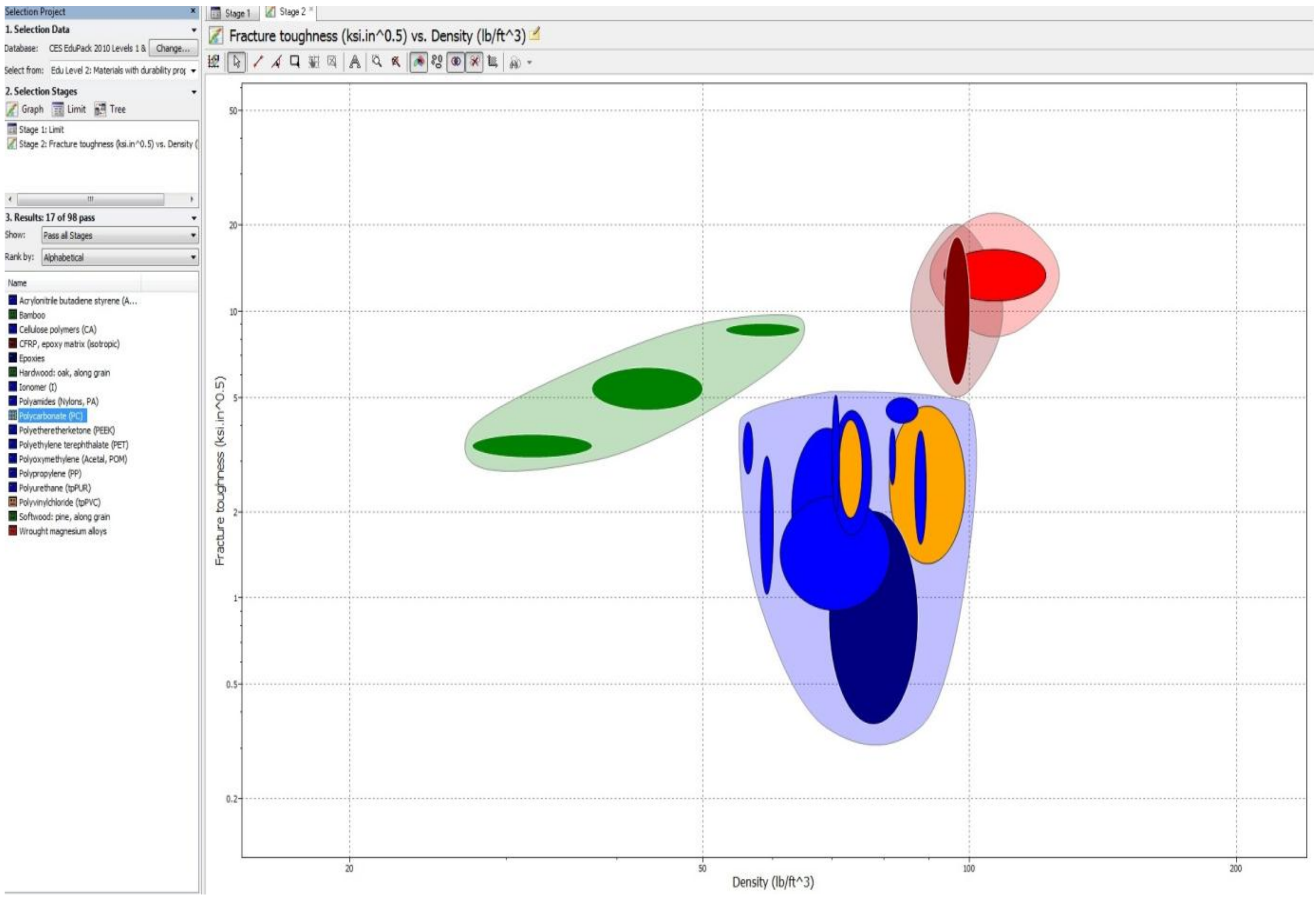
3. Results: 6 of 98 pass

Show: Pass all Stages

Rank by: Alphabetical

- 🟥 Age-hardening wrought Al-alloys
- 🟥 Cast Al-alloys
- 🟥 Commercially pure zinc
- 🟥 Non age-hardening wrought Al-all...
- 🟦 Polyethylene terephthalate (PET)
- 🟥 Zinc die-casting alloys

Figure I.2. Tensile Strength vs. Density



Database: CES EduPack 2010 Levels 1 & Change...

Select from: Edu Level 2: Materials with durability prop

Stage 1: Limit

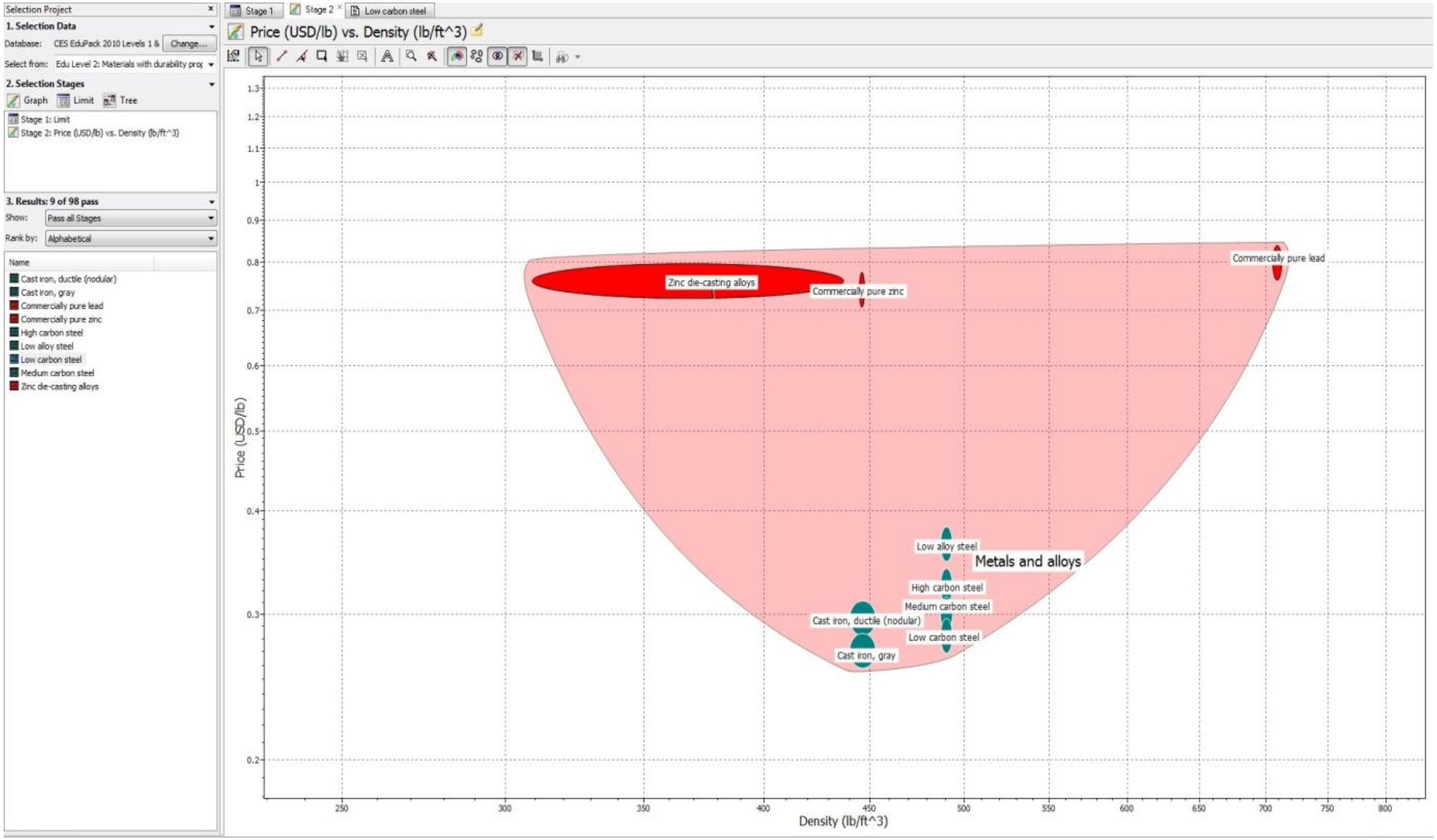
Stage 2: Fracture toughness (ksi.in^0.5) vs. Density (

Show: Pass all Stages

Rank by: Alphabetical

- Acrylonitrile butadiene styrene (A...
- Bamboo
- Cellulose polymers (CA)
- CFRP, epoxy matrix (isotropic)
- Epoxies
- Hardwood: oak, along grain
- Ionomer (I)
- Polyamides (Nylons, PA)
- Polycarbonate (PC)
- Polyetheretherketone (PEEK)
- Polyethylene terephthalate (PET)
- Polyoxymethylene (Acetal, POM)
- Polypropylene (PP)
- Polyurethane (tpPUR)
- Polyvinylchloride (tpPVC)
- Softwood: pine, along grain
- Wrought magnesium alloys

Figure I.3. Fracture Toughness vs. Density



Selection Project

1. Selection Data

Database: CES EduPack 2010 Levels 1 &

Select from: Edu Level 2: Materials with durability prop

2. Selection Stages

Stage 1: Limit

Stage 2: Price (USD/lb) vs. Density (lb/ft^3)

3. Results: 9 of 98 pass

Show: Pass all Stages

Rank by: Alphabetical

Name
- Cast iron, ductile (nodular)
- Cast iron, gray
- Commercially pure lead
- Commercially pure zinc
- High carbon steel
- Low alloy steel
- Low carbon steel
- Medium carbon steel
- Zinc die-casting alloys

Figure I.4. Price vs. Density

Appendix J. MATLAB/Simulink Model Screenshots

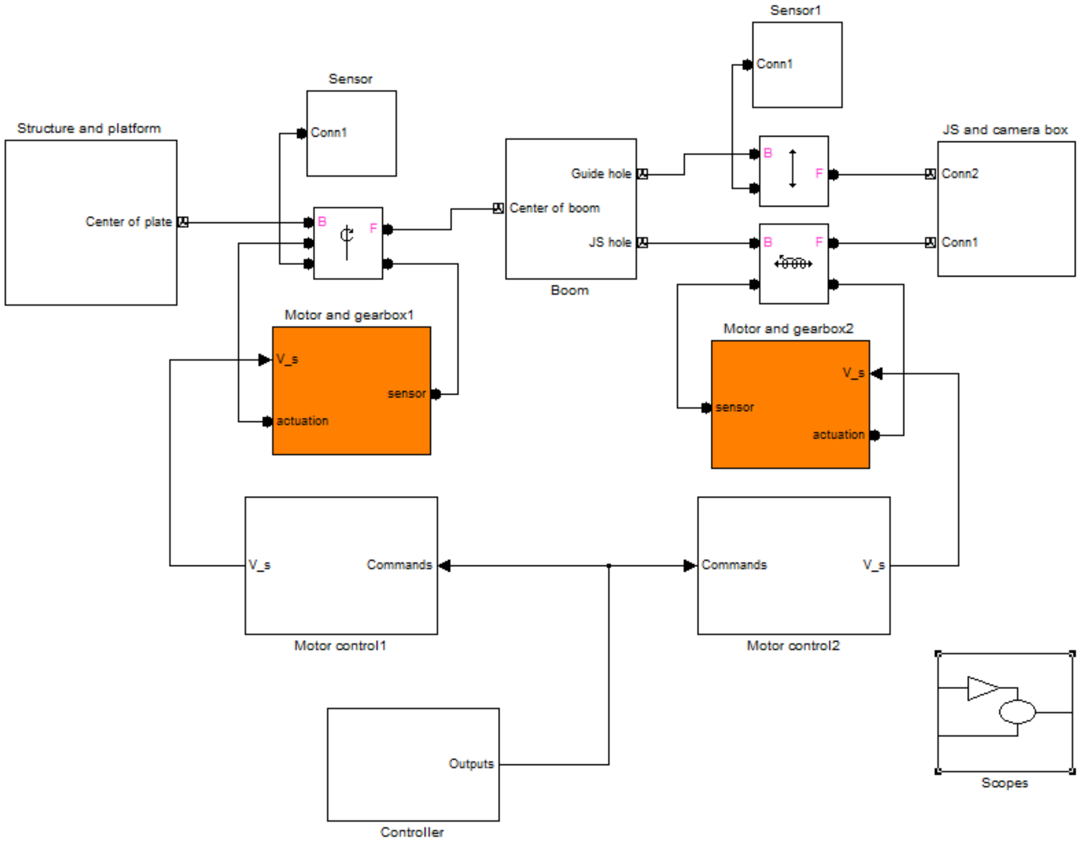


Figure J.1. Screenshot of overall model

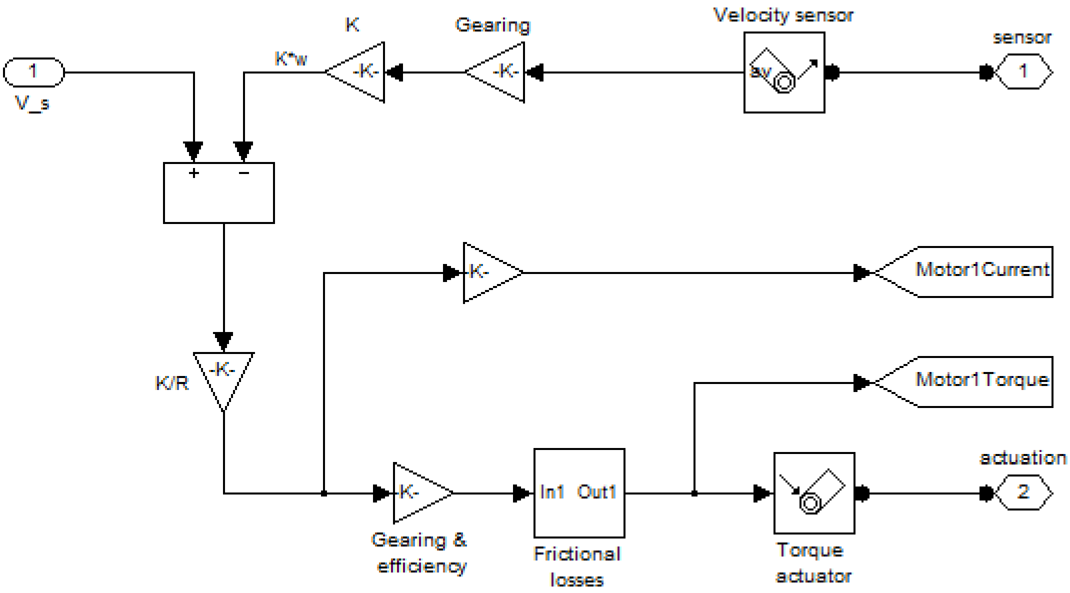


Figure J.2. Screenshot of “Motor and gearbox” subsystem

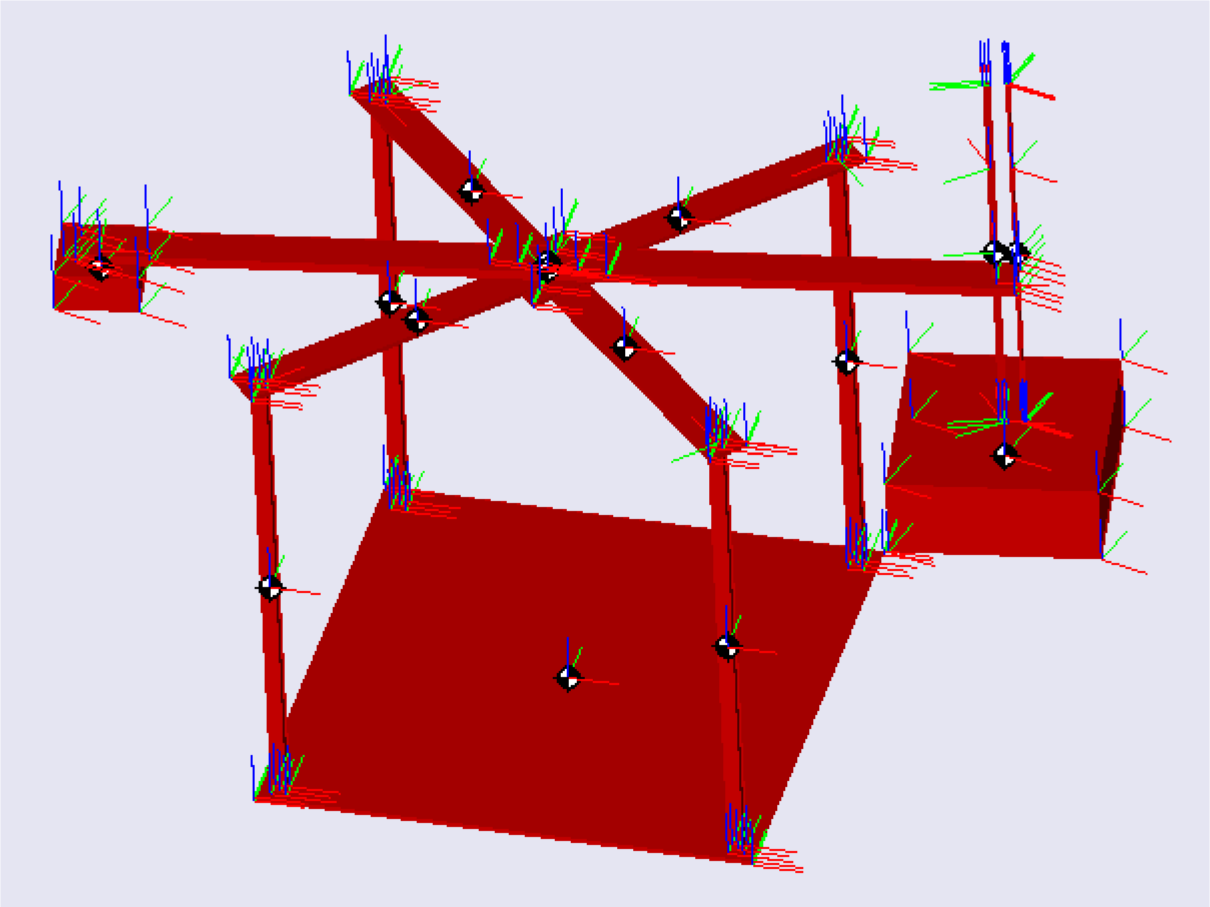


Figure J.3. Screenshot of 3D representation of computer model

Table J.1 Some of the parameters used for the system model. Dimensions, masses, and inertia tensors are not included in this list but were selected to be consistent with the parts used for our prototype (described in Section 8).

```
switch_closed_resistance = 0.001; % Ohm
switch_open_conductance = 1e-9; % 1/Ohm
wiring_resistance = 0.05; % Ohm
PWM_freq = 10; % Hz
supply_voltage = 12; % V
motor1_Wo = 100; % RPM
motor1_Wo = motor1_Wo * 2*pi/60; % rad/s
motor1_Io = 0.8; % A
motor1_Ts = 3.43; % N*m
motor1_Vs = 12; % V
motor1_resistance = motor1_Vs*(motor1_Io +
motor1_Ts*motor1_Wo/motor1_Vs)^-1; % Ohm
motor1_constant = motor1_Ts*motor1_resistance/motor1_Vs;
motor1_gear_ratio = 4;
motor1_gear_efficiency = 0.75;
friction_torque = 0.4; % N-m
motor2_Wo = 5000; % RPM
motor2_Wo = motor2_Wo * 2*pi/60; % rad/s
motor2_Io = 0.8; % A
motor2_Ts = 0.1; % N*m
motor2_Vs = 12; % V
```

```
motor2_resistance = motor2_Vs*(motor2_Io +
motor2_Ts*motor2_Wo/motor2_Vs)^-1 % Ohm
motor2_constant = motor2_Ts*motor2_resistance/motor2_Vs
motor2_gear_ratio = 4;
motor2_gear_efficiency = 0.75;
js_lead = 0.1; % inches
js_efficiency = 0.62;
```