Single-Axis Force-Reflecting Wheel

The Hoffman 3000

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EXECUTIVE SUMMARY

The purpose of this project is to design a commercially viable single-axis haptic device. Previous designs were only prototypes and are not sufficiently robust, aesthetically pleasing, or easily reproducible. Our haptic device will be a single axis-force reflecting wheel. It is intended to be used for multiple applications. Professors will be able to use our device to demonstrate system dynamics and controls in a classroom setting. Doctors and physical therapists will be able to use our device for the rehabilitation of stroke victims in medical settings.

The design for the haptic wheel is intended to be easily reproducible. To simplify the reproduction process and minimize cost, off-the-shelf parts will be used when possible. As is important with all commercial products, aesthetics is an integral part of our design, so the final product should have a professional appearance.

Our customers require that we design a robust device that accurately measures the angular position of the motor, motor torque, and the force applied by the user in the motor's axial direction. A diverse selection of handles is desirable, as well as a universal connector that is compatible to all handle types. The device should be able to interface with LabVIEW and advanced microprocessor programming environments. Securing the haptic device onto a table for use in two orientations is required.

The concept that we have chosen is a 5" in steel cube, or "haptic box," that houses a motor, wiring, electronics, and a load cell for measuring motor torque and axial force. Our haptic box is heavy enough that it is stable on a table without any additional mounting hardware. It is capable of 0^o and 90^o orientations relative to the table. It can interface with a variety of different handles using a rigid shaft coupler. Three different handles will be available, each connected to the motor shaft via a 6mm rigid shaft coupler. Serial cabling allows for two way communication between the haptic box and a variety of virtual environments. The design is also robust and pleasing to the eye.

Our design, not including electrical components, costs approximately $370. It can be machined and assembled in less then 30 man hours.

Our haptic box improves upon previous prototypes in several ways. Our design requires no additional mounting hardware, the load cell mounts internally to the box, and the overall size of the device is smaller than previous prototypes. We were unable to fully implement the load cell design due to time constraints. Our analysis of the load cell indicates that the load cell is capable of measuring motor torque and axial force, but a physical prototype has not been completed.

The final design we developed provides the robust functionality that is required of the device while maintaining its aesthetic appeal. Further revisions of our design may streamline the assembly process, but the current design is ready to be distributed to other educators.

ABSTRACT

A haptic interface is a device which allows a user to interact with a computer by receiving tactile feed back. Our single-axis force reflecting wheel design is intended to be distributed among educators as a way to teach system dynamics and controls using a haptic interface. It will measure angular position and torque. The motor command can deliver up to 0.5 Nm of torque. The device will feature modular handles, multiple operating orientations, and connectivity to LabVIEW and advanced microprocessor programming environments. The design will also be robust and have product-design appeal.

PROBLEM DESCRIPTION

Our group has been given the task to redesign a single-axis force reflecting wheel. The purpose of this device is to assist educators in teaching system dynamics and controls. Previous designs are not sufficiently robust or aesthetically pleasing. Multi-degree of freedom haptic devices exist on the market today, but a commercially viable design for a single axis force reflecting wheel has yet to be made. Our design is intended to be visually appealing, functionally complete, and easily reproduced. We intend to share the designs with other educators so that they can construct their own devices.

As shown in Figure 1, the design aspects that we are responsible for in developing the haptic wheel can be functionally decomposed into three aspects: interfacing with the user, achieving target performance levels, and packaging the product for production. The haptic device will interface with the user through an interchangeable handle, the LabVIEW environment, and a microcontroller interface. The performance characteristics that we are designing for are precision in measuring output torque, off-axis loading, and angle of rotation. The product packaging is currently the most underdeveloped aspect of the design for which we have to develop a component chassis, mounting system, and an external wiring scheme.

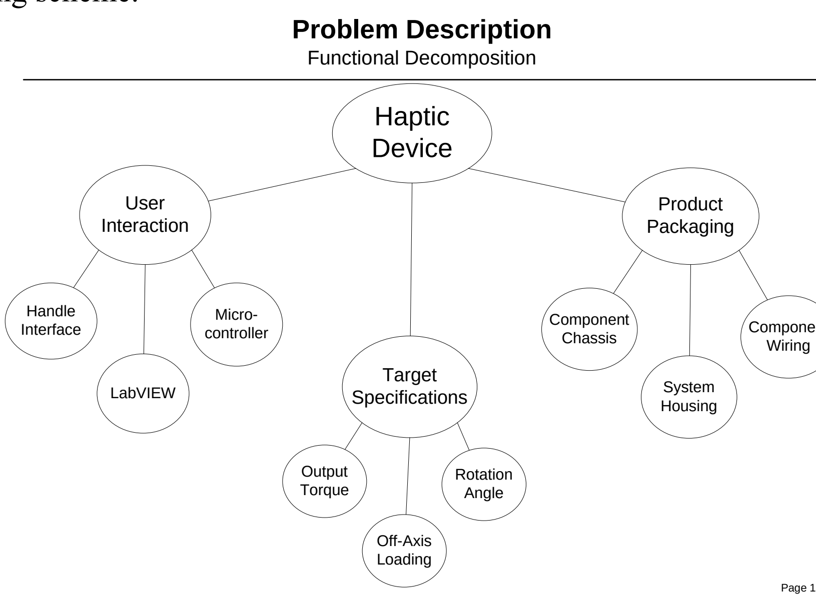


Figure 1: Functional decomposition of the single-axis haptic device

User Interaction:
The primary tasks performed by the device are sensing angular position and torque in addition to commanding the motor. Therefore, connectivity to a LabVIEW and advanced microprocessor programming environment is required. Although the current designs support the use of LabVIEW, a complete graphical interface has not yet been developed.

The primary goal of the device is to provide a haptic interface with which the user can interact. In order for the device to perform various functions, the handle that is used may vary depending on the application. Current designs do not allow for interchangeable handles which limits the applications for which the device can be used.

Target Specifications:
The primary electronic components in the system are the motor, encoder, and strain gauges. Figure 2 shows the schematic diagram of this system. In order for the motor, perhaps the most critical component in the design, to function properly, the power supply must deliver enough current at a given voltage. The encoder is responsible for providing the speed at which the haptic device is rotating and, depending on the mode, the direction of rotation. The strain gauge is responsible for measuring the strain on the device and outputting a proportional voltage.

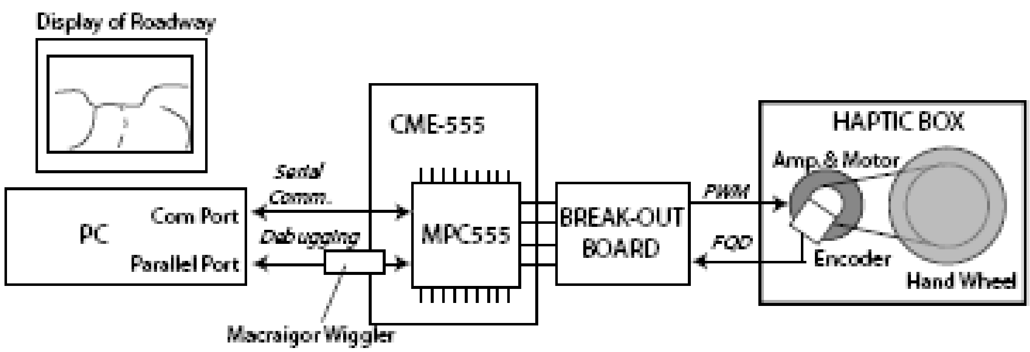


Figure 2: Macroscopic Diagram of System Electronics

The current system design uses a custom power supply and amplifier combination that does not provide sufficient power to the motor; for this reason, the desired output torque range can not be achieved. Additionally, the output voltages from the strain gauges are very small and are susceptible to capacitive and electromagnetic interference. The current design does not account for this interference; however, in order to reach the desired signal to noise ratio, these issues must be addressed. Previous designs of the system had the motor drive the haptic wheel through the use of a belt transmission system. In the current design, the haptic wheel is directly driven by the motor, so the mechanical advantage of the transmission system is lost as well as the sensitivity of the encoder to changes in angle.

The haptic device measures the torque applied by the user on the handle in the direction of the motor shaft. The result is sent to the encoder as both the input signal and feedback, depending on the application. Accurate and sensitive measurement of the torque is imperative to the performance of the device. The current design utilizes strain gauges mounted onto the cross shaped members in a housing frame to measure torque. This design is bulky and fails to measure force in the axial direction. Current noise level appears to be satisfactory but requires more detailed evaluation.

For a single axis haptic device, the user will apply torque in the axial direction when turning the handle. It is often the case that the user will also apply off-axis forces when handling the device, such as pulling, pressing, and yanking. Therefore, it is essential that the design is robust enough to withstand all types of external loading.

Product Packaging:

Proper packaging of the product is needed in order for the device to be commercially viable. The chassis must house the motor, encoder, amplifier, and cabling for the force reflecting wheel. However, in current designs the chassis is unattractive, limits the systems' functionality, and does not provide proper housing of the electronic components. Since the product is a stand-alone device and needs to be grounded, the product design must incorporate a mounting mechanism. The mounting hardware must be simple, aesthetically pleasing, and discrete so that it does not interfere with the user. Additionally, the hardware must provide a firm mount to sufficiently ground the device against various loading conditions. Standard interfacing of the device output with those of standard computer ports is not completely implemented in the current design. The lack of this feature prevents the interoperability of the device and limits its modes of operation.

BACKGROUND INFORMATION

Although there are devices similar to the wheel we are designing, no product has been developed that is readily manufactured or packaged well. The products that currently exist have shown growth in most of the performance related areas, but aesthetics and product packaging have all but been ignored. Our goal is to maintain the performance features that current product designs have while designing a housing that would make it attractive to a broad customer base.

User Interaction:

Using LabVIEW, virtual environments for visual and haptic display can be developed to demonstrate the device capabilities. These capabilities include the ability to sense angular position and wheel torque inputs from the user and to output numerical measurements through DAQ hardware and the LabVIEW environment. The reverse is also possible. Numerical values can be input by the user into the LabVIEW environment. The environment will then act as a motor control and enslave the motor according to the user's inputs. In addition to the LabVIEW environment, PC control of the device will also be possible through the use of a microcontroller. Two current designs that perform a function similar to that of our product are The Fishbowl and The Box. The fishbowl design uses a 4 inch diameter wooden wheel with an inner half-inch diameter knob. The problems with this design are that the wheel is not interchangeable and it uses a transmission in the form of a pair of Berg sprocket gears and a cable-chain. The transmission can easily become misaligned or damaged and makes the handle unnecessarily complicated. The other product design, The Box, uses a connector that can attach to a variety of different handles. Although the connector attaches directly to the motor, it is bulky and visually unappealing [3].

Target Specifications:
Motor function is critical for the haptic device to provide the required functionality. An important aspect that governs motor performance is the amount of power that the motor can draw. Proper matching of power supply and amplifier with the motor is needed for efficient and proper operation, and the current system is undersupplying the motor. Although custom power supply and amplifier combinations are ideal in exactly matching the desired power requirements, off the shelf solutions exist which are sufficiently robust and improve the reproducibility of the design.

There are several options for encoders that allow for measurement of rotary motion: mechanical, optical and magnetic index. The most popular method is optical encoding which utilizes a light source and a code disk which create a pair of digital output pulse signals, as shown in Figure 3. Optical technology eliminates much of the noise and distortion associated with the other methods. Optical encoders can be used to create an absolute output with very high resolutions; however, these encoders are very expensive and incremental encoders are used instead. [9] By using fast quadrature decoding and the generated pulse signals, the computer can determine the angle change and direction in which the wheel is traveling [10]. The optical encoder has low power consumption and typically high switching rates which allow for the quick transition of the rising and falling edges. [9]

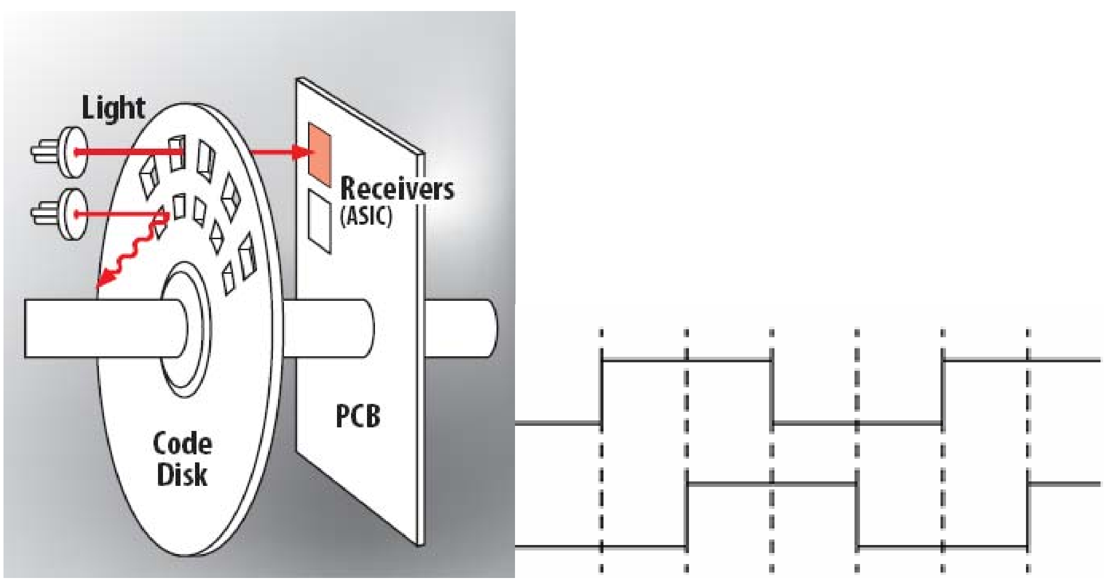


Figure 3: Optical encoder and its corresponding quadrature signal.[9,10]

Wiring of the electronic components is very important not only for the aesthetics but also the performance of the machine. The strain gauges will be generating very small voltages, on the order of millivolts, and are susceptible to noise. Voltages running through wires that are in close proximity may induce a voltage change in adjacent wires if not properly shielded. This induced voltage, termed capacitive interference, can come from any voltage source like function generators and power outlets. Shielding the wires from one another significantly reduces the effect of the interference. Inductive interference is caused by time varying currents in a conductor; this interference is minimized by separating the power source from the wires carrying small signals as well as ferromagnetic shielding which effectively separates the currents magnetically.

Various methods of measuring torque are available. Torque measurements are used to determine the power of rotating devices as well as for quality control in manufacturing [7]. The simplest method of measuring torque is rotary sensors, which are mounted directly onto the rotating shaft. This method eliminates the design of any additional components (such as a housing frame) and is very accurate. However, it requires open space around the shaft and is very expensive (range from $700-$3000) [11]. An alternative is "reaction sensors", which use strain gauges mounted onto the stationary housing of the rotating components to measure the reaction forces on restraining members. This is the method adopted in the current design of the haptic wheel. The drawback is that it disregards the motor's inertia and might yield inaccurate results; however, this is not imperative in our application due to the relatively small motor inertia. We decided this is the preferred method in our design.

Different types of strain gauges are also available. Mechanical devices such as extensometers directly measure the displacement of members under stress. They are usually bulky and have low resolution. Optical sensors measure strain with interference fringes. They are accurate and sensitive but very delicate and expensive. The most commonly used strain gauges in the industry are resistance gauges which utilize the property of changing the material's resistance under stress and deformation. The change in resistance is then picked up as electronic signals. They are small, cheap and accurate and are decided to be the preferred strain gauge choice in our design. Its only drawback is the measurement varies with temperature. However, our device will be used mostly indoor and the temperature variation is not significant.

A process termed "shunt calibration" is used to calibrate the strain gauges [6]. Periodic calibration might be necessary.

In order to determine the locations at which the strain gauges should be installed, it is helpful to use finite element analysis (FEA) technology. Using this technology, we can accurately predict the stress and deformation distribution on a model when its geometric and loading information is given. Unigraphics has robust and easy-to-use built in finite element analysis functionality and is our choice of the FEA processor.

One application for the single haptic device under development is in rehabilitation therapies for stroke patients [8]. The haptic device will create simple manual tasks such as turning a knob where patients exercise supination of their hands. The device also evaluates recovery of the patient's strength and motor function. The consideration of off-axis loading is especially important in this application due to the movement limitation of the stroke patients. It is common for stroke patients to involuntarily pull back their forearms to their torso when using arm muscles. Yanking and pulling on the handle constitutes the external loading and has to be considered in our design.

Currently, not many competitors exist in the market, especially at the level of finished product design. One of the few competing designs is the Big Wheel by the University of British Columbia. Like our design, its motion is single axis rotation. In addition to measuring the torque and force in the axial direction, this device measures 6 axes of decoupled force at 20-60N with 1/800 resolution and 3 axes of torque at 1Nm with 1/32,000 resolution. The sensor type is F/T (force/torque) sensor system with built-in silicon strain gauges and controllers. The apparent robustness of this design will likely increase the cost significantly too since the price of a single F/T sensor is in the range of $2000-$6000 [4]. Another design by Stanford is similar to iTouch: a low budget, single axis haptic device with limited range of motion designed by Professor Gillespie. It measures torque in the axial direction using cheap Hall Effect sensors.

The maximum torque of the Big Wheel by UBC is 1Nm, about twice as much as our torque requirement. The maximum torque of the Stanford design is only 0.035Nm, about 1/6 of iTouch and 1/14 of the customer requirement of our current project design.

Product Packaging:

The stand-alone design requires the use of mounting hardware to sufficiently ground the device to any desk or table. Another stand-alone device of similar size and weight utilizing mounting hardware is the camera. Cameras commonly use industrial strength magnets and suction cups to achieve a stable mount. Other potential mounting solutions include mechanical clamps such as ratchet and toggle clamps.

The fishbowl design uses a Plexiglas chassis created by using a laser cutter [3]. The design is cheap, easily manufactured and assembled, and is translucent allowing for the student to observe the internal workings of the device. However, the Plexiglas can easily deform or break over time even under normal loading conditions. The Box uses a section of square aluminum tubing for the chassis. Although this design is more robust and easier to manufacture, it utilizes an external load cell that can easily be damage if the device were dropped. Additionally, this box design prototype was never fully completed.

In the current fishbowl design, the motor interfaces with a PC through the use of a break-out board and the MPC555 controller. The breakout board simply provides a buffered interface with the MPC555 which protects the controller from damage. [2] The controller is then connected to the PC via parallel and serial port connection. Direct interface with the PC and control of the motor through LabVIEW are available in The Box model, but the two designs have widely different connection settings.

Information Sources:

General information about haptic research was gathered from research papers written by professors from the University of Michigan, the University of British Columbia, and John Hopkins University. These sources gave us a general understanding of haptic devices and their applications in research. The papers also gave us benchmarks for us to compare our design to including The Box [3], the Big Wheel [4], and the iTouch [3].

Specific information regarding our project was given to us by Professor Gillespie. We discussed with him specific aspects of the design regarding load cell design, chassis design, the types of cables to use, handle selection, and handle couplers.

We have spoken to graduate students Kari Danek and Felix Huang at the University of Michigan regarding handle design. Kari Danek gave us insight into handle design, as well as specifications for a special handle that she wanted us to create which would be used for rehabilitation of stroke patients. Felix Huang gave us ideas on how to connect the handles to the motor shaft using a clamp that he had designed.

REQUIREMENTS TO CONCEPTS

In developing a design for the haptic wheel, our primary concern should be addressing our customers' needs. This step in the design process not only involves receiving and extrapolating concrete technical specifications from the customer but also acquiring design constraints by other means. Since we had two separate customers with considerably different applications and requirements, our design process was a little more complicated. Ideally we would be able to satisfy each customer's requirements; however, this was not always possible and compromises had to be made. Our interaction with our customers was the primary means of developing design parameters which we then had to translate into technical specifications.

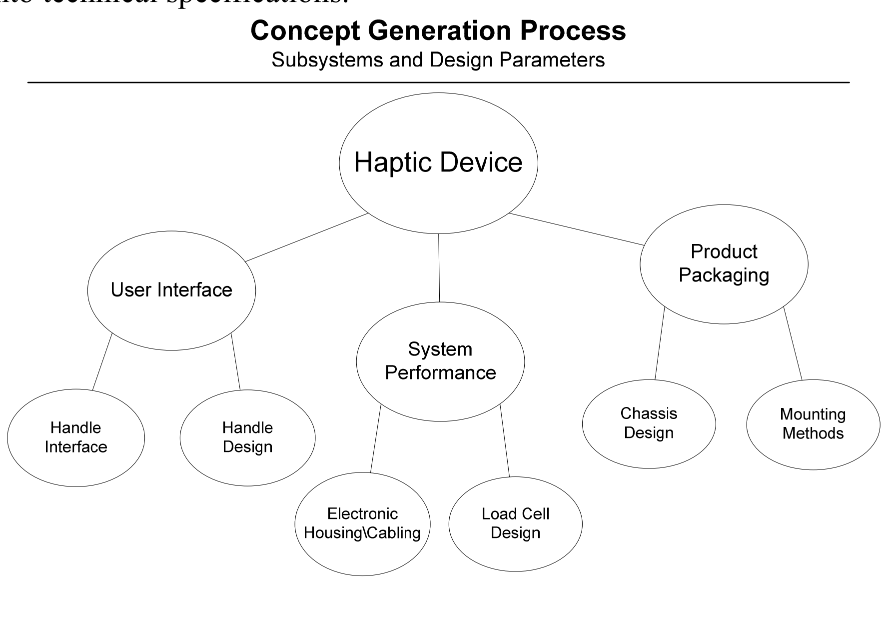


Figure 4: Concept Generation Subsystem Focus and Corresponding Design Parameters

The concept generation process is intimately related to this task because it allowed us to refine existing design parameters and identify new ones. Through our communication with our customer we identified three primary aspects that would affect our design process as shown in Figure 4 above, and when we generated concepts we typically focused on a single one. Through the idea development process we created some unique models, and, although not all of them were feasible, they all allowed us to refine the customer requirements and develop a more complete set of design parameters.

User Interface:

Due to the various potential uses of the product design and the different customers that may use it, a universal connection joint is required which allows for interfacing with a family of different handle types. The handles must be able to handle off-axis load so they do not break when a large torque is applied, and the handle must be large enough so that the user must use his hand to turn it rather than his arm. These handles should also have a low moment of inertia and can not have any spokes, which could be potentially dangerous. From the standpoint of manufacturability the customer requires that the handles should be easily manufactured or readily available. Although it is not required, our client would like a pre-designed set of symmetric handles that can be sold alongside the haptic device allowing for different types of interaction.

The interface with LabVIEW has not been explicitly defined, but two-way communication between the motor and LabVIEW environment as well as connectivity with strain gauges is a must. The microcontroller must have a similar interface with the haptic device without the need of a visual interface.

Concept Generation

In order to make the handle interface as robust as possible, it was important for us to minimize its size. A large handle interface is infeasible from not only an aesthetic stand point but also a functional standpoint. To develop this interface we would need some method of attaching the motor shaft to the handle the user either purchased or manufactured. One idea we looked into was the use of standard coupling devices and the other was a clamping mechanism developed by Felix Huang, a graduate student at The University of Michigan.

The clamping device created by Huang consists of a small metal clamp which cinches to the motor shaft by tightening a screw as shown in Figure 5. This same piece acts as a keyway to the motor handle and will provide a backlash free solution to prevent the handle from rotating about the motor shaft. The advantages to this method are clear: the device is small, light weight, and will not slip about the motor shaft. However, the size of the device makes it difficult to manufacture. Achieving proper tolerances between the male and female parts of the keyway was difficult. Additionally, the clamp is simply press to the motor shaft and may not sufficiently prevent axial motion along the motor shaft.

Figure 5: a) Felix Huang's method of clamping b) Rigid set-screw couple c) Rigid clamping couple

Another method of attaching the handle is through the use of standard coupling devices available off the shelf. Most rigid coupling devices attach to the motor shaft through the use of set-screws, but this only provides friction at a few points of contact. Clamping shaft couples are also available which allows us to attach a handle to the motor quickly and securely, but these solutions are quite long and may not be suitable for use in our application.

We have spoken with our customer and graduate students at the University of Michigan to help come up with the set of handles that will be sold along side the haptic box. One of the handle designs is The Wheel which is simply a circular handle with a diameter of roughly 2-3" to be controlled by you hand and a smaller inner diameter to be controlled by your fingers. It will allow for a simple intuitive interface with the haptic box. Another design is The Knob which is a circular handle with a finger dimple on it as seen in Figure 6. It will have a low moment of inertia so that it can be turned easily using your finger.

One of our customers requires a handle that is shaped similar to a bicycle pedal, and you must be able to operate it by either gripping a side or by laying your palm flat on it. This handle will be used for medical rehabilitation; one of the challenges is that due to its size a large off-axis moment is produced on the motor shaft. This could potentially damage the motor, so a support will be placed on the handle which will allow it to perform the same rotational motion while decreasing the load on the motor shaft.

Engineering Specifications

The two methods to address the user interface issues were the keyway clamping device developed by Felix Huang and a standard off the shelf clamp on couple. The off the shelf clamp is quite large relative to Huang's design, but it increases the reproducibility of the design. Our design team decided that although the manufactured keyway method would be ideal from a functional stand point the use of an off the shelf couple would be better from an overall perspective. Before we could select the clamping coupling device, we needed to verify that the motor shaft could sustain the increased radial loading.

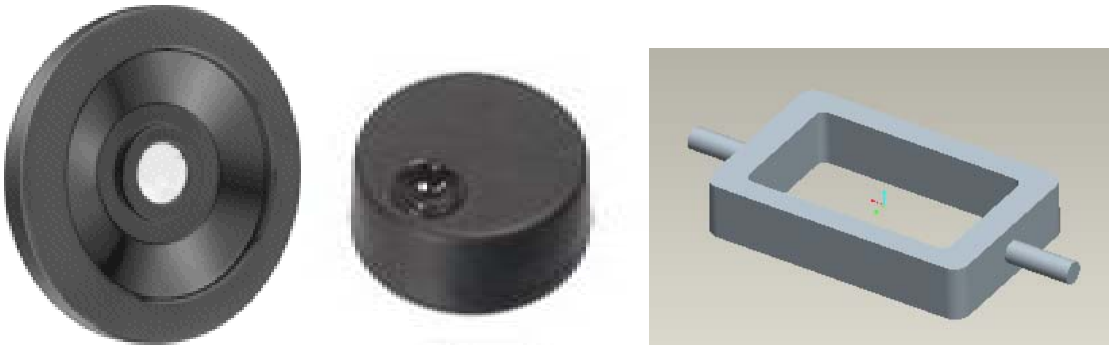


Figure 6: Various handles that may be sold alongside the haptic box

To obtain the maximum off-axis loading which causes bending moment on the handle, we experimentally determined the maximum off-axis force using a spring scale. We imitated the possible yanking motion of a stroke patient and recorded a maximum force of 10lbf or 44.5N.

The lever arm consisted of four components: the one-piece coupling, the thickness of the handle, the clearance on the motor shaft and the clearance on the handle shaft. The lengths of these components were determined to be 3cm, 2.5cm, 0.95cm (upper limit) and 0.32cm (upper limit), respectively. The total lever arm length is then 6.81cm. The maximum dynamic bending moment on the handle was calculated to be 3.0Nm using this information.

Problem Analysis

The main problems that we analyzed for the handle interface were how securely a handle is fastened and the length of the interface, so as to avoid large forces on the motor bearings. We performed preliminary tests on the existing motor, but we will have to conduct further tests with the actual prototype to determine whether the handle interface is sufficiently strong for our purposes. Testing will be done to see how much torque that the interface can withstand before slipping.

By consulting the motor specification sheet, we found a maximum sustainable radial load of 28N applied 5mm away from the flange. Although this result is well below our value, it corresponds to static loading conditions whereas our calculations correspond to a dynamic load. The bearings in the motor can sustain these dynamic loads, but they may decrease the lifetime of the motor. Preliminary testing of the motor has shown that these loads do not cause immediate failure. From these calculations we also noticed that we need to limit the size and moment of inertia of the handles as well as the method by which they connect.

In order to analyze the handle design we will have to make sure that the handles themselves can interface with our haptic box properly. This includes determining their moment of inertia as well as whether they can be used with the handle interface that we choose. Tests will be performed on the selected handle prototypes to verify that they can be safely used in our design.

Concept Selection

From our preliminary analysis of the problem we have determined that the off the shelf rigid shaft coupler is the best choice for the handle interface. The main reason that we choose the rigid shaft coupler over Huang's method of clamping is that you can purchase it off the shelf whereas the Felix Clamp must me carefully machined. The rigid coupling device is about 30mm long which is a longer moment arm than with the Felix Clamp, but our team decided that a readily available part with sufficient performance characteristics is a better fit for our customers needs. Even with the longer moment arm, preliminary analysis has shown that the bearings should be able to support the dynamic loads generated by using the rigid shaft coupler. A scoring matrix is shown below highlighting the selection process and our decision to use a rigid single piece clamping couple.

Table 1: Scoring Matrix for Handle Connector Types

Selection Criteria	Set screw coupling	Felix Clamp	Rigid 1 piece coupling
Compatible with all handles (10 pts)	6	8	6
Off the shelf availability (10 pts)	10	0	10
Tight grip (10 pts)	4	10	10
Size (5 pts)	3	5	3
Aesthetics (5 pts)	3	5	4
Cost (incld. Manufacturing) (7 pts)	6	6	5
Total Score (pts)	32	34	38

The handles that we selected were based off of customer suggestions. Our customer wants all the handles discussed in our concept generation section. The Wheel and the Knob can both be ordered from suppliers and require little machining to make them compatible with our handle interface. The Pedal will need to be manufactured, but considering this is a special handle our customer requires this cannot be avoided.

System Performance:

The customer we are designing the device for has already purchased a specific motor and encoder, so our power supply and amplifier selection will have to match the motors parameters.[12] Our customer requires that the torque applied on the handle in the motor's axial direction be accurately and precisely measured. Eliminating noise is necessary in order to yield sensitive measurements with high resolution. It is also desirable to measure the force in the axial direction of the motor, a feature not yet available in other designs.

Concept Generation

The primary functionality performed by this device is torque measuring, rotational displacement, and off-axis loading. The component of our design that is responsible for them is the load cell. Ideally we could purchase a load cell that had performed these functions and then incorporate it into our product design. We found several load cells that could measure single axis forces for between $80 and $500. A load cell capable of measuring torque in addition to axial forces would be at least $600. In addition to these methods being cost prohibitive, the resolution of the torque sensing was far worse that what our customer required.

Our team found that the only way to address the customer requirements was to design a load cell of our own. The three concepts we investigated were the tube, plate, and ring designs. The tube design, as shown in Figure 7 is essentially a hollow tube within which the motor would mount. Strain gauges on the length of the tube would allow for torque measurement, but in order to develop high stress concentrations material would have to be removed from the tube. Although torque measurement would be simplified, measurement of axial forces would be quite difficult.

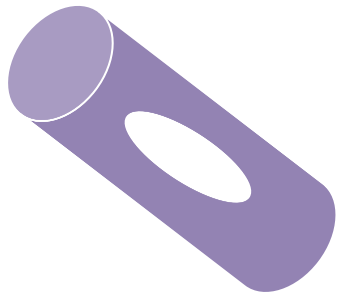


Figure 7: Tube Design for Load Cell

The plate method is a modified version of the current load cell design, as shown in Figure 8. Instead of having four members, which may have been statically indeterminate, it only has three. Additionally, access to strain gauge mounting locations would be easier since there would be more space for your fingers. The existing load cell was improperly manufactured so axial force measurement was not possible, so in the new design the outer ring is milled through and axial force can be measured. With the Y-shaped members, we can achieve the same amount of deflection as in the four member model while using a smaller plate. The problem with this design becomes the size of the plate. Although we can decrease the size of the plate and measure torque with the same accuracy, we need to add an additional ring to measure the axial forces.

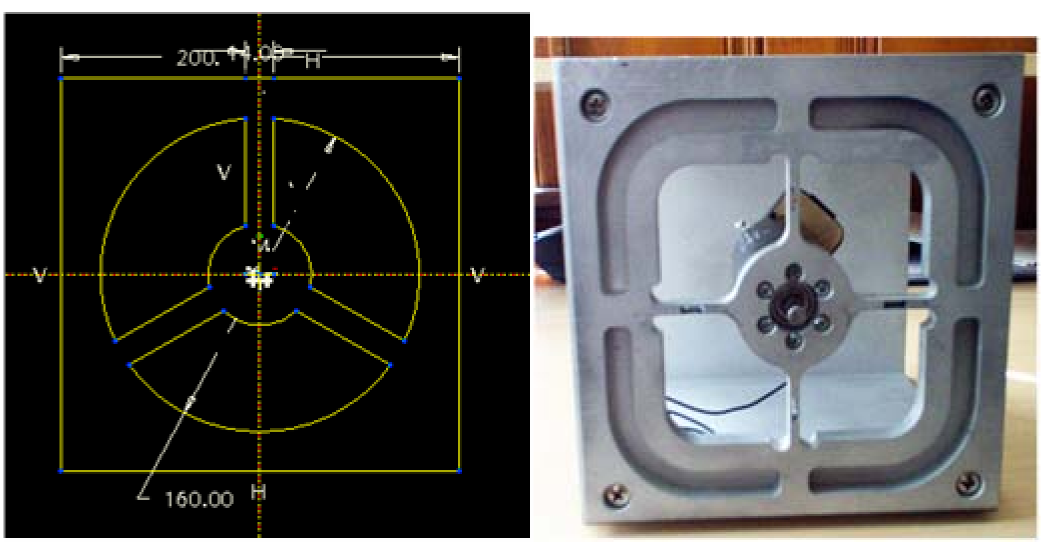


Figure 8: Plate Load Cell Design. Cad Version (left) and existing Model (right)

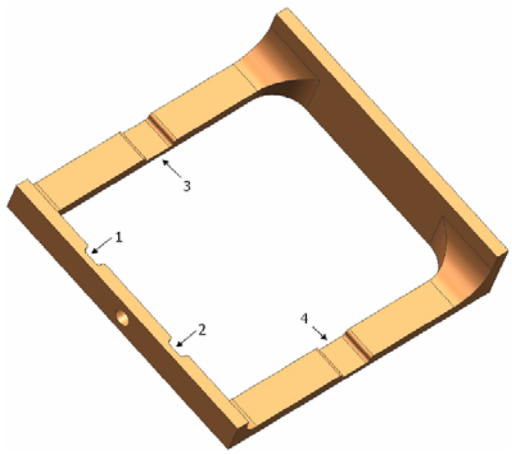


Figure 9: Ring Design for Load Cell and Strain Gauge Locations (indicated as 1, 2, 3 and 4).

The final design we developed is the ring design with the strain gauges mounted as shown in Figure 9. The motor will be mounted to the ring which is attached to the back of the box. The strain gauges mounted to the load cell above and below the motor will be responsible for measuring axial force, and the other two strain gauges will be responsible for measuring torque. The ring design will provide ample room to access the strain gauge location and can be modified to fit within a smaller housing. One problem with this load cell design is that it restricts the mounting locations of other subcomponents.

The signals produced by the strain gauges are very low voltage and typically must be amplified by a couple orders of magnitude. The strain gauge amplifier magnifies whatever the input signal is including any interference or noise, so the signal must be amplified before much noise is introduced. The haptic box will have two input wires which carry the power signal for the motor and it will have four output signals corresponding to each strain gauge. The box can have connectors for power and strain gauge signals individually or a single connector which will handle both. The single connector will allow for a single cable to plug into the box, but the strain gauge and power signals will be going to different locations. Two separate connectors allows us to take the power supply and strain gauge signals to two different locations, but there will be two cables and two connectors on the box itself.

Engineering Specifications

The goal of our load cell design is to measure axial force and torque with great sensitivity while remaining relatively unaffected by off-axis loads. Strain gauges measure the change in length of load cell beam as shown in Figure 10. In order to obtain large deformations and correspondingly large strain gauge outputs, in the x-y plane, where strain gauges are attached, it is important that the thickness of the beam in the direction of the force (z axis in this case) is significantly smaller than its length (in the x direction.) Often, this is achieved by carving out a slot in the plane where deformation occurs (x-y plane in this case).

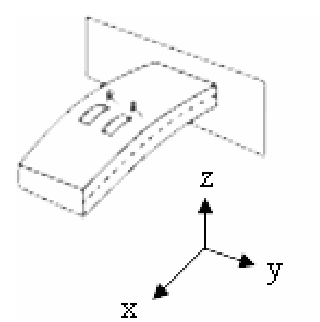


Figure 10: Load Cell Design and Strain Gauge Placement

The second important factor of the load cell design is that "useful" loads, the axial torque and force in our case, need to be isolated from all other off-axis loads. This is done by designing load cells that contain distinct planes on which only "useful" loads cause deformation. In our case, the axial force and torque cause deformation in two planes that are perpendicular to each other. This requires our load cell to contain at least two perpendicular planes onto which strain gauges can be readily attached. Beyond the useful loads we are concerned about there may be loading in other axis. By changing the orientation of the strain gauge at a particular location, these loads can effectively be ignored.

The motor encoder performs an important function and is perhaps the most important part of developing virtual haptic environments. The current encoder has 1024 ticks per revolution; however, some customers may require increased resolution. In order to increase the encoder resolution, a transmission system could be used. Our customer, however, requires that the encoder is directly driven, so the only method of increased resolution is by purchasing a larger encoder for a nominal increase in price.

In order to minimize the affect of noise and maintain a high signal to noise ratio, the amplifier must be placed within the motor housing. Additionally the material we choose for the motor housing should provide ferromagnetic shielding. If a single connector method is chosen, the power supply and strain gauge signals must use shielded cables to prevent capacitive interference. Because the power supply will be drawing a large current to produce the required torque, the wire we use must be much thicker than the wires transmitting the strain gauge signals.

The relevant technical specifications that we derived are:

- Minimum of 1500 microstrain measured by the strain gauges
- Maximum torque of 0.5Nm
- Minimum of 20:1 S/N ratio, optimal 100:1 ratio
- Linear relationship between torque and strain
- Power\amplifier output ~20 Amperes @ 24V [12]
- American Wire Gauge Current Load Limits:
    - Power Supply Wiring < 17 Gauge
    - Strain Gauge Wiring ~ 29

Problem Analysis

The main design issue with the load cell is that the strain must be large enough so that we can measure it using strain gauges. In order to determine whether the strains are large enough in the load cell we need to use finite element analysis. Making a CAD model of the load cell and using a FEA post processing tool we will be able to identify the stress concentrations which will in turn tell us the points of maximum strain. It is at these points that we will be placing the strain gauges.

Another design problem that needs to be analyzed with the load cell is how it mounts into the chassis. The load cell must be placed in a way that allows us to fit the electronics and the mounting system in the chassis as well. We will determine this by analyzing the size of the chassis design, the size of the electrical components, the size of the mounting system, and the size and shape of the load cell itself and then optimize the model to minimize housing size.

In order to choose the proper cabling we need to determine the strengths of the signals that will be traveling through the cable and based on the current that will be traveling through it select the appropriate wires. We also need to take care to minimize noise propagation within our system by using properly shielded wires.

Concept Selection

The final design for the load cell that we have chosen is the ring design. The reasons we choose this design is that the strain gauge placement intuitively makes more sense, it will provide ample room to access the strain gauge location, and can be modified to fit within a smaller housing. The plate design can measure torques easily; but it requires a more complicated shape to measure both the torques and the axial forces. Due to its size and complexity it will be difficult to place the strain gauges which need the proper amount of heat and pressure to properly secure to the material. The tube design will have high stress concentrations, but it is difficult to accurately measure the axial forces and would increase the difficulty of our machining. Another advantage of using the ring design over the plate design is that it allows a reduction in the size of the box. Because we already have a specific motor and encoder, we must develop a housing that can easily accommodate both. The dimensions of the motor limit the amount by which we can shrink the existing housing size, but we still managed a 42% reduction in volume of the box by using the ring design. This is advantageous to our customer who requires that the box fit on a table easily. The one problem with the ring load cell design is that it restricts the mounting locations of other subcomponents. A selection matrix is shown below highlighting the selection process and shows that the ring design is the best choice.

Table 2: Scoring Matrix for Load Cell Designs

Selection Criteria	Cylinder	Plate	Ring
Accurately measure torque (10 pts)	10	10	10
Accurately measure force (8 pts)	3	8	8
Manufacturability (10 pts)	4	7	8
Easy strain gauge attachment (8 pts)	4	4	8
Aesthetics (5 pts)	5	4	5
Cost (incld. Manufacturing) (7 pts)	4	6	5
Total Score (pts)	**30**	**39**	**44**

The power supply and motor amplifier will both be housed together separate from the haptic box. We are doing this so that the haptic box itself can be as small as possible and we can considerably decrease the electromagnetic interference caused by the power supply. We plan on using a pre-made electronic housing box to contain these components which size can vary to fit any power supply and amplifier combination. The exact housing box can be changed depending on the final specifications of the power supple and amplifier that our customer will be purchasing.

We decided to use single connector for all the cabling that will be leaving the haptic box. This will allow for a clean interface to the box. A y-cable will be used to split the cabling that goes form the box to the power supply from the cabling that goes box to the LabVIEW interface.

Product Packaging:

The product packaging is perhaps the most important aspect of the product design since it has not been address sufficiently in other products. The customer requires that the chassis design must be strong and durable so that it does not break or wear out over time as well as designed for ease of manufacturing. The design should be small enough so that it can easily fit on any workspace, yet be large enough to contain all the parts and allow for easy access to them. In order for maintenance and teaching purposes, disassembly of the housing and components is necessary. The customer would like a translucent chassis so students can see how the device works, but this feature is not a requirement. The design, most importantly, should be aesthetically pleasing with a professional finish.

The haptic wheel design is required to mount directly on any standard table, desk, or laboratory countertop. The customer also requires that the product be capable of mounting at various angles, specifically 0° and 90°, to allow for various user interactions. In addition, the existing design includes a bulky frame where sensors are embedded which should be changed.

Concept Generation

Our concept generation process with regards to product allowed us the most freedom in design, and we focused on two primary areas: chassis design and mounting methods. The chassis will be responsible for holding the motor and encoder, the load cell, and the strain gauge amplifier. We generated concepts for the chassis from a variety of different sources. Inspiration was drawn from everything from everyday household items to previous haptic wheel designs. Different ideas for the chassis include The Lamp, The Web-Cam, The PVC-Pipe, and The Box.

For The Lamp chassis we would use a lamp available from a hardware store and replace the light bulb with the motor and subcomponents. For this design, we would not have to manufacture our own chassis and we could achieve a full 180° of rotation. It would also be available off the shelf and be inexpensive, but finding a lamp that is large enough and the right shape to fit our motor and load cell would be difficult. Additional concerns are the strength and availability of a specific lamp.

The Web-Cam chassis would have a range of motion similar to that of the web camera, and would have the motor with the strain gauge mounted in a sphere that could rotate on a base. The design allows for the position of the motor to be adjusted in all three axes as well as being aesthetically appealing. However, this design would require a lot of manufacturing, and could not be created from parts available off the shelf.

The PVC-Pipe chassis would be constructed entirely out of PVC pipes. The motor and load cell would be housed in a T-shaped section of pipe. The T-shaped pipe section could be detached and reconnected to the design at a different orientation. The design would be could be produced from cheap readily available parts and have a PVC pipe motif which we feel would add to the aesthetic value and its product appeal. PVC material is difficult to work with particularly when precise and accurate tolerances are required. Additionally the PVC might not be strong to withstand the loads that would be applied on it.

The Box design is based on the previous prototype, see Figure 8. It would be a piece of square extruded steel tubing where the tubing is cut leaving two sides exposed. The load cell would attach to one of the four remaining faces and allow for easy access to the interior of the housing. The tubing is readily available and can be easily machined; the motor can be easily mounted and the subcomponent placement is not heavily restricted. The Box design restricts the positioning of the box to only two positions, 0° and 90°, and requires that the chassis be removed to switch between these positions.

The bowling ball design, shown in Figure 11, is somewhat a variation of The Box design. Using a bowling ball, which is readily available, we can remove a cavity from it where the chassis would reside. This adaptation of The Box would allow for orientation in virtually any position; however, securing the ball to the table might be an issue. One difficulty we could not address was the machining aspect of the ball. Securing it to a milling surface would be difficult, and the material within the bowling ball was unknown to us.

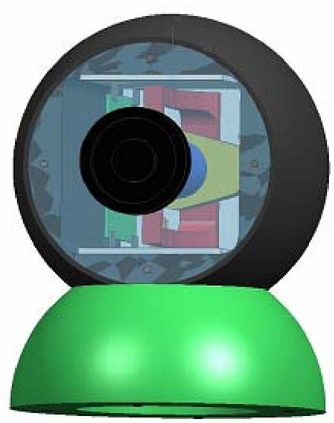


Figure 11: The bowling ball design is a variation of the box design.

We considered various methods of mounting the haptic box to our table. These methods were typically chassis specific, so for each chassis type we had a corresponding mounting method. We primarily investigated the use of suction cups, magnets, clamps, and frictional methods to secure the box. The magnet method would have a magnet placed within the box and one below the table surface. Industrial strength magnets are capable producing large amounts of force. In our application, there would be a table a couple inches thick so the magnets would have to be strong enough to resist a fairly large sheer force. This method of mounting the haptic box would be unobtrusive and the magnets can easily be disengaged. The magnetic field produced by the magnet would have to be shielded from the wire carrying the strain gauge signals.

Suction cups were also considered as a method of securing the box to the table. There are very strong suction cups available on the market that could be strong enough for our needs. The suction cups would allow us to quickly and securely fasten the box to the table. The problem with this method is that not all table surfaces would allow for good suction which limits its range of use. Another concern is how long the suction will hold and the backlash associated with a set of suction cups.

In the clamping method we investigated, we secure a base to the table and attach the haptic box to this base. The method of clamping we came up with involves a U-shaped channel for the base that fits over the lip of the table. The bottom of the U-channel is secured to the table by tightening a fastener to the bottom of the table. The chassis is then attached to the base using bolts that slide into slots as shown in Figure 12.

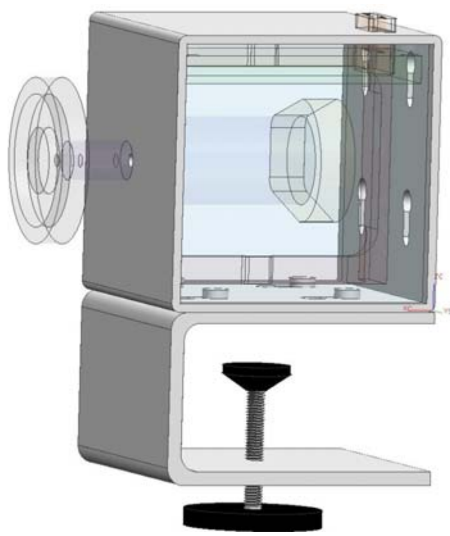


Figure 12: U channel with key slots mounting method

Due to the spherical nature of the bowling ball it would be difficult to secure the device to the table, but due to its increased size and mass we developed a base within which the ball would sit. A rubber gasket around the rim of the base would create sufficient friction to prevent the ball from moving. Additionally, the base could be created from a simple cylindrical base or even another section of a bowling ball.

Although, these methods provide secure methods for attaching the device to the table they all introduce new problems or compromises in our design. Because of these things, we reevaluated the purpose of the mounting device and considered the useful features of each method. The appeal of the frictional method was that it would be unobtrusive and would use the natural weight of the bowling ball in order to secure it to the table. Similarly, we decided that the weight of The Box, being made of ¼” steel along with the electronic components that would be placed within it, may be sufficiently heavy so as to eliminate the need for an additional securing device. By placing rubber pads on the base, we could ensure that enough friction existed to make sliding The Box across a table very difficult.

Engineering Specifications
The chassis housing and mounting mechanism have very little influence on the performance and operation of the haptic wheel. The minimum size of the motor housing is primary limited by the size of the motor and encoder, but the load cell and strain gauge amplifier take up a significant portion of the internal space within the housing. The minimum space required for the motor and a large encoder is 3.5” x 2.3” x 2.9” and the addition of strain gauge amplifiers and the load cell restricts the size of our box.

Problem Analysis
The main problems that need to be addressed with the chassis design is housing all of the components and obtaining different orientations. In order to determine if all the components can fit in the chassis we are be using CAD software to accurately model how all of the components fit together. By using the CAD software we can determine the size constraints of the box without actually building one.

The different orientations available for the box are strongly related to the design that we choose for the chassis. We will need to analyze whether or not the box can function at the different orientations for the design that we choose. Testing will be performed on the prototype to see if we can achieve our desired orientations. In addition, we must verify our mounting design choice, and rather than building the complete alpha prototype and testing it we plan on performing tests using the existing prototypes so as to decrease our lead time if changes are to be made.

Concept Selection
The design for the chassis that we have decided to go with is The Box. The reason we chose the box is because it is simple and easy to manufacture while providing the robust performance that the customer wants. The PVC Pipe method would be difficult to manufacture and its suitability for our application has not been validated. The Web Cam design will require far more machining then any of the other design, and the functionality gained from the extra machining does not justify the extra cost and labor. We feel The Lamp design is unfeasible because a lamp housing was not designed to house a motor and it would be difficult to find a lamp that met all our needs. Also, in terms of reproducibility, a specific lamp may not be available everywhere and may not stay in the commercial market for very long. We determined that machining the bowling ball would be far too difficult due to the abrasive nature of the material inside of it, and eliminated it as a potential design.

The Web Cam, The Lamp, PVC Pipe, and The Bowling Ball designs are considered more aesthetically desirable and are capable of obtaining many different orientations. However these are only two of our design considerations and The Web Cam, The Lamp, and The PVC Pipe do not fulfill our other design specifications very well. The Box design will have orientations at 0 and 90 degrees, which meets our customer requirements, while allowing for greater functionality and simplicity. A comparison matrix of all the designs is shown below.

Table 3: Scoring Matrix for Motor Housing Designs

Selection Criteria	Dome	Lamp	Pipe	Box
Material available off the shelf (10 pts)	0	2	10	10
Enables different orientations (10 pts)	10	10	10	8
Manufacturability (10 pts)	0	7	7	9
Easy to interface with mounting device (7 pts)	2	7	6	6
Aesthetics (10 pts)	10	10	4	8
Cost (incld. Manufacturing) (6 pts)	1	5	5	5
Total Score (pts)	**23**	**41**	**42**	**46**

Because we determined that the weight of The Box itself would be sufficient to prevent motion of the device we decided that no additional fixation method would be necessary.

CONCEPT DESCRIPTION

In its simplest form, our design consists of two components, the haptic box and the power supply housing. The haptic box can be broken down into three primary components: the load cell, the electronic components, and the actual enclosure. Each of these subsystems has its own function and design criteria but will all assemble together to create the final design. The power supply housing, a much simpler part of our design, is responsible for housing the components that will power the box as well as routing of the signals between the haptic box, the computer, and within itself.

The Haptic Box

The haptic box, as shown in Figure 13, is the core of our entire design because it is responsible for providing all of the functionality of the device. It serves as the interface for the user, provides accurate measurement of the target specifications, and is the primary component that would reside on the work surface.

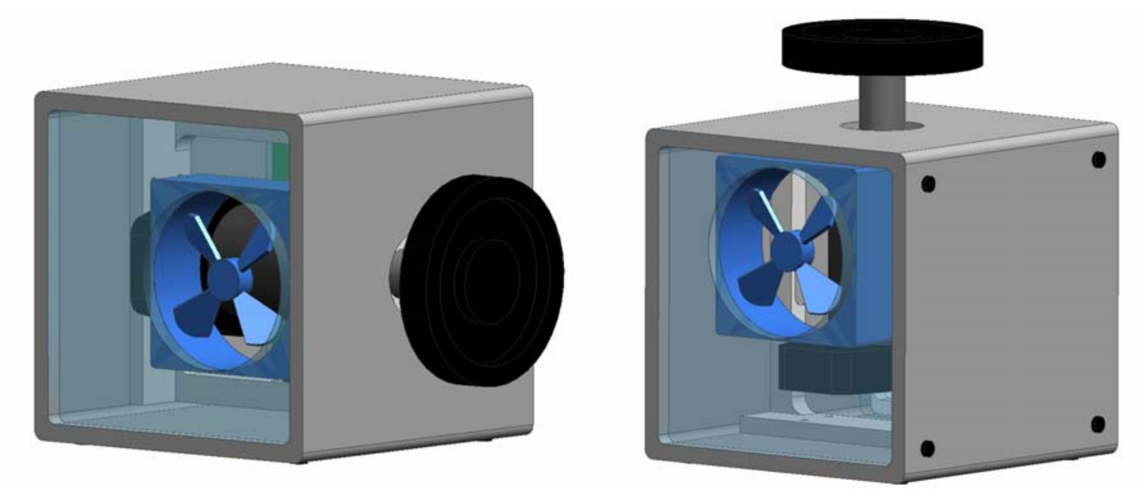


Figure 13: Haptic Box Design Shown in Two Orientations

Load Cell Design

The load cell we designed creates the necessary stress concentrations in order to get the precision that is required. The load cell will mount to the back wall of the box’s housing and will allow for the motor to mount to its front as shown in Figure 14. In order to generate high stress concentrations, portions of the load cell were made thin. Modifications were made to the original design which made it easier to manufacture using a two-axis mill. Additional considerations were given to machining, with respect to mounting and fixturing the device.

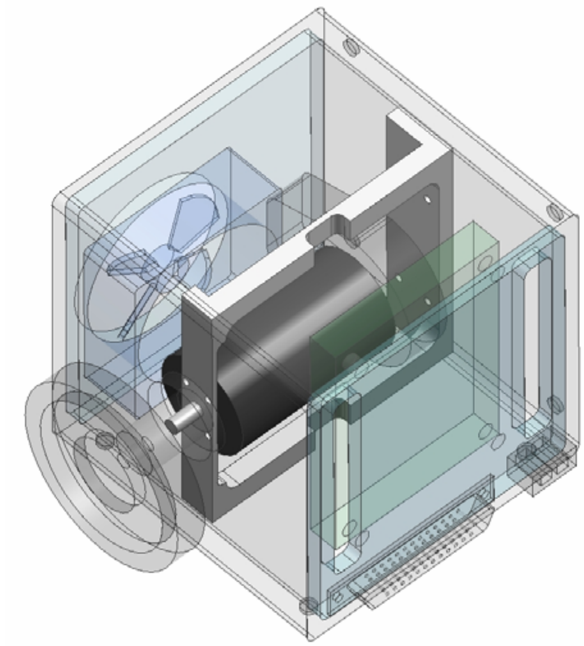


Figure 14: Load Cell Placement within Haptic Box

Electrical Components

The electrical components are very important for proper functioning of the haptic box. Even though we were not responsible for designing any of the electronics, we were responsible for proper cabling. The electrical components were mounted to the side insert panels which allows for easy removal and access as shown in Figure 15.

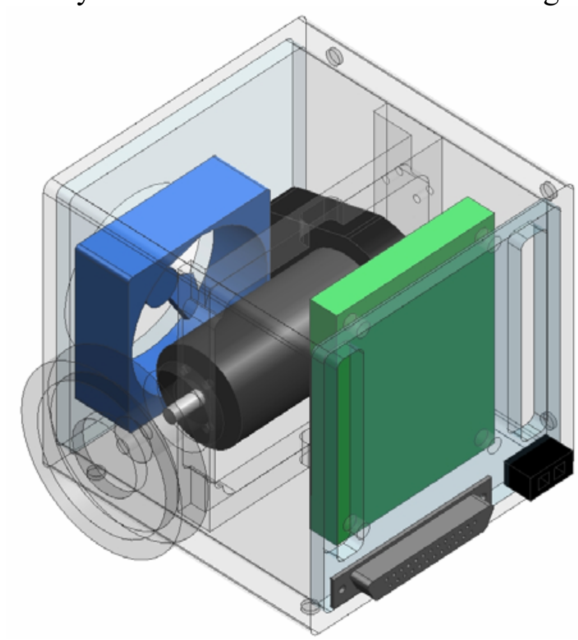


Figure 15: Drawing depicting electrical components and how they fit within the haptic box.

The schematic in Figure 16 shows the internal interactions of the various electrical components. From an overall view point the haptic box interfaces with the power supply box via a standard 25-pin D-Sub connector and a custom 2-pin power connector. The components housed within the haptic box are: the motor, encoder, instrumentation amplifier, strain gauges, and enable switch, and case fan. The motor provides the user with feedback, and through the coupler and handle it interfaces with the user. The optical encoder is attached to the motor itself and has two outputs corresponding to the quadrature signal it outputs. The strain gauges and instrumentation amplifier are intimately related; the instrumentation amplifier provides the +10V output which is passed over the Wheatstone bridge and then amplifies the voltage difference read across the specified terminal inputs.

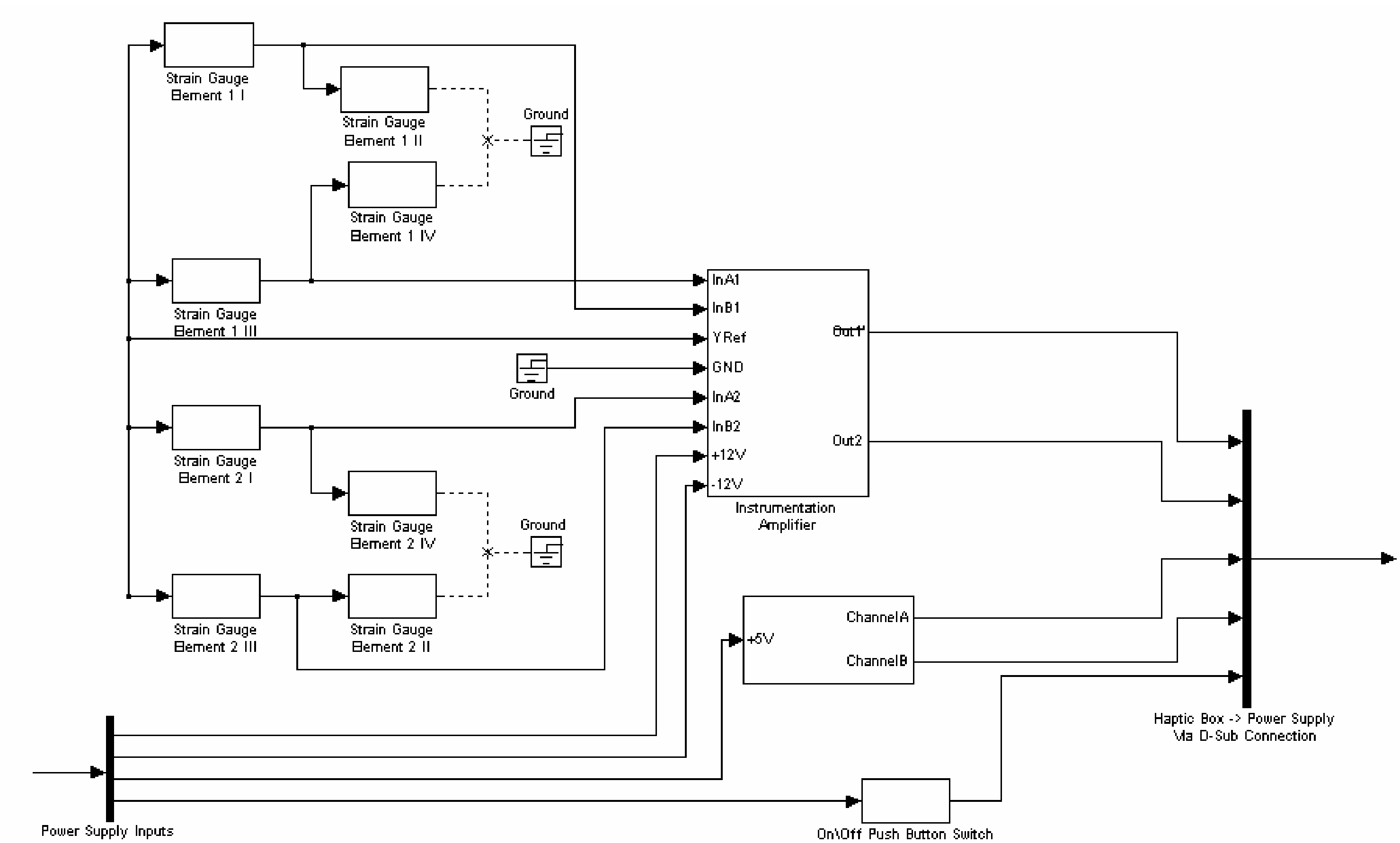


Figure 16: Interactions of Electrical Components Within the Haptic Box

Haptic Box Housing

We decide to use ¼" thick square steel tube for the housing because of its ferromagnetic properties as well as its strength and weight. We selected a 5" cube to house the electronic components and the load cell; if the box were any smaller access to the electronic components and wiring would become a problem. Future revisions of the design may call for redesign of the instrumentation amplifier board where we could embed the signal routing and minimize the amount of wiring. The side plates are created from Plexiglas and are secured in place by using four set screws. The Plexiglas is easy to machine and allows for easy modification in connection layout, and if removed all the cabling is connected to one face so not all wires must be detached. One of the concerns that was introduced by our customer during our final design review was that of heat dissipation in both the haptic box and power supply housing. We introduced fluid bearing case fans which provide sufficient air flow through the haptic box.

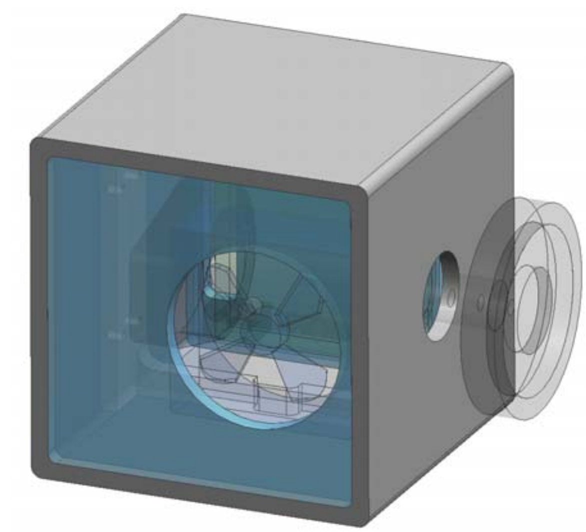
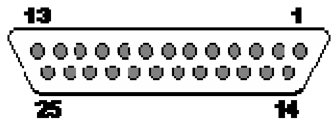
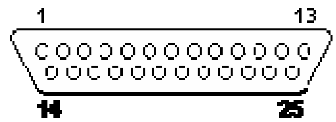


Figure 17: Haptic Box Housing with Plexiglas Inserts

Power Supply Housing

The power supply housing box is a commercially available steel enclosure which contains a primary power supply, which features 24V output, and a secondary power supply with three outputs: +12V, -12V, and +5V. The primary power supply will drive an amplifier, also housed in the power supply box, which will drive the motor. Because the motor may draw large amounts of current, it needs a 16 AWG wire which goes through the special 2-pin connector. All other signals both power and data will be sent through the 25-pin connection. There also is a power entry module on the box which will take the AC input from the wall and power all three of the devices contained within. The pin layout in Table 4 and schematic in Figure 18, respectively, outlines the input and output signals of the power supply housing and shows the internal cable routing within the power supply housing.

Table 4: Pin Layout of D-Sub Connections on Power Supply Housing

Pin #	 Connection to Computer	 Connection to Haptic Box	
1	Amplified Out 1	Amplified Out 1	Strain Gauge
2	Amplified Out 2	Amplified Out 2	
3	NULL	-15 V	
4	NULL	Ground	
5	NULL	+15 V	
6	NULL	Enable Bit +	On
7	NULL	Enable Bit -	
8	NULL	Ground	Optical Encoder
9	NULL	Index Pulse	
10	Channel A	Channel A	
11	NULL	+5 V	
12	Channel B	Channel B	
13	NULL	Fan +	Fan
14	NULL	Fan -	
15	PWM Signal	NULL	

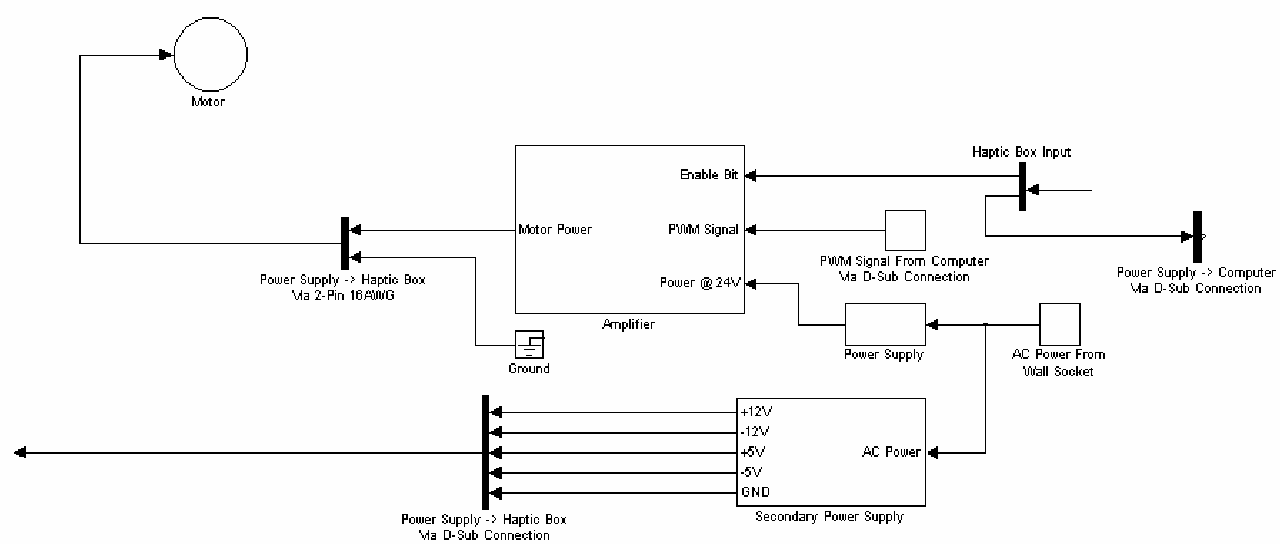


Figure 18: Interactions of Electrical Components within Power Supply Housing

ENGINEERING ANALYSIS

Before production or prototype of our design can begin, our team conducted analysis of several different aspects of the haptic device design. Our primary concerns were our loading on our base, strain concentrations in our load cell design, and wiring and placement of strain gauges all of which affect the performance of the device. We analyzed and verified our design using static load, circuit, power transfer, and finite element analysis tools.

Load Cell Analysis

The load cell is the core of our design functionality. The load cell is responsible for sensing both torque and axial force while working in conjunction with strain gauges. It is essential that the load cell intentionally concentrate strain in specific areas to achieve accurate and precise measurements through the stain gauges. A good design effectively concentrates strain in a particular area depending on the type of load. For example, strain caused by a torque on the motor will concentrate in specific locations while an axial force on the motor concentrates strain in different locations. Secondary levels of strain do overlap in undesirable areas relative to load type however. This secondary strain is rejected from measurement by connecting the strain gauges in a Wheatstone bridge formation. The Wheatstone bridge will be discussed later.

Material Considerations

For our final design we chose Aluminum 6061 for its low modulus of elasticity and manufacturability. The low modulus means that the material can achieve high levels of strain at low levels of stress relative to many other metals such as steel. High strain is important because accuracy increases as strain increases. Aluminum 6061 is readily available and easily machined. These are desirable qualities as one of our objectives is to develop a reproducible design.

Deformation Effects of Loading

The functionality and performance of the haptic device hinges on the effectiveness, namely the precision and accuracy, with which the strain in the model can be measured. Strain is the relative deformation of a material and is calculated using *Equation 1*, with the correct notations shown in Figure 19.

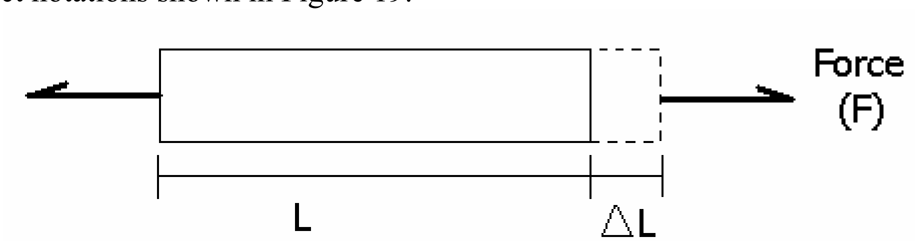


Figure 19: Axial Loading and Beam Deformation

$$Strain(\varepsilon) = \frac{\Delta L}{L}$$

Equation 1: Strain Relationship to Deformation

In order to get good readings from the strain gauges we use, we need to have high concentrations of strain; the load cell design allows us to develop these high stress areas.

Load Cell Development using Finite Element Analysis

To make the transition from our preliminary design to our final design we used a form of finite element analysis (FEA) provided through the Unigraphics NX2 software package. The “Structures” application within Unigraphics allows us to simulate various types of loading and predict stain levels and concentrations. Beginning with our preliminary design, we ran a simulation to see which design characteristics were effective and which were not. We would then modify those characteristics that were not initially effective and run another simulation. After many minor geometric fixes and simulations we arrived at our basic design geometry. We then began to adjust dimensions that we determined to be critical in achieving high, localized strain concentrations. After manufacturing our load cell we plan to debug and calibrate our design with actual hardware.

The graphical results of our analysis using Unigraphics FEA simulation are shown in Figures 20 and 21. It is important to note that the cylinder located at the symmetrical center of our design is used to simulate the motor connection to the load cell and is not actually part of the design. Figure 20 illustrates the strain concentrations due to axial loading in the negative x-direction.

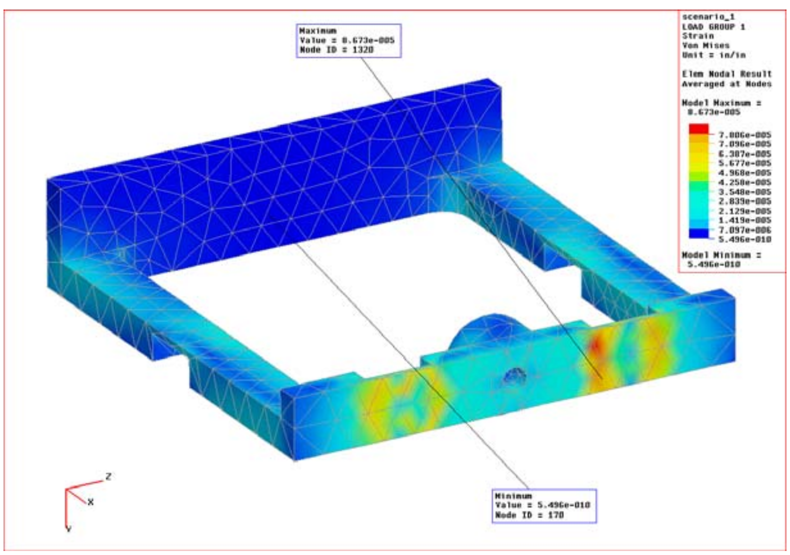


Figure 20: Strain concentrations due to axial loading in negative x-direction

Figure 21 illustrates the strain concentrations due to torque loading about the x-axis.

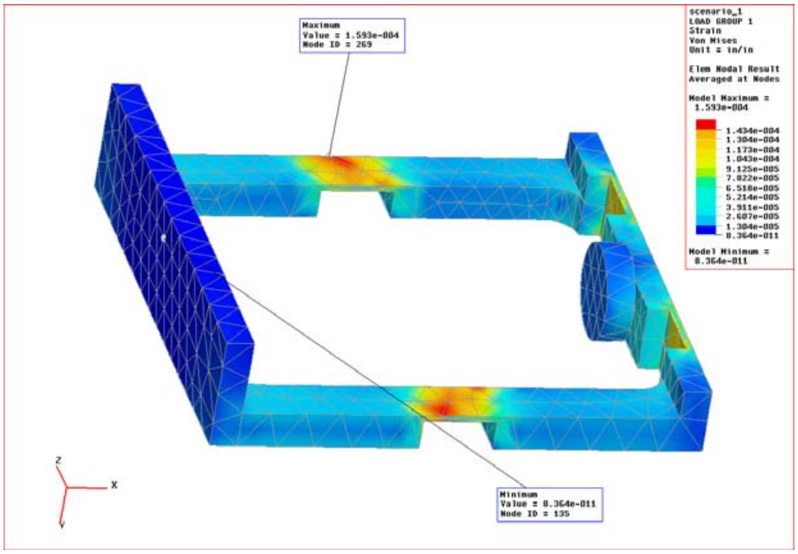


Figure 21: Strain concentrations within dashed circles due to torque loading about the x-axis

Determination of Failure Criteria

To determine the optimal thickness of the strain gauge placement areas for our load cell, we manufactured two test specimens (Figure 22) using Al 6061 with t values equal to 1/16" and 3/32" and the depth (into the paper dimension) equal to 0.4". These are the relevant dimensions we would use in the final design of the load cell. We drilled a hole on the specimen at point A through which we tied a piece of string. We then applied force directly downward onto the specimen using a spring scale with the left end of the specimen clamped down on the table as shown.

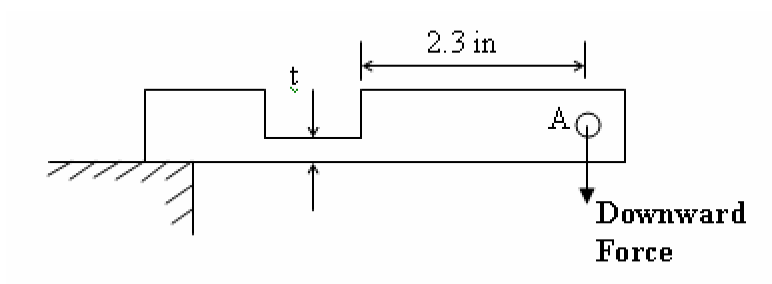


Figure 22: Experimental setup to determine the thickness of the strain gauge placement area.

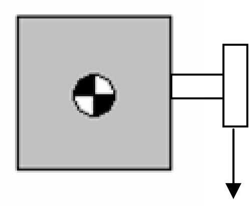
We recorded the magnitude of the force at which the specimens yielded. In our haptic box design, the measured distance from the point of force application to the strain gauge placement location is 3.75". Since he equivalent failure load in the haptic box for different t values can then be calculated by

$$F_{box} = \frac{F_{spc} \times 2.3}{3.75}$$

where F_{box} is the predicted failure load for the load cell inside the box and F_{spc} is the measured failure load of the specimens. The results are summarized below in Table 5.

Table 5: Failure load for specified load cell thickness of the strain gauge placement area

t (thickness of strain gauge placement area)	F_{spc} (lbf)	F_{box} (lbf)
1/16"	7	4.3
3/32"	24	14.72



The maximum possible load applied by the user on the load cell equals the force required to tilt the box as shown on the right. The total weight of the box was approximated as shown in Table 6 to be 7.3 lb. Taking moment at the pivot point (the bottom right corner of the box), the required force to tilt the box was calculated to be 9.33 lbf. In other words, the maximum possible force that will be applied on the box before it moves is 9.33 lbf.

Table 6: Weight Determination for the Haptic Box

Component of the Box	Weight (lbs.)
Steel box (5x5'', 1/8'' thick, 4 faces)	3.5
Motor (Maxon RE-40)	1.1
Load cell (Al, volume=2.23 in3)	0.2
Amplifier/cabling/encoder	1.5
Handle/coupler	1.0
Total weight	**7.3**

With the above analysis, the t value of 1/16" will fail under the maximum loading condition while the t value of 3/32" will withstand the load with a safety factor of 1.6. Therefore, we determined that the optimal thickness of our strain gauge placement area for the load cell was 3/32".

Load Cell Strain Response

Although strain is always the relative deformation of a material, different loading conditions result in different areas of strain localization. To properly measure torque and axial forces we must determine what type of strain these loads will generate and the method of measuring it that will produce the highest resolution and precision. A torque produced by the motor or by the user generates a torque on the load cell about the motor shaft axis as shown in *Figure 23*. This torque effectively creates a shear force *F* at a distance *r* from the center of the shaft. This sheer force creates deformation and high stress concentration at points A and B. Similarly, axial force on the face of the load cell results in stress concentrations at points C and D; however, this only accounts for two specific loading conditions which we are concerned about.

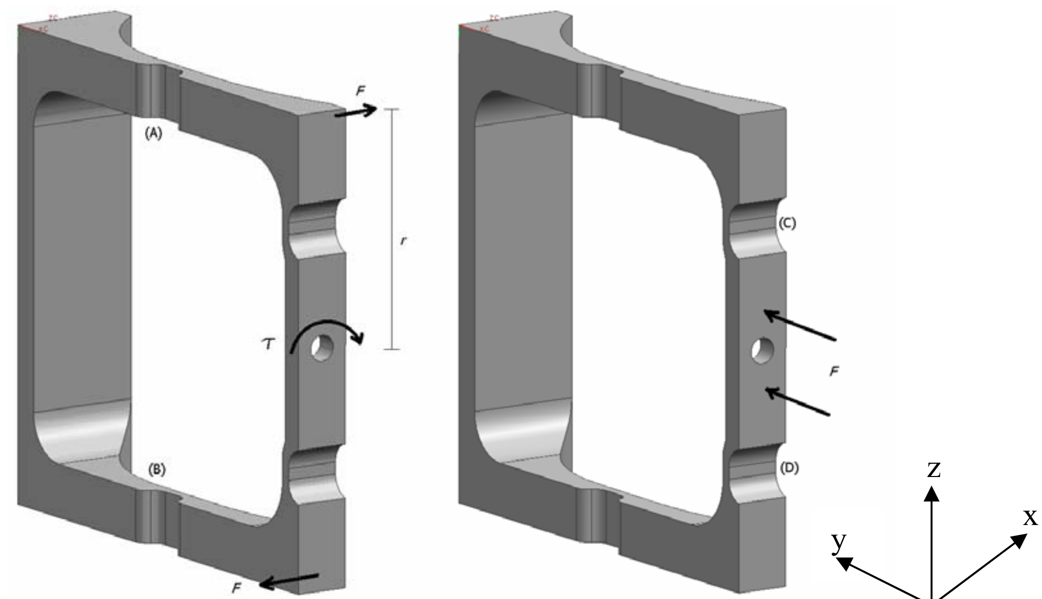


Figure 23: Applied Torque and Axial Load

Our load cell design is responsible for measuring axial force and torque about the motor shaft, but in each case there are five other loads that will generate strain within our member. The load cell is not only responsible for creating areas of high stress but also eliminating or minimizing the effect of unwanted loads. For axial force measurement we need to be able to isolate the effect of F_y, but ignore the other forces. The structure will absorb F_x, F_z, M_x, and M_y with minimal deformation or strain which leaves M_z and F_y as the two critical loads. Similarly, for torque measurement, we wish to measure My. We can eliminate F_x, F_y, and M_z in a similar fashion as before leaving F_z, M_x, and M_y as the loads of concern. Just as important as the load cell design is the placement and wiring of the strain gauges which is responsible for rejecting the irrelevant load conditions. In addition to rejecting these loads, proper wiring of the strain gauges also decreases the sensitivity of the system to variation in temperature and material properties.

Strain Gauge Response to Loading

When an element is subjected to a load the surface, at the location where strain gauges will be placed, either undergoes tension or compression. The strain gauge responds to this tension and elongates while the cross sectional area decreases which increases the resistance of the strain gauge according to *Equation 2* below.

$$R = \frac{\rho L}{A}$$

Equation 2: where R is resistance, r is resistivity, L is length, and A is cross-sectional area

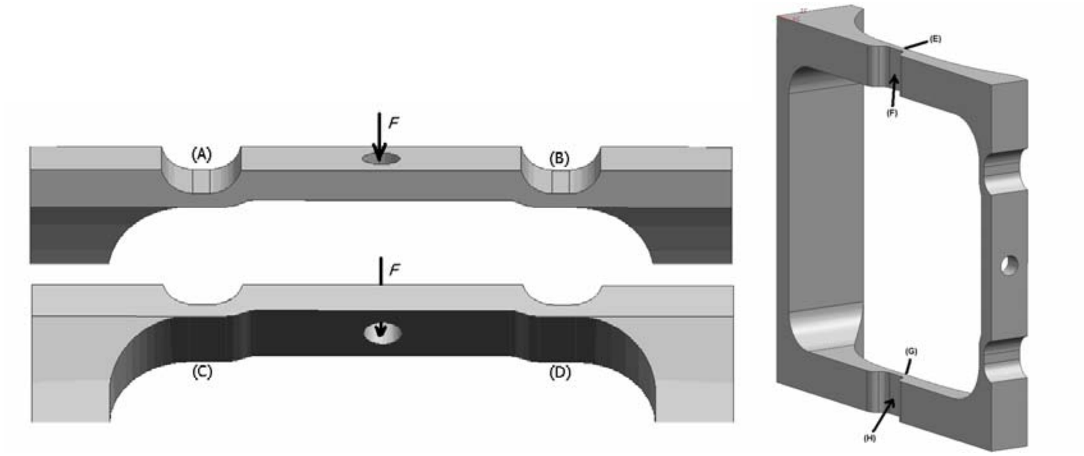


Figure 24: Axial and Torsional Strain Location Models

When the load cell is subjected to loads in the axial direction, surfaces A and B, shown in *Figure 24*, are in compression and surfaces C and D are in tension. If the structure is subjected to a moment, M_z as in *Figure 23*, surface A and D are placed in tension and surfaces B and C are placed in compression. When the load cell undergoes torque about the motor shaft, surfaces F and G are in tension and surfaces E and H are in compression. F_z and M_x, defined by the axis in *Figure 23*, both generate the same tension compression characteristic with surfaces A and C in compression and with B and D in tension.

Torque and Force Circuit Design

By designing the appropriate electrical circuit and using the unique tension and compression characteristics, we can reject the loads which the load cell could not eliminate. A typical strain gauge circuit, shown in *Figure 25*, uses four strain gauge elements to construct a Wheatstone bridge, where a small change in resistance to a member in the bridge results in a relatively large output. *Equation 3* shows the output voltage as a function of the resistive parameters.

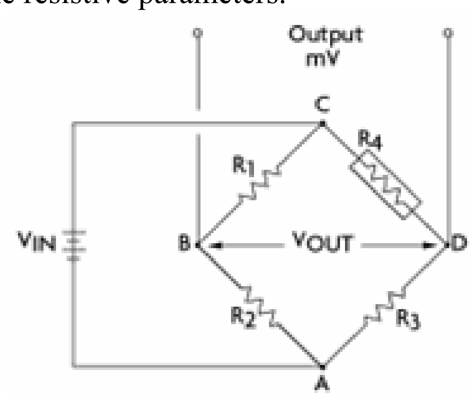


Figure 25: Wheatstone Bridge where R1-4 are resistors
VIn is applied voltage , and Vout is the output voltage

$$V_{Out} = V_{In}\left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2}\right]$$

Equation 3: Voltage Output Function

It is clear from the equation that if the ratio between R_1 and R_2 is the same as that between R_4 and R_3 the circuit will remain balanced. For axial force measurement strain gauges will be placed on surfaces A and C where the strain gauges would map to R_4 and R_1 respectively. This will keep the circuit balanced if M_z is applied and would become unbalanced, and thereby creating an output voltage if F_y is applied. Similarly, strain gauge placement for the torque sensors would be on A and C as well and correspond to R_4 and R_1 as well.

Signal and Power Routing Design

The electrical components are divided up into three separate groups: the power supply box, the haptic box, and the computer. The power supply box houses the power supply and motor amplifier. Based on a Pulse Width Modulation (PWM) signal sent from the computer the power supply and amplifier together deliver the power that is sent to the haptic box. The haptic box measures torque, radial loads, and the speed of the motor using strain gauges and an optical encoder. It then sends the signals from these devices to the computer. The computer receives and interprets signals form the haptic box and processes these inputs and sends a signal back to the power supply box. The following sections analyze how the electronics are assembled in each of theses three components.

Figure 16 shows a schematic of how the power supply box is wired. 120 V will come in from the wall to the *Power*Bank PB1005AC/DC power supply. This power supply delivers 20 amps at 24 V to the Zircon Z-16E-T03 motor amplifier. The motor amplifier receives a low voltage and low amperage PWM signal form the computer and generates the corresponding power signal which it sends to the motor. Within the power supply box there will also be a 15 V power supply which will be responsible for powering several components in the haptic box including an emergency stop button. When the emergency stopper is tripped it cuts off power to the motor through the use of an enable bit on the amplifier.

Figure 16 and 18 show schematics of how the computer, haptic box, and power supply box are wired together. The computer sends a low voltage and low amperage PWM signal to the power supply box. It receives signals from the haptic box that carry the strain gauge and encoder information.

Figure 16 shows a schematic drawing of how the haptic box will be wired together. 24 V is being supplied from the amplifier through a standard power connector to the motor. The encoder that is attached to the motor sends its signal through the d-sub connector back to the computer. The strain gauges receive a nominal 5 V, and the output of the strain gauge is then passed onto the strain gauge amplifier. The strain gauge amplifier increases the magnitude of the strain gauge signal and then sends it to the computer via the d-sub connector. The emergency stopper will receive power from the secondary power supply and will send the appropriate enable signal to the motor amplifier depending on the stopper's state.

FINAL DESIGN AND SYSTEM VALIDATION

One of our primary goals was to finalize the system and have it ready for distribution in either engineering drawing or final product form. Because of this requirement, the prototype we created is fundamentally complete. Further modifications to the design will only simplify and revise the current prototype, so the prototype performance characteristics should meet all of the technical specifications as outlined at the beginning of the document.

Load Cell Validation

The load cell along with strain gauge placement and wiring was an important element of our products design, and we performed preliminary tests in order to validate its functionality. By fixing the base and applying the appropriate range of torques and axial forces, we observed the resistive changes of the strain gauge elements using a multi-meter. Previous models showed change of resistance of $<1\Omega$ whereas our design showed resistance changes of $<3\Omega$ under the same force and torque ranges. Using a breakout board and a computer we were able to verify that the motor was able to receive command voltages and the encoder was able to deliver position and direction. These tests provide preliminary indication that our device will exceed the performance of previous designs. Another aspect of concern was the aesthetics of the design; this element is difficult to quantitatively verify, but generally, based on user response from the University of Michigan Design Expo 06', our prototype satisfied this requirement. The engineering drawings and schematics in Figures 26-31 should allow for reproduction of our prototype design.

Ease of Reproduction Validation

Based on our final design, the customers will be able to reproduce the Haptic Box with considerable ease. Table 7 summarizes the number of parts along with the approximated machining time in our final design.

Table 7: Number of parts and approximated machining time for our final design

Description of Parts	# of Parts	Approximated Machining Time (hrs)
Off-the-shelf (No Machining)	32	0
Major Machining Required (Milling, Lathing)	6	15
Minor Machining Required (Drilling, tapping, etc.)	3	4
Total	**41**	**19**

* This table does not include the pedal handle and its base since these are optional parts.

The total machining time is approximately 19 hours for a person with reasonable shop experience. The facilities required to manufacture the prototype are available in most university machine shops (please refer to Manufacturing Plan section for required machines). The majority of the parts (78%) can be purchased off the shelf. All supplier and part number information is listed in the Bill of Material in Appendix C. Most of the suppliers we chose offer various shipping options and reliable technical support. Once all the parts are obtained and machined, the approximated assembly time (including wiring) is 5 hours. The final design meets the criterion of being easily reproducible for our potential customers.

Heat Dissipation Validation

Graduate students who have used the same motor at the University of Michigan have advised us to utilize computer fans in the motor housing box and the power supply box for heat dissipation. After being on for 4 hours at the University Design Expo '06, we observed minimal temperature rise in both the motor housing and power supply boxes. Since our product will not be used for an excessive period of time in either an academic or medical settings, the heat dissipation by the electrical fans was satisfactory.

Dimensioned Drawings

This section includes the dimensional drawings for the major components requiring manufacturing.

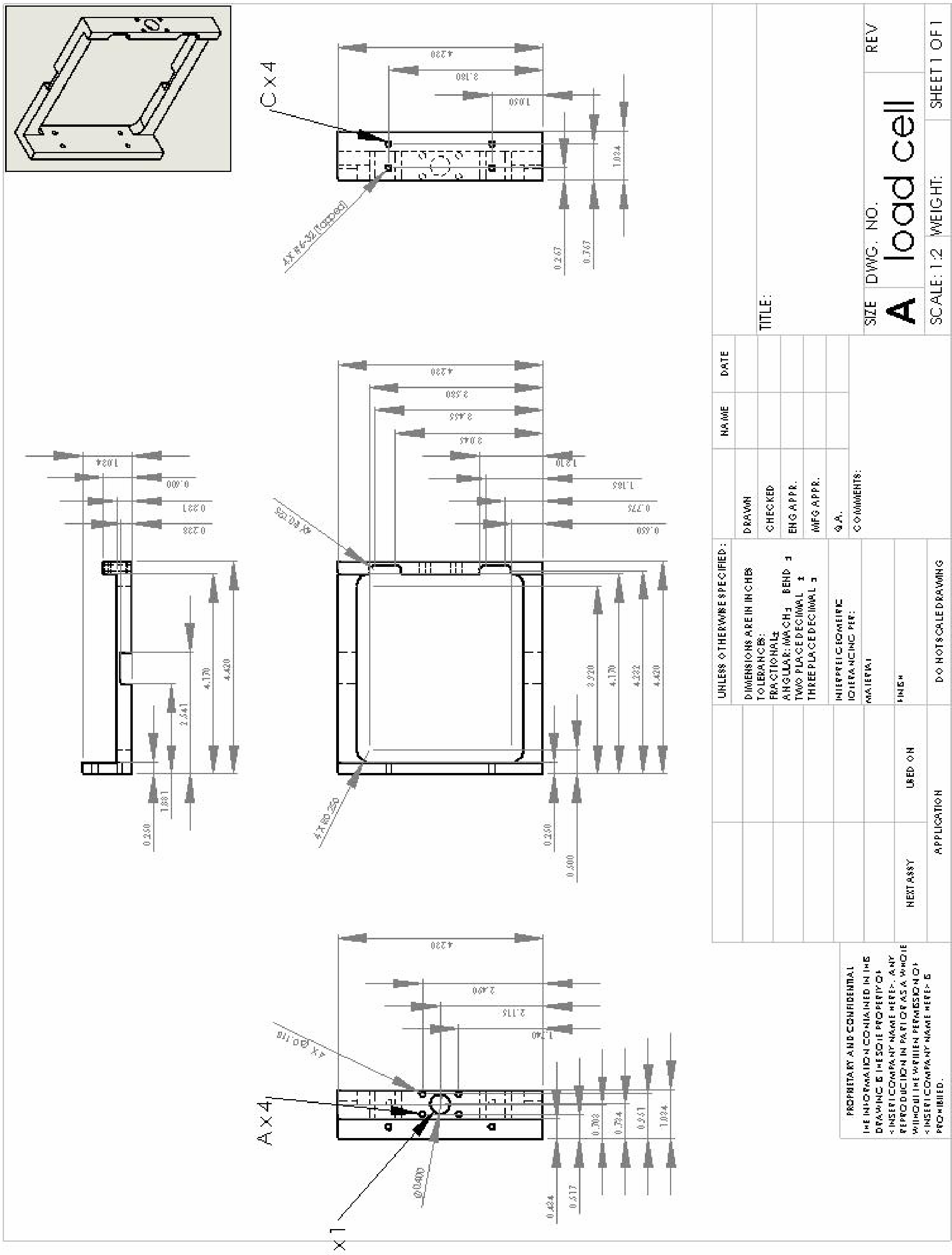


Figure 26: Dimensioned Drawing of the Load Cell

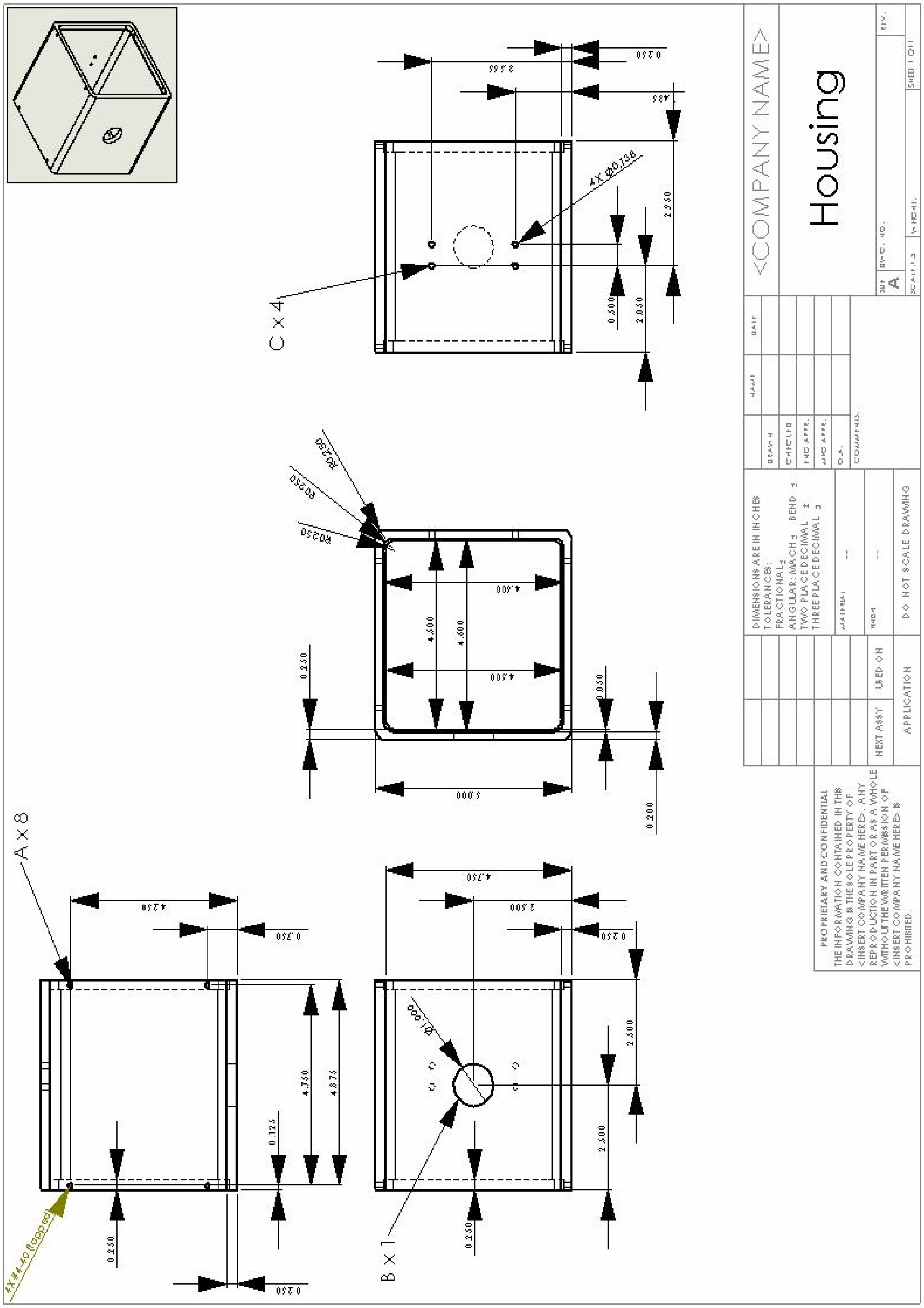


Figure 27: Dimensioned Drawing of The Box

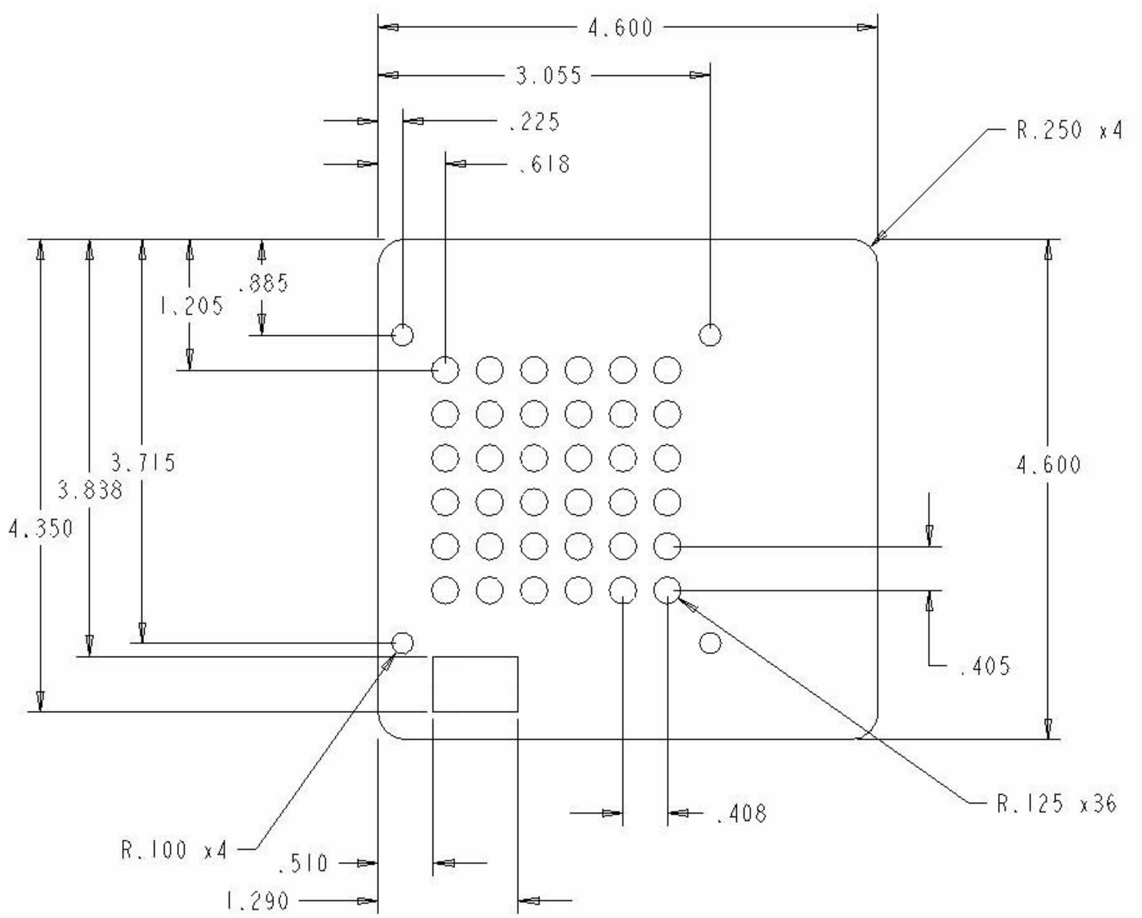


Figure 28: Dimensioned Drawing of Left Side Insert

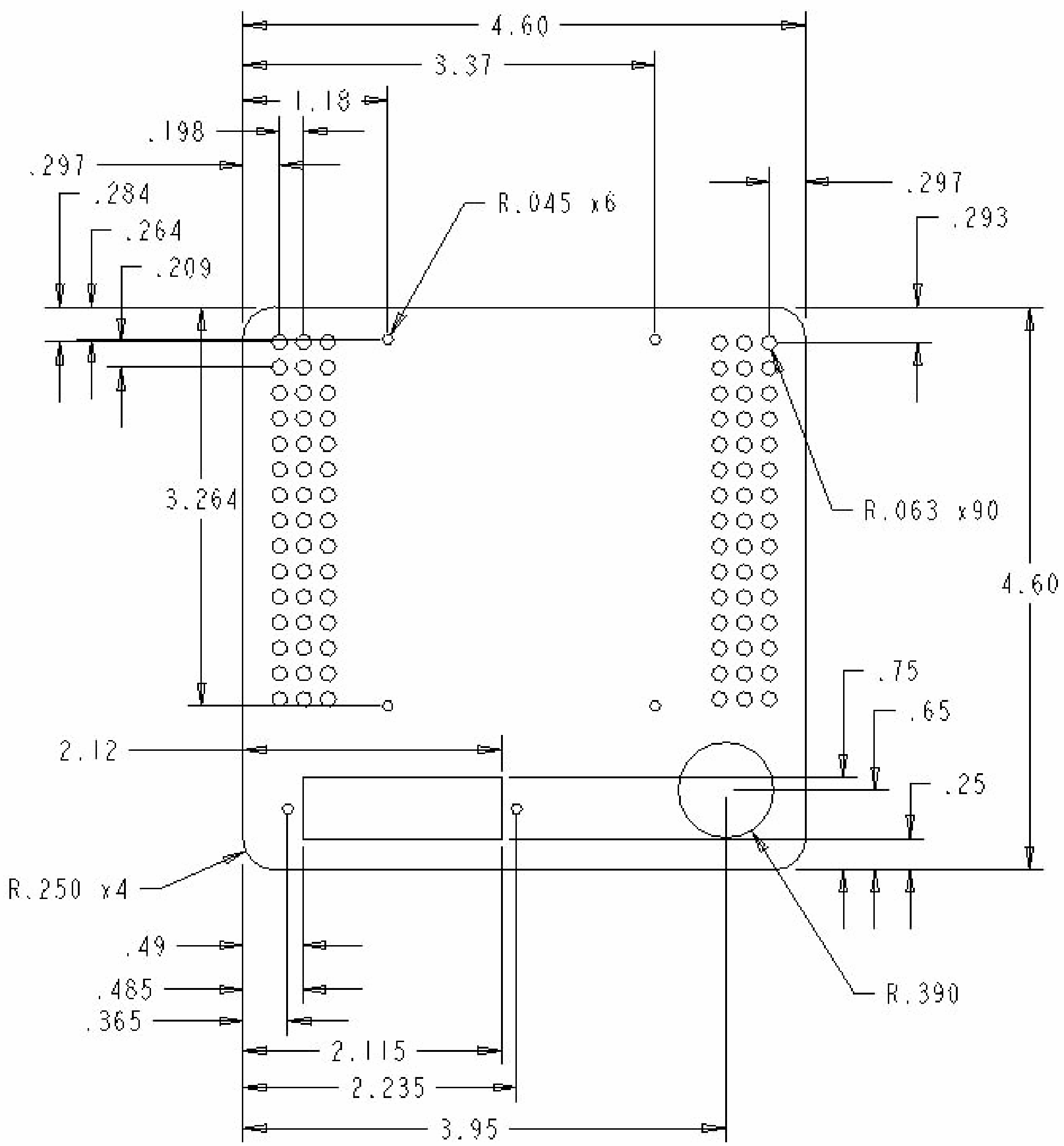


Figure 29: Dimensioned Drawing of Right Side Insert

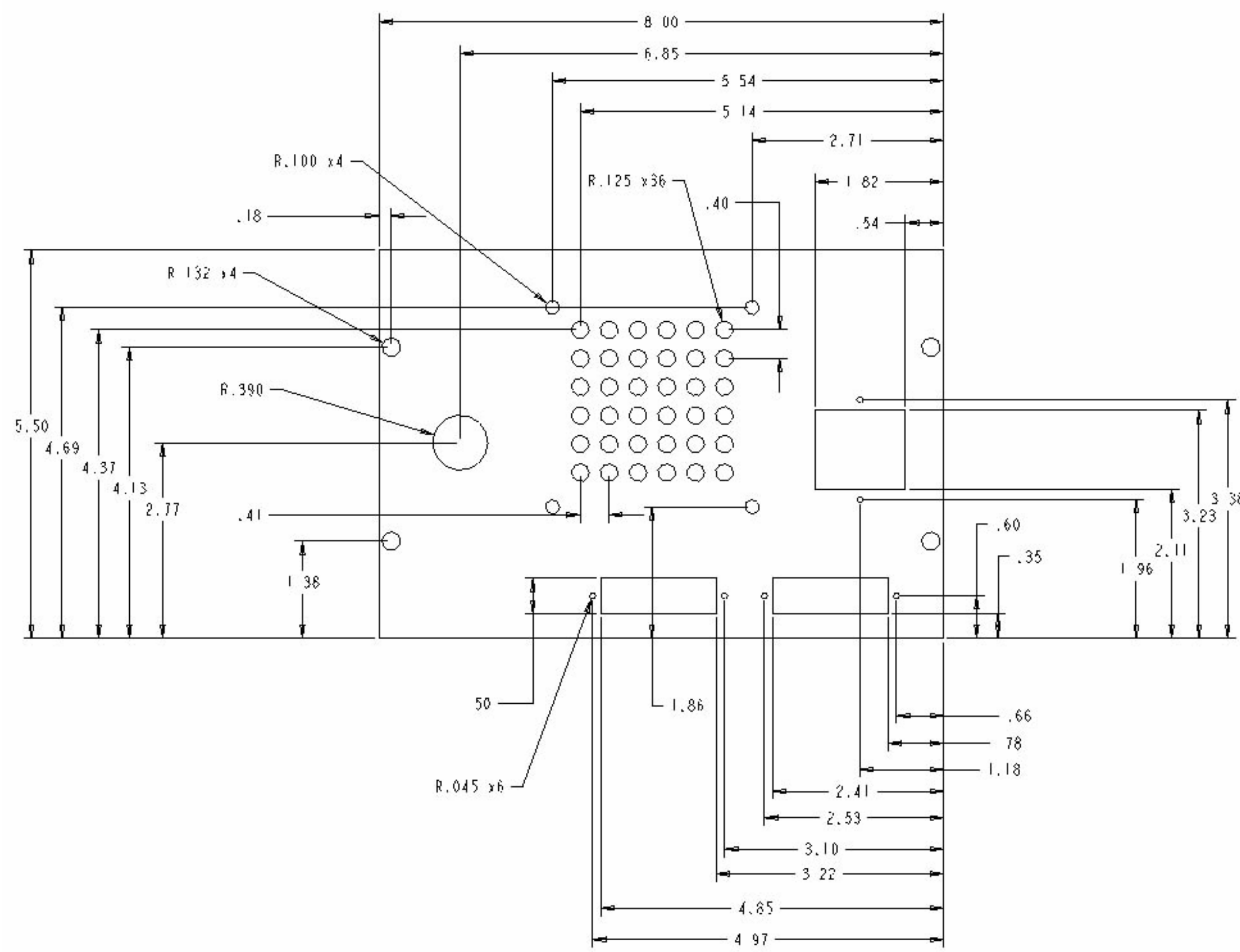


Figure 30: Dimension Drawing of Power Supply Box   Plexiglas Panel

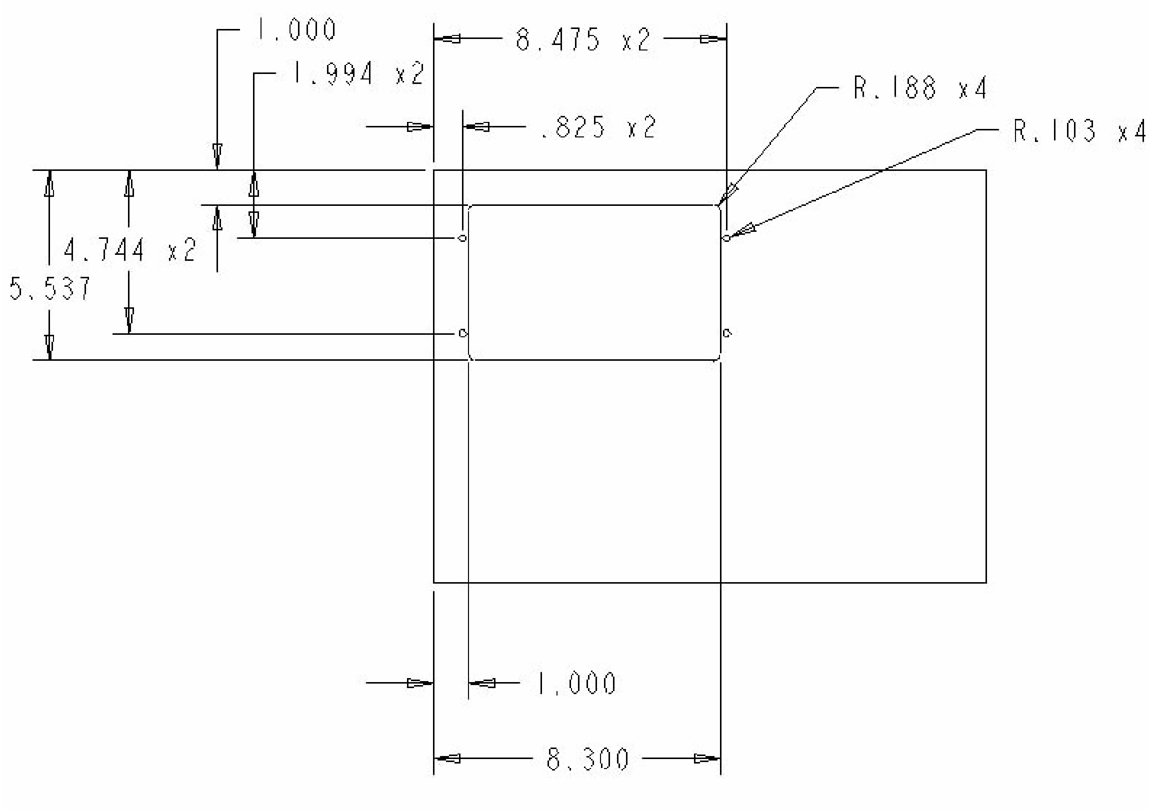


Figure 31: Dimensioned Drawing of NEMA Type 1 Enclosure Lid

MANUFACTURING PLAN

The steps needed to reproduce our haptic box are shown below. The Production section describes how to fabricate the individual components. The Assembly section gives step by step instructions for putting the haptic box together.

Production Procedure

Load Cell

-Material*:* 6061-Aluminum; 1"x5"x5"; (ASAP)

-Process

1. Operation: Milling
   Tools: 1" mill bit
   Description: First edge off the piece, then mill it down to size using a 1" mill bit. The dimensions of the piece should be 1.032"x4.42"x4.23", this is shown in Figure B1.
2. Operation: Drilling and threading
   Tools: #36 drill bit; 6-32 tap
   Description: Drill holes at locations C using the #36 drill bit as seen in Figure B1. Thread the holes using a 6-32 tap.
3. Operation: Drilling
   Tools: 1/8 drill bit; 5/16 drill bit
   Description: Drill holes at locations A using the 1/8 drill bit as seen in Figure B1. Next Drill a hole at location B using the 5/16 drill bit as seen in Figure B1
4. Operation: CNC Milling
   Tools: ½" mill bit, ¼ mill bit
   Description: Mill out the cavity in the center of the load cell as seen in Figure B1.
5. Operation: Milling
   Tools: 1" mill bit
   Description: Mill slots on the bottom of the load cell at as seen in Figure B1.
6. Operation: Milling
   Tools: 1" mill bit
   Description: Mill the top of the load cell to size as seen in Figure B1.
7. Operation: Strain gauge mounting
   Description: Mount and wire the strain gauges according to the strain gauge manufacturers specifications.

Box

-Material*:* A-500 steel; 5" Square tube x ¼" thick x 5" long (ASAP)

-Process

1. Operation: Drilling
   Tool: 1" saw drill
   Description: Using the 1" saw drill bit, drill a hole into the center of one of the faces of the box as seen at location B in Figure B2. (Note: make sure that the face that you drill into or the one opposite of that does not have the weld on it.)
2. Operation: Milling

Tool: ½" end mill
Description: First edge off the two open faces of the box so that they are parallel. Then mill a shelf inside the edges of the two open faces of the box as seen in Figure B2. The shelves are ¼" deep and the ledge is .05" into the box all the way around..

3. Operation: Drilling and threading
   Tool: #43 drill bit; 4-40 tap
   Description: Drill and thread the set screw holes at locations B as seen in Figure B2.
4. Operation: Drilling
   Tool: #27 drill bit
   Description: Drill holes for the load cell mounting at locations C as seen in Figure B2.

Plexiglas Panel Inserts

-<u>Material</u>*:* ¼"   Plexiglas; at least a 6"x12" piece; (McMaster-Carr 8560K354)

-<u>Process</u>

1. Operation: Laser cutting
   Description: Laser cut the left and right sides of   Plexiglas according to Figure B3 and Figure B4.
2. Operation: Threading
   Tools: 4-40 tap, 6-32 tap
   Description: Thread the holes at location A on the right side piece using the 4-40 tap and thread the holes at location B on the left side piece using the 6-32 as seen in Figure B3 and Figure B4.

Handles

The Knob

-<u>Material</u>*:* Aluminum Knob 2" diameter; (McMaster-Carr 6077K14)

-<u>Process</u>

1. Operation: Lathing
   Description: Lathe down the solid hub of the aluminum knurled-rim knob to 6mm

The Wheel

-<u>Material</u>*:* Dished hand wheel, 4.92" wheel diameter; (McMaster-Carr 61405K63)

-<u>Process</u>

1. Operation: Press fitting
   Description: Press fit a rod with a diameter of .237" and a length 1.25" into the hole in the solid phenolic dished hand wheel. A rod of the proper diameter will have to be lathed down to size for this operation.

Pedal Handle

-<u>Material</u>*:* ½"   Plexiglas sheet at least 5"x4" (McMaster-Carr 8560K265)
length of steel rod 6mm in diameter (McMaster-Carr 7936K311)
A-500 steel; 5" Square tube x ¼" thick x 4" long (ASAP)

-<u>Process</u>

1. Operation: Laser cutting
   Description: Laser cut the piece of Plexiglas according to the dimensions in Figure B7.
2. Operation: Band saw
   Description: Cut one of the sides off of the A-500 steel square tube using a band saw. This will leave you with a U-shaped channel as opposed to a square tube.
3. Operation: Drilling
   Tools: L drill, #20 drill
   Description: Drill a hole using the L in the center of one of the arms of the U-channel and drill another hole using the #20 in the center of the other arm of the U-channel.
4. Operation: Drilling
   Tools: 1/8" drill bit
   Description: Drill holes into the Plexiglas piece through the center line of the piece.
5. Operation: Lathing
   Description: Cut a piece of 6mm rod and cut it into a 1.2" piece. Lathe down 1" of this rod to 1/8". Cut a second piece of 6mm rod down to a 1" piece. Lathe this second piece down to 1/8" all the way.
6. Operation: Epoxy
   Description: Place the handle into the U-channel with the holes that were drilled into it lined up with the holes drilled into the U-channel, then epoxy the rods into the handle.

Power Supply Box

-<u>Material</u>: 16"x12"x4" NEMA type 1 enclosure (McMaster-Carr 75065K18)
¼" Plexiglas sheet at least 9"x6" (McMaster-Carr 8560K354)

-<u>Process</u>

1. Operation: Milling
   Tools: 3/8" mill bit
   Description: Mill a cavity into the lid of the NEMA type 1 enclosure as seen in Figure B6.
2. Operation: Drilling
   Tools: step drill
   Description: Using a step drill, drill ¼" holes into the lid of the NEMA type 1 enclosure at locations A as seen in Figure B6.
3. Operation: Laser cutting
   Description: Laser cut the Plexiglas piece according to the dimensions in Figure B5.
4. Operation: Threading
   Tools: 6-32 tap, 4-40 tap, ¼-28 tap
   Description: Referring to Figure B5, thread the following holes
   Thread the holes at location A with a 4-40 tap
   Thread the holes at location B with a 6-32 tap
   Thread the holes at location C with a ¼-28

Assembly

Figure 32 shows an exploded drawing of the haptic box. The haptic box is assembled by first mounting the load cell in the box and attaching the motor. Then Plexiglas sides should be assembled and secured to the box.

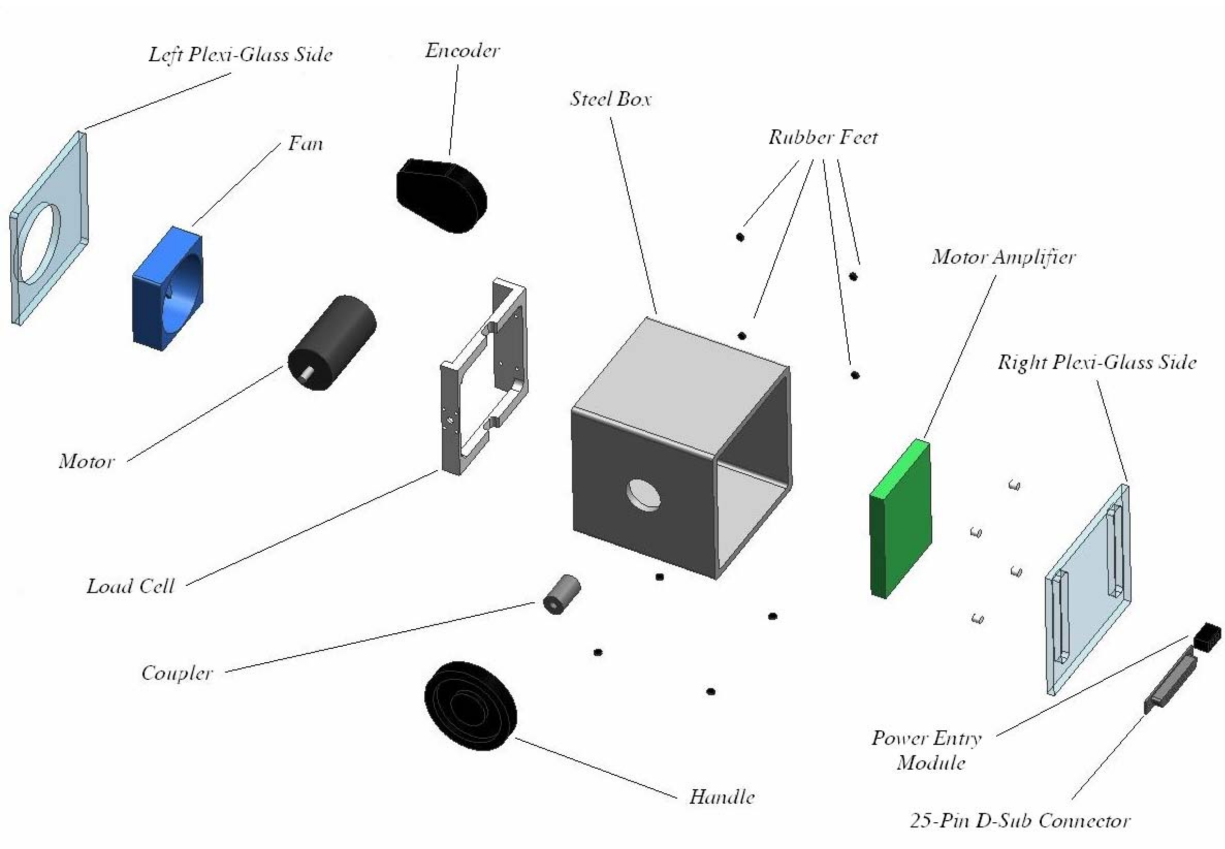


Figure 32: Exploded view of the haptic box

Motor and Handle Mounting:

Step 1) once the load cell has been properly wired it can be inserted into the box. Figure 33 shows how it should be oriented. 6-32 x ½" (McMaster-Carr 90272A148) screws should be used with 6-32 (McMaster-Carr 90480A007) nuts to secure the load cell to the back of the box.

Step 2) Insert the motor (Maxon148867) with the Encoder (US Digital e6s-2048) attached to it into the load cell. 8 mm long M3 machine screws (McMaster-Carr 1274T15) should be used to mount the motor to the load cell. The hole in the front of the box will allow axis to the front of the load cell so that you can secure the motor. Figure 33 shows how the motor should sit in the Load cell.

Step 3) The coupler (Climax Metal MISCC-06-06) should first be fastened to the motor shaft, then a handle can be fastened to the other end of the coupler. The coupler is fastened using a hex wrench.

Step 4) The rubber feet (Home Depot 039003999646) of the box are attached to the outside of the box as shown in Figure 33.

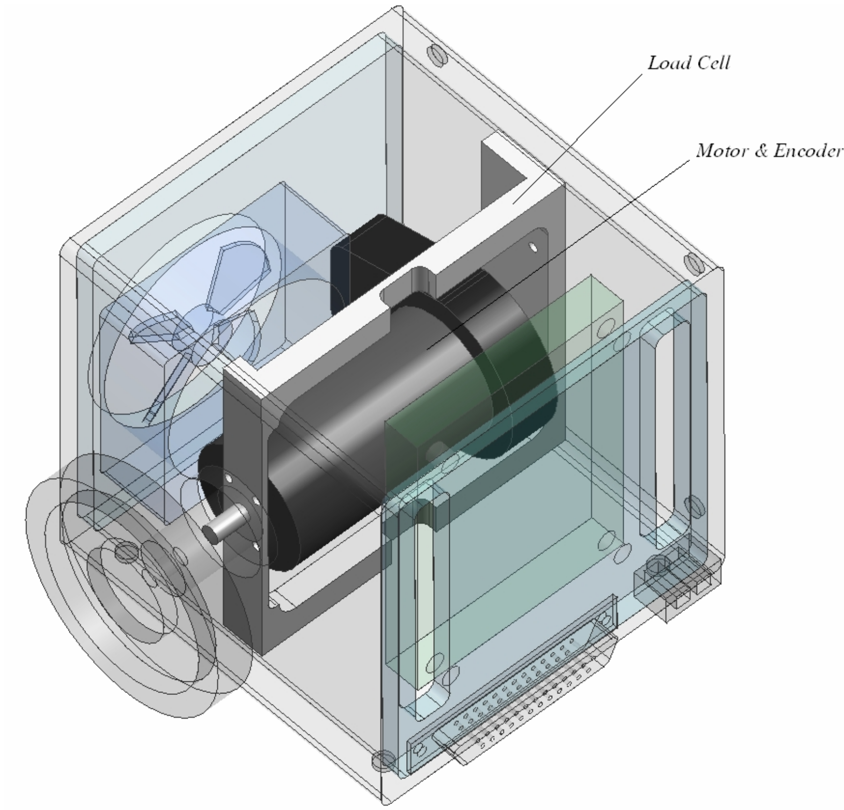


Figure 33: The Motor and the Load Cell

Plexiglas Insert Assembly:

Step 1) The Fan (Arctic N82E16835186006) should mount to the left side Plexiglas piece as seen in Figure 34. It screws in using 6-32 x 1" screws (McMaster-Carr 90272A153). The emergency stop button (Del City 7500002) can be affixed to the left side Plexiglas using epoxy.

Step 2) the strain gauge amplifier, 25-pin male D-sub connector (Digikey CMP25G-ND), and the male power entry module (Digikey SC1231-ND) are attached to the right side plexi glass piece. The strain gauge amplifier is attached to the Plexiglas panel insert using four 4-40 x1/2" screws (McMaster-Carr 90272A110) and four 3/8" standoffs (McMaster-Carr 92415A686). The 25-pin D-sub connector screws in using the same 4-40 x1/2" screws as the strain gauge amplifier uses. The power entry module screw in to the Plexiglas according to the manufacturers specifications.

Step 3) Once the Plexiglas sides have been assembled. Wire the cabling in the box according to the electronics production section above in Figure 16. Once this is done, the Plexiglas sides can be set screwed into the box using 4-40 set screws (Home Depot 030699726189).

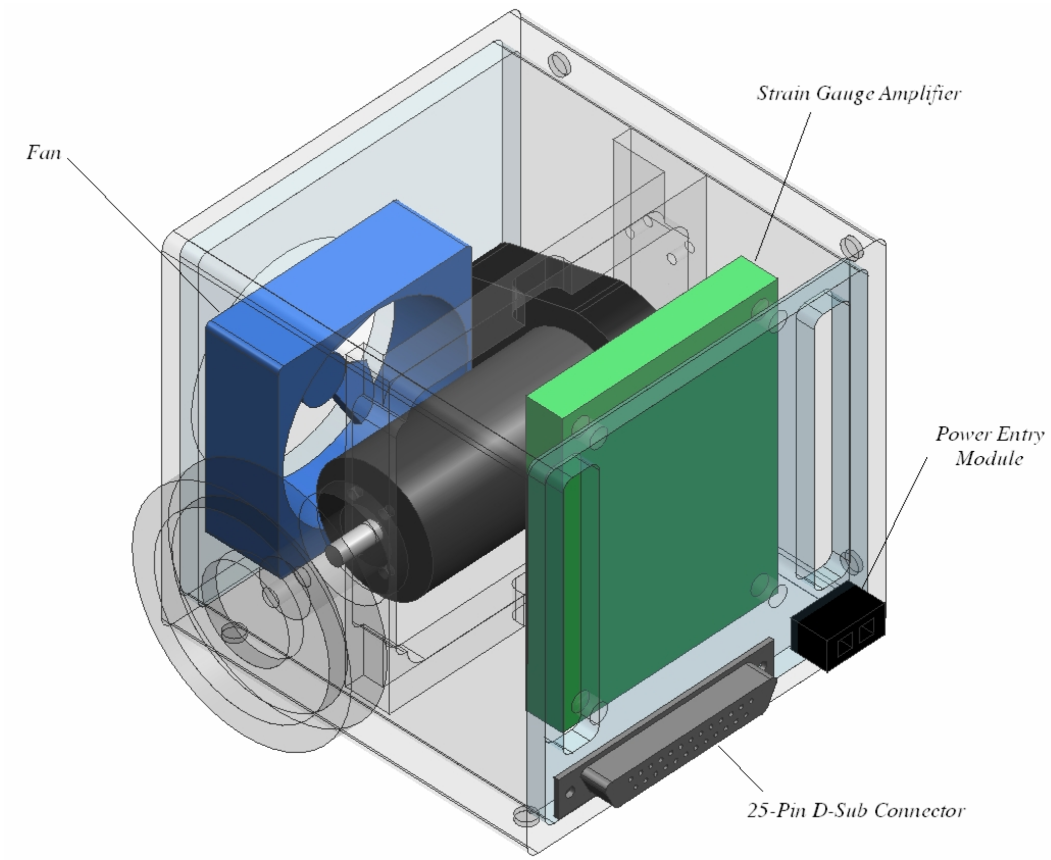


Figure 34: The electronic components of the haptic box

Power Supply Box Assembly:

Step 1) Firstly, attach all of the connectors and the fan to the Plexiglas plug piece (see Figure B6) cut for the lid of NEMA Type 1 Enclosure (McMaster-Carr 75065K18).

- The Fan (Arctic P/N N82E16835186006) should be screwed into place using 6-32 x 1" screws (McMaster-Carr P/N 90272A153).
- The Power Entry Module with rocker switch (Digikey 486-1045-ND), the 25-pin female D-sub connector (Digikey CFP25G-ND) , and the 25-pin male D-sub connector (Digikey CMP25G-ND) should be screwed into place using 4-40 x 1/2" screws (McMaster-Carr 90272A110).
- The Female Power Entry Module (Digikey SC1231-ND) should screw in to the Plexiglas according to the manufacturer’s specifications.

Step 2) Next, attach the Plexiglas plug piece to the lid of the NEMA Enclosure by using ¼-32 x ¾” screws (McMaster-Carr 91772A559) and ¼-32 nuts (McMaster-Carr 91078A205).

Step 3) After the motor power supply, the secondary power supply (Mouser 597-AA15-0.8), and the motor amplifier (Servo Dynamics Zx-24) are fixed and wired in the NEMA Enclosure, the connectors on the NEMA Enclosure lid should be wired according to the schematics in the electronics production section above. The lid is then fixed to the NEMA Enclosure using the screws that came with it.

DESIGN CRITIQUE

After manufacturing and interacting with our design, several strengths and weaknesses of our design have become evident.

Strengths

Small package

We were able to decrease the overall device size by 42% compared to the previous prototype. This improvement adds a great deal of aesthetic appeal to the design. In addition, the smaller footprint of the device leaves more desk space for the user.

Simple yet aesthetically appealing

It is difficult to find a balance between appeal and simplicity. Our simple cubic shape offers little appeal on its own. To increase appeal while maintaining the simple cubic shape we incorporated clear Plexiglas walls to give the user visual access to the internal components. We also utilized a blue-LED case fan to give the device some color and flair. Lastly, the polished metal finish gives our design a sleek and robust look.

User-friendly cabling

All external connections are made using cables with connectors on both ends. This allows all components to be completely detached from one another making transporting the device very easy. Also, the power connectors are keyed to eliminate the potential for human error powering the device. The serial connectors are also arranged in such a way that prevents improper connections.

Weaknesses

Soldered internal connections

Some connections within both the housing and the power supply box were done by soldering rather than connectors due to time constraints. These connections make disassembly difficult. If all internal connections were done using simple connectors, the device could be completely disassembled and reassembled without having to solder, desolder, and resolder the wiring.

Undersized hole for drive train

On the front face of our device there is a 1” diameter hole through which the motor shaft and shaft coupler extend and connect to the handle. The shaft coupler in essence clamps to both the motor shaft and the handle shaft forming a rigid mechanical link between the two. This clamping force increases as a series of four hex machine screws are tightened. The 1” hole in the face of the housing allows the motor shaft and coupler to fit though the face unobstructed. At 1”, however, the hole does not allow enough room for an Allen wrench to sufficiently tighten the coupler screws. One solution is to simply increase the diameter of the hole in the face of the housing to 1 ½” as shown in Figure 35. Another solution is to mill a slot out of the face to allow an Allen wrench access to the coupler screws.

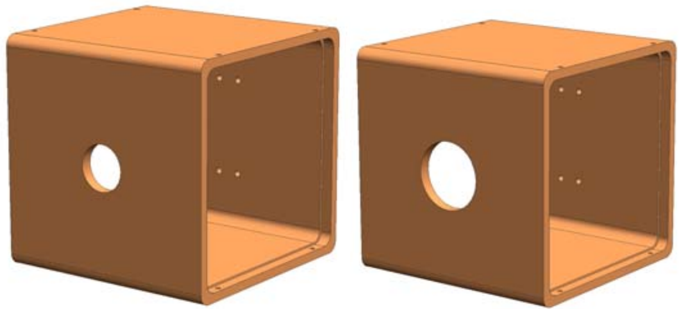


Figure 35: a) Current Design 1" Hole b) Suggested Design 1½" Hole

Load cell design is not robust

To achieve high strain levels in our load cell we chose a thickness of 3/32" at the locations where strain gauges were placed. At this thickness we noticed that the load cell flexes under normal off-axis loads. This flex does not permanently deform the load cell though it does flex the strain gauges beyond the recommended specifications. Over-working the stain gauges will shorten their life. To solve this problem we recommend thickening the load cell in areas of concentrated strain. An alternate solution is to develop a eye slot rather than the current notch-method as shown in Figure 36. More analysis is on this method is required before its benefits can be quantified.

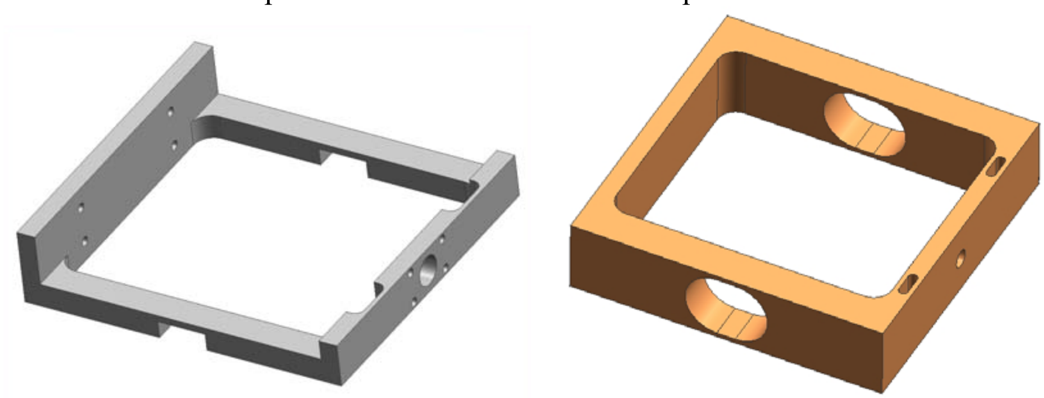


Figure 36: a) Current Load Design b) Suggested Robust Design

RECOMMENDATIONS

Throughout the design of our device we noted a few design modifications that would add robustness and functionality to our design. The purpose of this section is to convey our design improvement recommendations.

As discussed in the previous section, three simple design improvements include; making all internal connections using connectors to allow for disassembly, increasing the diameter of the hole in front face for drive train from 1" to 1 ½" to allow access to couple screws, and increasing load cell thickness in areas of high strain to increase robustness.

Another design improvement would be to add a functional base. One problem that we encountered during our design is that the small 5" cubic package limits handle diameter. Handles that are too large may not allow the housing to sit flat on the table or may be so close to the table surface that the user's fingers are obstructed by the table along the bottom edge of the handle. This problem can be eliminated by constructing a base for the housing. A base could lift the housing higher off the table allowing for larger handle diameters. A base also grants the opportunity to achieve additional orientations if designed with such things in mind.

Additionally, we recommend using stainless steel rather than A500 steel tubing. Though possible to achieve an appealing finished look with plain steel, give time and the presence of water and oxygen, plain steel will rust. It is also possible to achieve a shiny, finished look with stainless steel with no concern for corrosion.

Lastly, we recommend further analysis be performed on torque and axial sensing components of our device. Preliminary testing on the load cell and strain gauges indicates a fully functional design. As we discovered using an ohmmeter, the resistance through the strain gauges changes as forces is applied to the load cell and strain increases. This indicates that the system is functioning properly though due to time constraints, no further testing could be performed.

CONCLUSIONS

Our goal is to develop a commercially viable easily reproducible single-axis force-reflecting haptic wheel. Our design is intended to be distributed among educators as a way to teach system dynamics and controls by using a haptic interface. Incorporating the student's sense of touch and motion will enhance and enrich the learning experience. The devices use can extend into medical applications where it can be used for motor skill rehabilitation. Current models exist but are not commercially available or do not provide sufficient functionality.

In order to meet the functional requirements of the device, we designed a load cell, to use in conjunction with a motor and encoder, which would allow for both accurate and precise measurement of three important parameters: axial force, torque about a handle, and angular displacement. Based on the initial feedback we received from our customer, we believe that the load cell performance characteristics will exceed those of previous designs and be satisfactory for our customer.

The Box design we developed houses all electrical components within the box, but still allows for easy access and maintenance through easily removable Plexiglas panel inserts. Through the use of standard D-Sub connectors the haptic box can interact with both LabVIEW and other advanced microprocessor environments.

Another aspect of concern was the packaging and user interface of the product. We created a design which allows for interchangeable handles as well as having a small footprint on the table top. Despite its small size the device can sit on the table top without the need for any additional fixation methods. In our design, we incorporated commercially available components which make it easy to reproduce while not sacrificing functionality.

The final design we developed provides the robust functionality that is required of the device while maintaining its aesthetic appeal. Further revisions of our design may streamline the assembly process, but the current design is ready to be distributed to other educators.

ACKNOWLEDGEMENTS
The success of this project would not have been possible without the help and support of many people. We would like to take this opportunity to personally thank the following people for their time, knowledge and generous assistance.

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Taeyoung Shin
Bob Coury
Marv Cressey
Kari Danek
Paul Griffiths

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APPENDIX A: Heat Analysis Equations

$$< Q_{k,p-o} > + < Q_{ku,p-o} >= S$$

$$< Q_{k,p-o} >= \frac{(T_s - T_o)}{< R_k >}$$

$$< R_k >= \frac{L}{A_k k}$$

$$< Q_{ku,p-o} >= \frac{(T_s - T_o)}{< R_{ku} >}$$

$$< Q_{k,p-o} >= \frac{(T_s - T_o)}{< R_k >}$$

$$< Nu >_L = [< Nu_{L,l} >^{10} + < Nu_{L,t} >^{10}]^{1/10}$$

$$< Nu_{L,l} >= \frac{1.4}{\ln[1 + 1.4/(o.835 a_1 Ra_L^{1/4})]}$$

$$< Nu_{L,t} >= .14 Ra_L^{1/3}$$

$$a_1 = \frac{4}{3} \frac{.503}{(1 + (.492/\Pr)^{9/16})^{4/9}}$$

$$Ra_L = \frac{g\beta(T_s - T_{f,\infty})}{\nu_f \alpha_f}$$

APPENDIX B: Engineering Drawings for the Manufacturing Plan

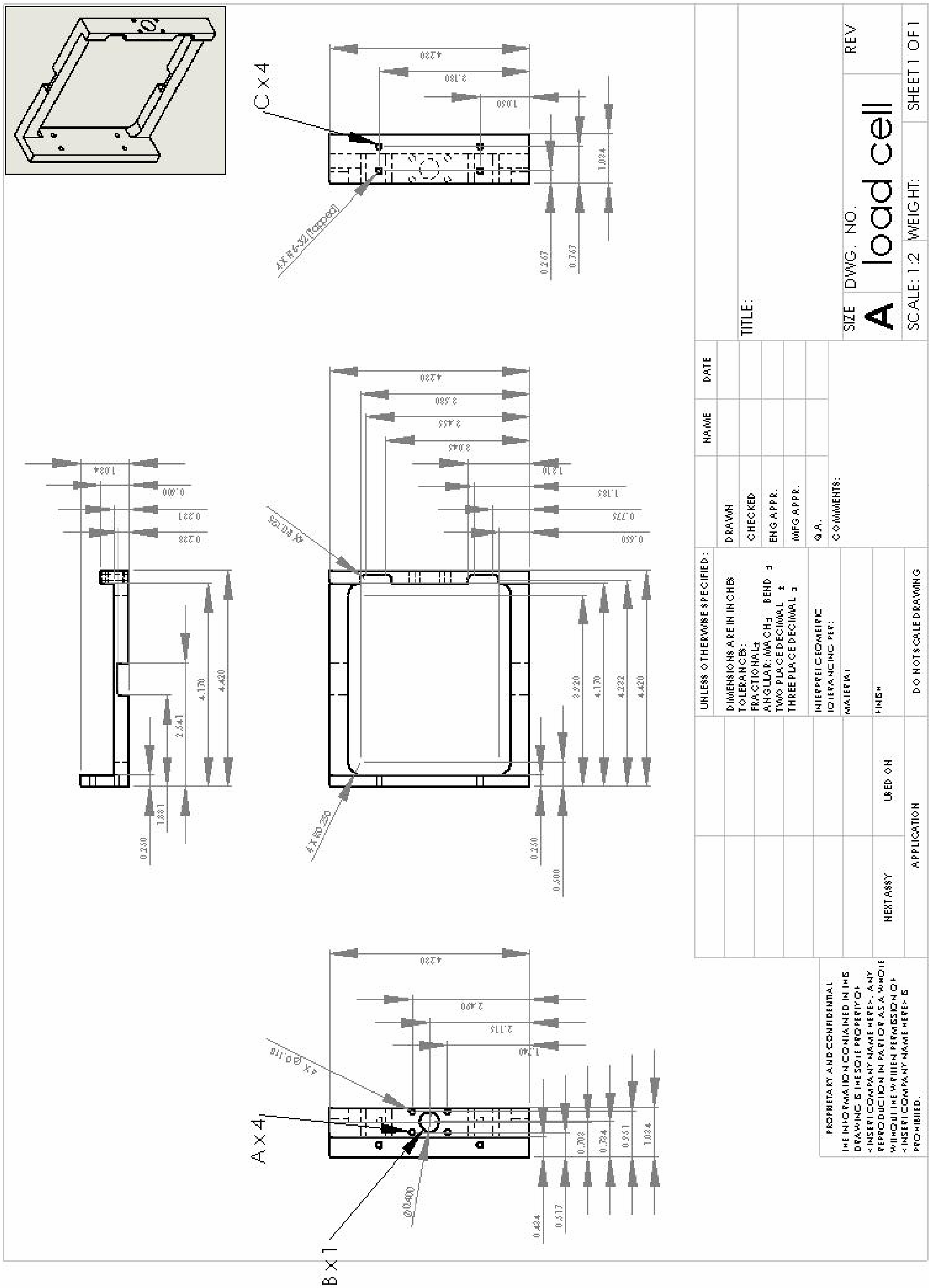


Figure B1: Dimensioned Drawing of the Load Cell

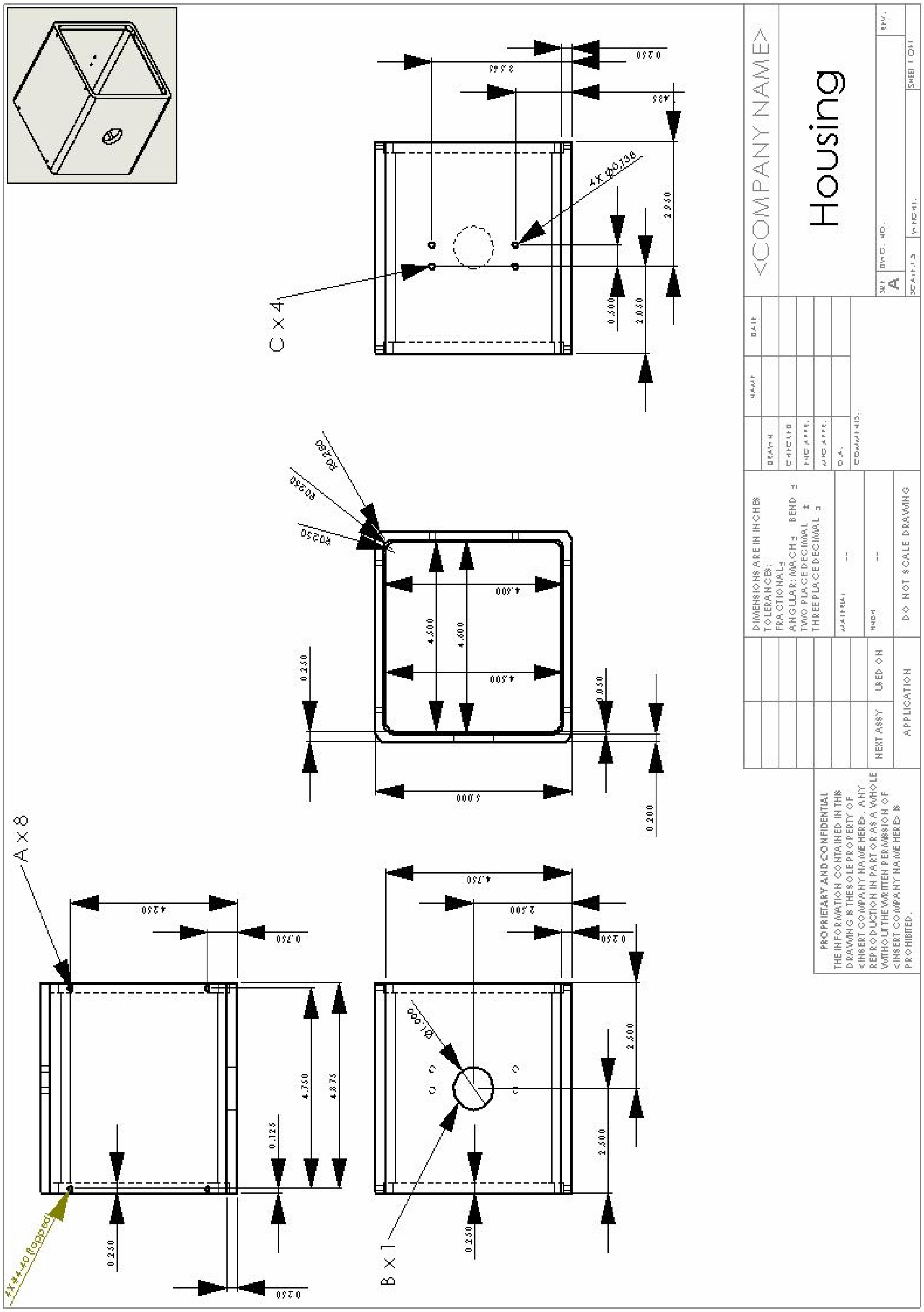


Figure B2: Dimensioned Drawing of the Box

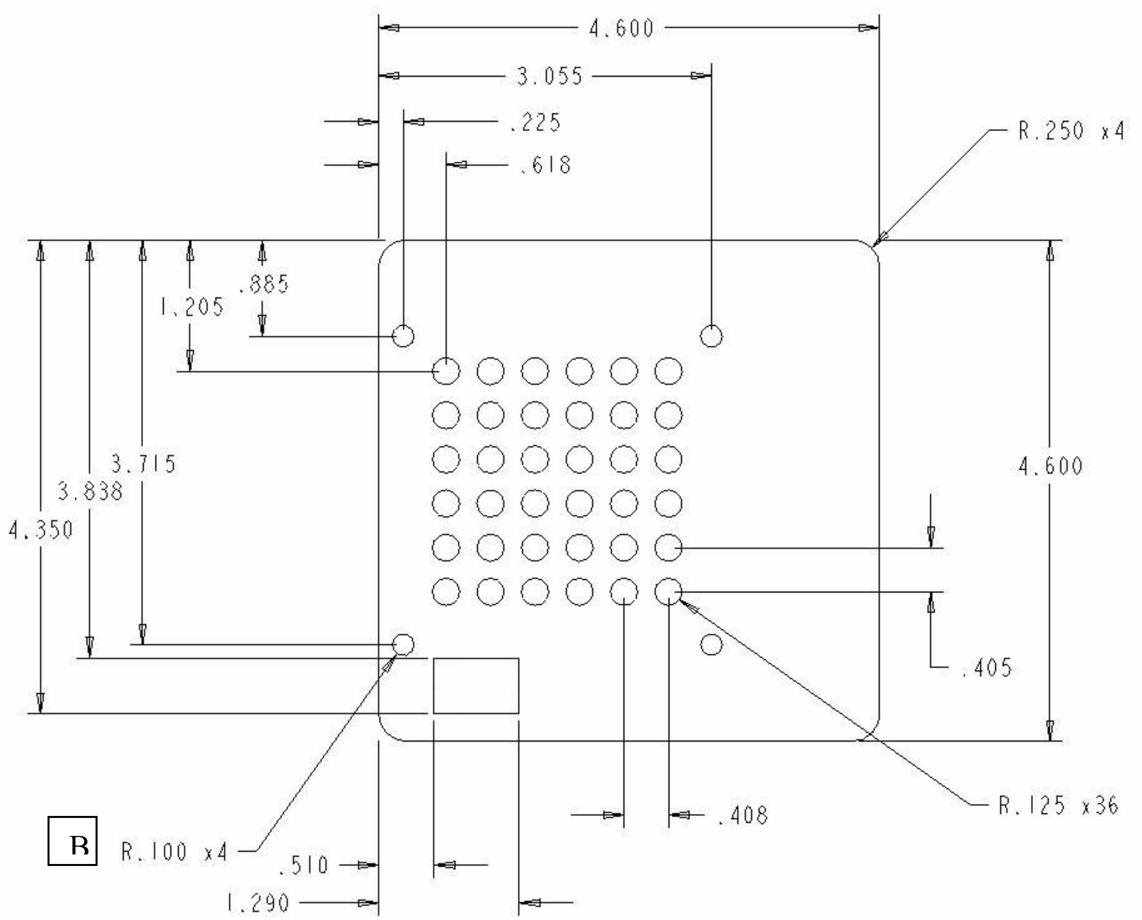


Figure B3: Dimensioned drawing of the left side   Plexiglas piece

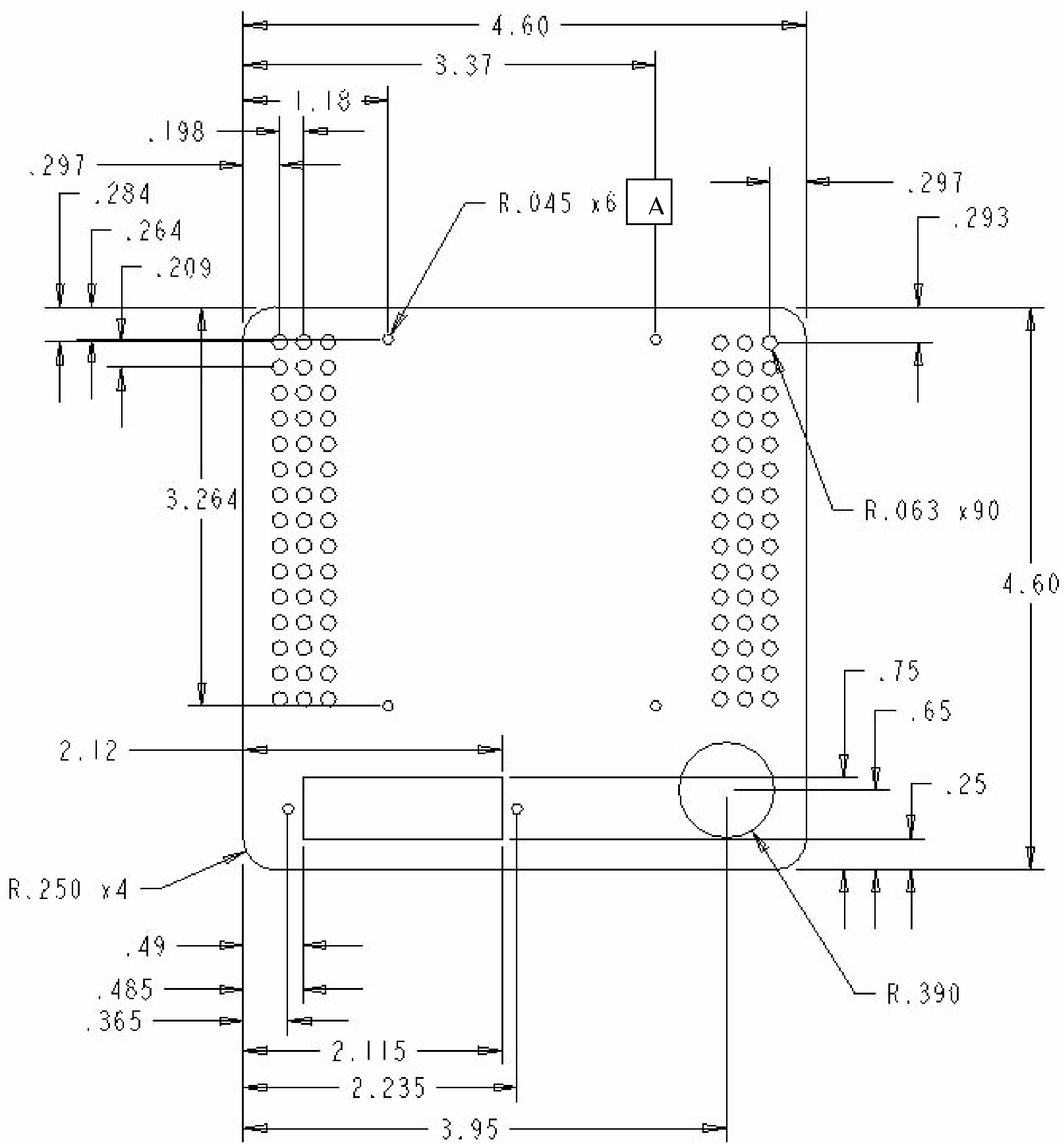


Figure B4: Dimensioned Drawing of right side Plexiglas piece

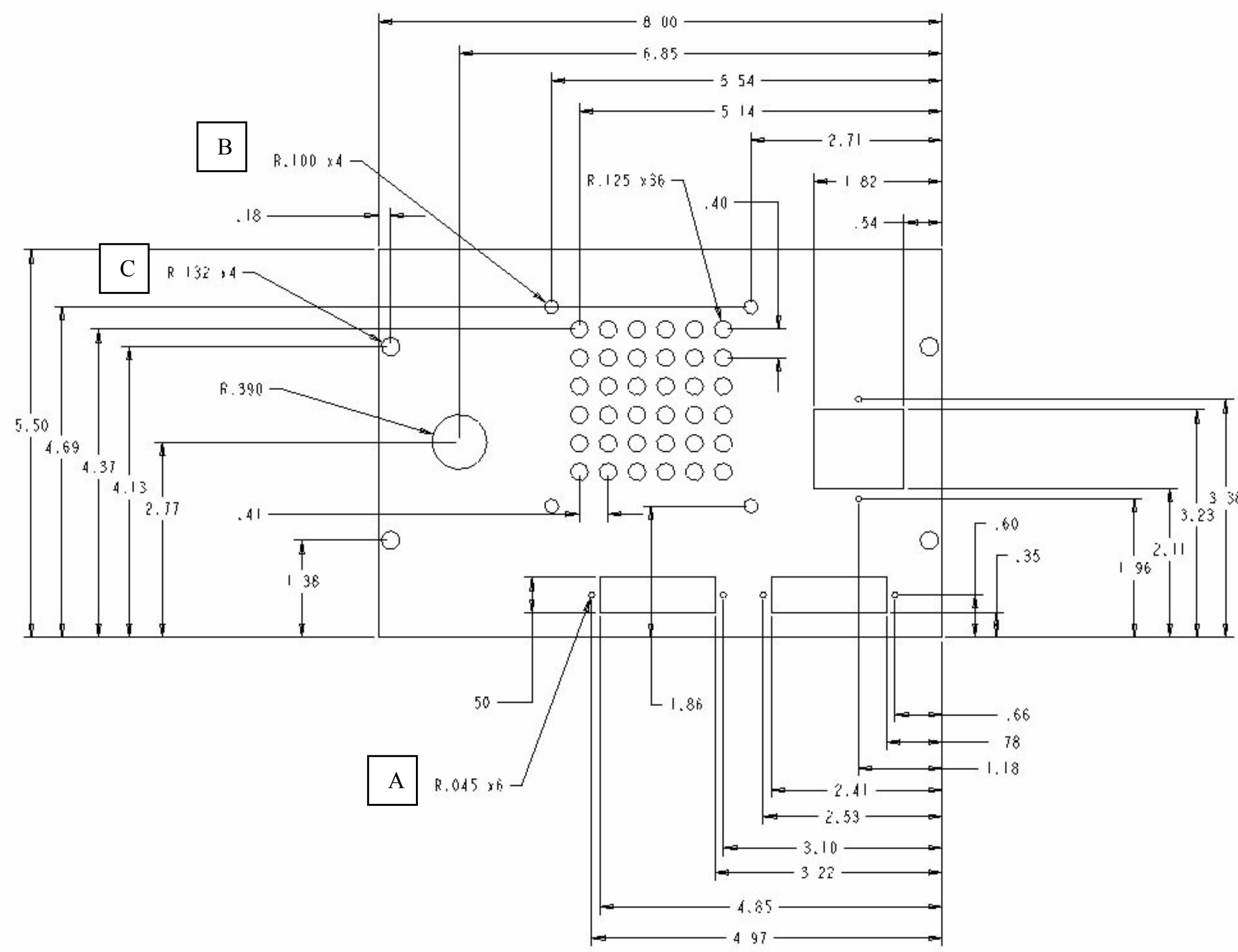


Figure B5: Dimensioned Drawing of the plex-glass plug piece

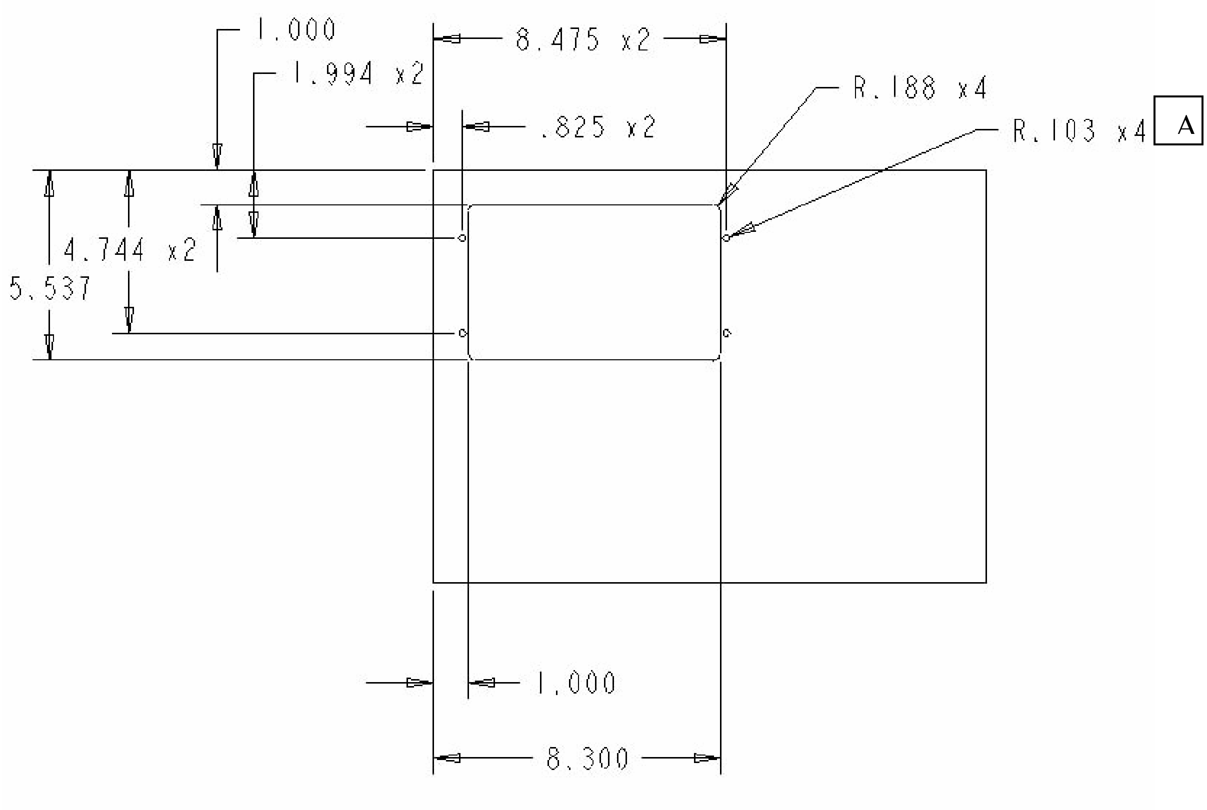


Figure B6: Dimensioned Drawing of the lid for the NEMA Type 1 Enclosure

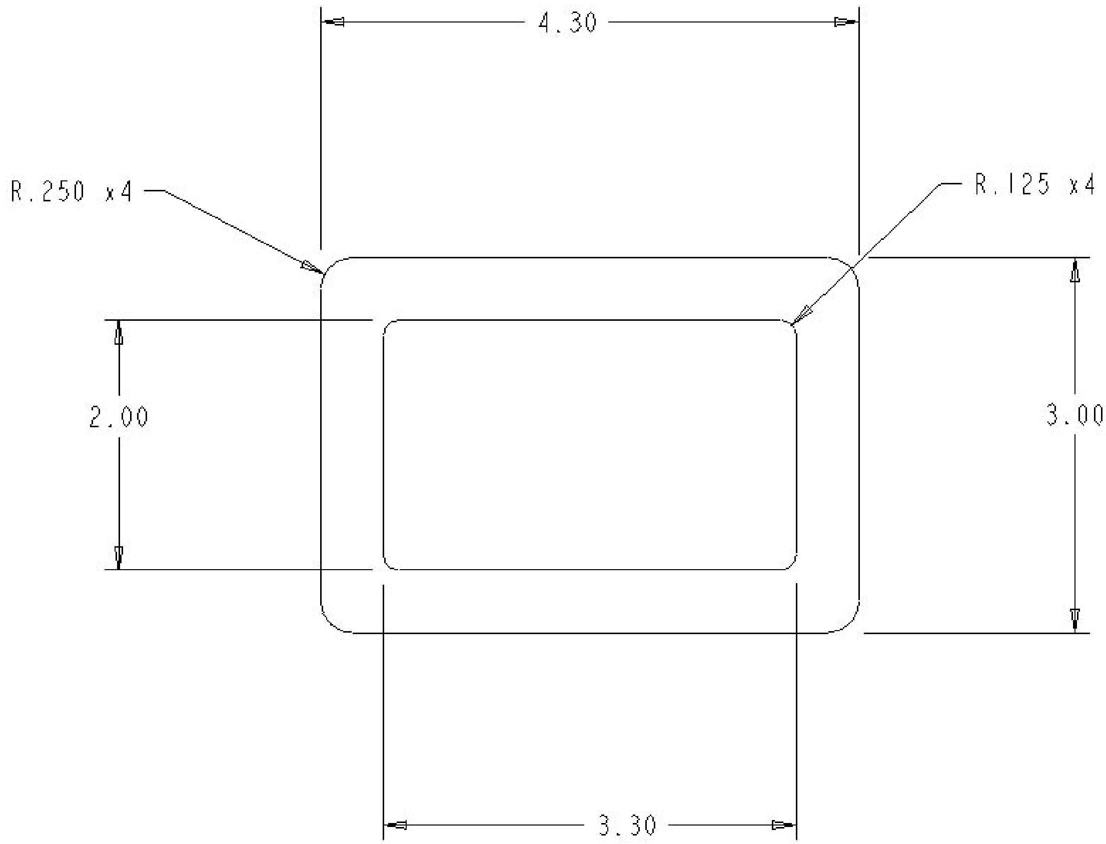


Figure B7: Dimensioned Drawing of the lid for the NEMA Type 1 Enclosure

APPENDIX C: Bill of Materials

Subsection	Components	Quantity	Supplier	P/N	Price	Machining (if any)
The Haptic Box	Extruded box	5x5x5"	ASAP	Steel A500	$31.55 (for 9")	Drilling, Milling, Tapping
	Load cell	5x5x1"	ASAP	Al 6061	$25	Drilling, Milling, Tapping
	DC Servo Motor	1	Maxon	148867	$300	
	Encoder	1	US Digital	e6s-2048	$51.45	
	Amplifier	1	R. Brent Gillespie	N/A	Contact Supplier	
	Strain gauges	4	Vishay	N2A-XX-S014N-350	Contact Supplier	
	Plexiglas walls	12x6x1/4"	MMC	8560K354	$10.96 (for 12x12 sheet)	Laser cutter, Tapping
	Fan with blue LED	1	Arctic (New Egg)	N82E16835186006	$5.99	Tapping
	Rubber feet	8	Home Depot	039003999646	$2.76	
	25 pin D-Sub Connector Male	1	Digikey	CMP25G-ND	$5.92	
	Power Entry Module Female	1	Digikey	SC1231-ND	$4.40	
	Emergency Stop Button	1	Del City	7500002	$0.29	
	6-32 x 1/2" screws (load cell)	4	MMC	90272A148	$2.18 (for 100)	
	6-32 Nuts (load cell)	4	MMC	90480A007	$0.97 (for 100)	
	Washer (load cell)	4	MMC	90126A509	$0.97 (for 100)	
	M3 Screws (motor)	4	MMC	1274T15	$2.41 (for 100)	
	4-40 set screws (Plexiglas walls)	8	Home Depot	030699726189	$1.44	
	6-32 x 1" screws (fan)	4	MMC	90272A153	$2.99 (for 100)	
	4-40 x 1/2" screws (connector etc)	6	MMC	90272A110	$1.66 (for 100)	
	4 x 3/8" standoffs (amplifier PCB)	4	MMC	92415A686	$4.56	
Handles	Plexiglas (Pedal) - **OPTIONAL**	5x4x1/2"	MMC	8560K265	$19.63 (for 12x12 sheet)	Laser cutter, Drilling
	Pedal base (C channel) -	5x5x4"	ASAP	Steel A500	-	Band saw, Drilling

	OPTIONAL					
	Steel rod -**OPTIONAL**	6mmx12"	MMC	1274T15	$14.28	Lathing
	Rubber feet	4	Home Depot	039003999646	$2.76	
	Wheel	1	MMC	61405K63	$17.77	Press fitting
	Knob	1	MMC	6077K14	$10.47	Lathing
	Steel rod	1/4" x 2"	MMC	7936K311	$4.91 (for 12")	Lathing
	Coupler	1	Climax Metal	MISCC-06-06	$45	
Power supply box	Chassis box	1	MMC	75065K18	$41.02	Drilling, Milling
	Dual Output Linear Power supply	1	Mouser	597-AA15-0.8	$45	
	Amplifier (24A cnt/48A pk)	1	Servo-dynamics	Zx-24	$386.75	
	Fan with blue LED	1	Arctic (New Egg)	N82E16835186006	$5.99	Tapping
	25 pin D-Sub Connector Male	1	Digikey	CMP25G-ND	$5.92	
	25 pin D-Sub Connector Female	1	Digikey	CFP25G-ND	$6.82	
	Power Entry Module Female	1	Digikey	SC1231-ND	$9.76	
	Power Entry Module with rocker switch	1	Digikey	486-1045-ND	$34.90	
	16 AWG 1000V wire	-	Mouser	602-1557-100-02	$27.07 (for 100 ft)	
	1/4-32 x 3/4" screws (lid)	4	MMC	91772A559	$4.89 (for 25)	
	6-32 x 1" screws (fan)	4	MMC	90272A153	$2.99 (for 100)	
	1/4-32 Nuts (lid)	4	MMC	91078A205	$2.15 (for 100)	
	4-40 x 1/2" screws (connectors)	6	MMC	90272A110	$1.66 (for 100)	
Other	Power Entry Module Male	2	Digikey	SC1214-ND	$10.36 (for 2)	
	Connector (power supply plug)	1	Molex	42818-0412	$1.08	
	Male to Male 25 Pin D-sub cable	1	CompUSA	472283	$15.89	

APPENDIX D: Major Design Changes since DR #3

Many design changes have been made since Design Review #3 due to the manufacturability of the bowling ball design. We made several attempts to mill into the bowling ball. However, after the initial polyester shell which was fairly easy to machine into, the core material inside the bowling ball proved to be highly abrasive and cut into regular mill bits in the machining process. Three mill bits were dulled at their tips before we had to terminate machining. The dust from the milling process also produced a highly repulsive smell and it could potentially be harmful to human bodies. All of these contributed to our decision to change our design to the current prototype box design.

Motor Housing

We changed the motor housing design from the bowling ball to a simple steel cube. We will no longer remove one face of the steel tube as in the original bowling ball design, but leave all four to enclose the inside components. With added thickness of the steel box (1/4”) and the additional face, the weight of the new design is comparable to that of the bowling ball, therefore ensuring mechanical stability.

Base

The box design eliminates the need for a base because of its flat surfaces (no rolling). Rubber bumpers will be attached to two surfaces of the steel box to prevent sliding.

Cover Walls

Instead of a circular Plexiglas cover window for the bowling ball design, the box design will utilize two square shaped Plexiglas walls to close the open sides of the steel tube. They will be fastened with 4-40 set screws (2 on each edge).

Load Cell

To improve manufacturability, we simplified the load cell design by making various design changes:

- All curves are eliminated, leaving only straight edges so that it can be manufactured using a 2-axis mill machine.
- The thickness of the strain gauge placement area was increased from 1/16” to 3/32” after experimental testing to prevent yielding.
- The load cell placement areas were made flat to make mounting easier.
- The holes on the load cell for mounting onto the steel box were made threaded instead of through holes. Originally nuts were to be used to fasten the load cell onto the steel box. This was changed due to the space limitation inside the box during installation.
- Further FEA was done to ensure the validity of the new load cell design.

Fans

We added a ventilation fan in each of the motor housing box and the power supply box to prevent overheating. Appropriate holes were added in the Plexiglas walls to mount the fans.

Power Supply Box

To simply machining, in our final design we attached a piece of Plexiglas with precut connector and ventilation holes onto a rectangular opening we milled out on the power supply chassis lid. This was done because laser cutting was much more precise and efficient than milling; without the Plexiglas piece, we would have to mill out the connector and ventilation holes on the power supply chassis lid.

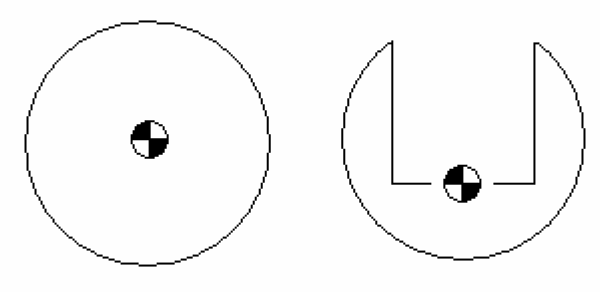
APPENDIX E: Base Interface Design for Original Haptic Ball Design

The base for the original Haptic Ball design serves the purposes of the securing the ball so that it won't rotate or be lifted off under normal loading conditions. The ball should be stably resting on it when no external loads are applied.

Center of Mass Calculations

Because a large amount of material has been removed and replace with the motor housing box, the center of mass (COM) might have shifted from the original position inside the bowling ball. Calculation of the new COM is important in determining the mechanical effects of the applied loads and thereby determining the dimensions of the base for the Haptic Ball.

The mass of the bowling ball after the material is removed from it is determined as such: the original mass and volume of the ball are 14 lb 4oz and 344.8 cubic inch, respectively. Therefore the density is calculated to be 0.041 lb/in^3. The new volume of the ball after material removal as determined by Unigraphics is 165.4in^3. Assuming uniform density, the new mass is calculated to be 6.84 lb.

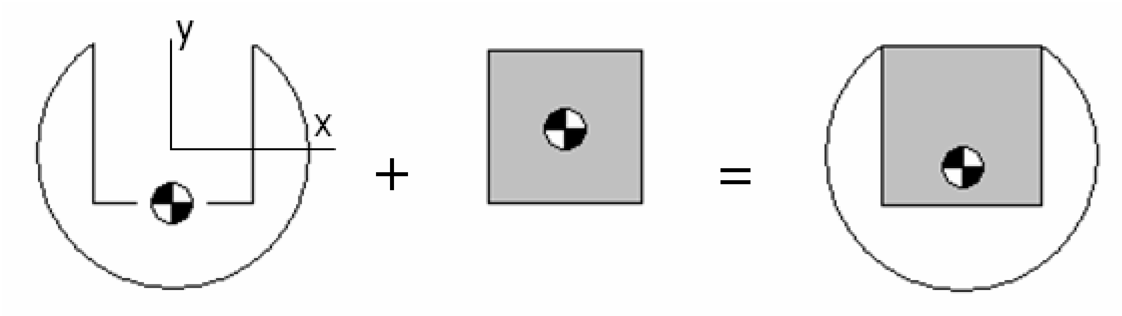


The center of mass of the ball after material removal, according to Unigraphics, is 0.67in below its original COM (the centroid of the sphere).

The mass of the motor housing which replaces the removed material is determined by calculating the mass of each individual component. The result is summarized in the table below.

Part	***Weight (lbs.)***
Steel box (5x5'', 1/8'' thick, 3 faces)	2.6
Motor (Maxon RE-40)	1.1
Load cell (Al, volume=2.23 in3)	0.2
Amplifier/cabling/encoder	0.4
Total weight added	4.3

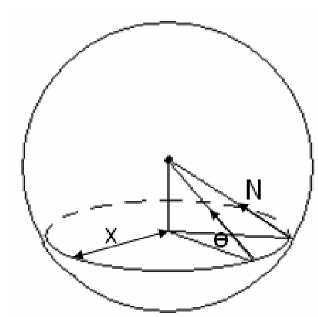
The center of mass of the motor housing box is assumed to be at its centroid. We then calculated the combined COM of the Haptic Ball using $(\Sigma y)(\Sigma M) = (y_{ball})(M_{ball})+(y_{box})(M_{box}) = -0.025$in lb. therefore Σy is then -0.002in. We can assume that the COM of the Haptic ball is the same as the original COM of the sphere (its centroid). This greatly simplifies our future calculations.



The center of mass calculation of the Haptic Ball also implies that the ball will rest stably on its base as long as the base is directly under the center of the ball.

Torque Analysis

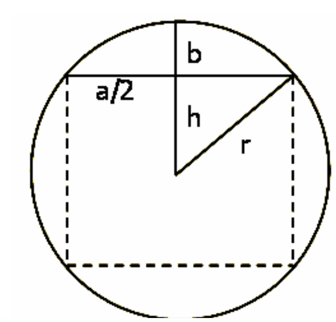
The only force resisting the ball's rotational tendency under 0.5Nm torque is the static friction between the ball and its base. The circle on the sphere's surface indicates the location of the rubber ring with radius x when the ball is resting on the base. The normal force applied on the ball at any location is indicated by N, as shown. Assuming symmetry about the vertical axis, the sum of the normal forces is equivalent to the opposite of the weight of the Haptic Ball, or $N\sin\Theta=W$. Therefore the normal force $N=W/\sin\Theta$. The static friction force can then be calculated Friction = $N*\mu$ = $W*\mu/(\sin\theta)$. The torque caused by friction is then Torque = Friction*x = $[W*\mu/(\sin\theta)]*x$, which in order to resist rotation has to be equal to or greater than 0.5Nm. Also, $\sin\theta$ = sqrt(r2-x2)/r based on Pythagorean theorem. Finally, the governing equation used to solve for x is $[W*\mu*r/(\text{sqrt}(r2-x2)]*x \geq 0.5$.



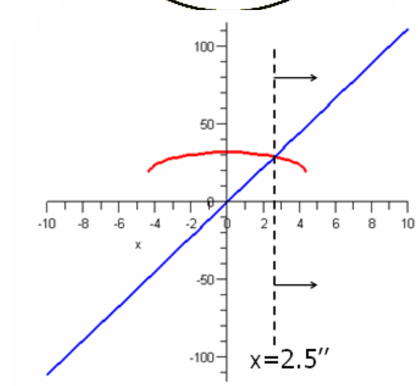
The coefficient of static friction for rubber ranges from 0.6 to 0.8. Taking the minimum value (most slippery), we calculated the value of x to be equal to or greater than 0.7in. In other words, as long as all the weight of the ball is resting on the rubber ring with a minimum radius of 0.7in, the ball will not rotate under 0.5Nm applied torque.

Off-Axis Loading Analysis

Before analyzing the effect of off-axis loading, we first need to determine the location of force application for the new geometry (due to design change from the box to the ball). To determine the distance between the face of the motor housing and the COM of the ball, we first calculated distance b in the figure. Because r = 8.7/2in, a = 5in, we found that h = sqrt [r2-(a/2)2] = 3.56in. Therefore b = r-h = 0.79in. The distance between the point of force application on the handle and the COM is then r – b + 2.68 = 6.24in.



The following figure shows the FBD of the Haptic Ball when it's at 90 degree orientation (handle pointing up

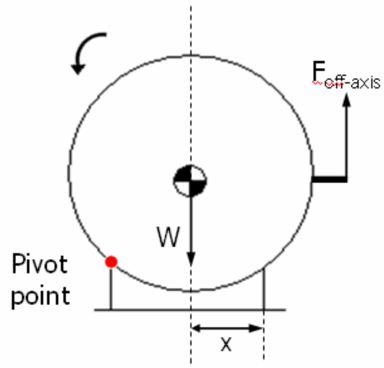


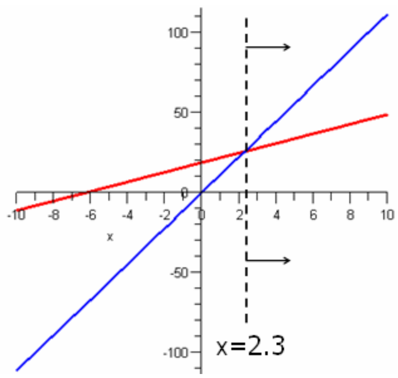
vertically) and an off-axis force is applied to create tendency of rotation about the shown pivot point. The forces at the pivot point are eliminated because they do not contribute to resisting the ball from being lifted off. For stability, the value of x should be chosen so that the moment due to the weight of the ball is equal to or greater than the moment due to the off axis load. Summing moments about the pivot point, the governing equation used to solve for x is then

$$F_{off-axis} \times [6.24 + \sqrt{(\frac{8.7}{2})^2 - x^2}\,] \leq W \times x$$

Plotting both sides of the equation using Maple, with a chosen off-axis load of 3lbf, the following Maple output is obtained. For a minimum base radius of 2.5in, the ball will not be lifted off by off-axis forces.

When the ball is orientated with its handle pointing sideways (0 degree orientation), an acceptable x value can be obtained in similar ways to prevent the ball from being lifted off of its base. The corresponding FBD, the governing equation, along with the Maple output solution are shown below.





$$F_{off-axis} \times (6.24 + x) \leq W \times x$$

When the ball is orientated this way, a minimum base radius of 2.5in is required to prevent the ball from being lifted off by off-axis forces.

Summary of the Base Design Analysis

Based on the aforementioned analyses, we conclude the following:

- The weight of the ball will not cause it to roll over the base as long as the base is directly below the center of the ball.
- A rubber ring (μ=0.6) attached to the base will prevent any rotational motion of the ball.
- Under maximum off-axis loading of 3 lbf, the radius of the base ring needs to be at least 2.5'' to prevent the ball from being lifted off of the base.

APPENDIX F: Thermal Analysis

Power Supply Box

The power supply and motor amplifier are to be housed in a separate housing from the haptic box. The housing must be large enough to hold the amplifier and power supply. It also needs to dissipate the heat generated by the amplifier and power supply so that they can safely operate.

A 16" x 12" x 6" NEMA (National Electrical Manufacturer's Association) steel enclosure will be used for the housing. These dimensions allow for the amplifier, which is 3.71" x 7.35" x 4.43", and the power supply, which is 10.5" x 7" x 1.7", to fit inside the housing.

Table F1Operating Temperatures for Power Supply and Amplifier

	T_{min}	T_{max}
Power Supply	-20°C	+70 °C
Amplifier	0 °C	+40 °C

The safe operating ranges for the power supply and for the amplifier are shown above in Table F1. The table shows that the maximum temperature that the inside of the housing can be is 40 °C. Any higher then this and the amplifier won't work properly. In order to determine the operating temperature inside the box we must use thermal circuit analysis

The temperature inside the box is affected by the heat generated from the power supply, the heat dissipated through conduction of the steel housing, and the heat dissipated through convection from air that will pass through vents on the steel housing. Equation F1 shows this mathematically.

$$< Q_{k,p-o} > + < Q_{ku,p-o} >= S$$

Equation F1

Where $Q_{k,p-o}$ is the heat transferred through conduction, $Q_{ku,p-o}$ is the heat transferred through convection, and S is the heat generated by the power supply box. These are illustrated in a thermal circuit diagram as shown in Figure F1 below.

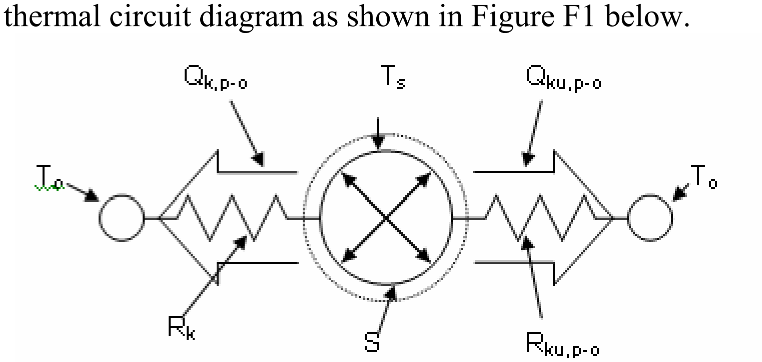


Figure F1: Thermal circuit diagram for the power supply

Most of the heat will be dissipated through conduction through the metal box because we will not be forcing air over the power supply. We will simply be cutting slits into the metal box to allow hot air to rise and have thermobuoyant flow cool the power supply.

Equation F2 below shows how to calculate the heat transfer due to conduction.

$$< Q_{k,p-o} >= \frac{(T_s - T_o)}{L} A_k k$$

Equation F2

Where T_o is the ambient temperature, T_s is the temperature of the power supply box, L is the thickness of the metal housing, A_k is the area of conduction, and k is the thermal conductivity of the steel box.

Equation F3 shows how to calculate the heat transfer due to convection.

$$< Q_{ku,p-o} >= \frac{(T_s - T_o)}{< R_{ku} >}$$

Equation F3

Where R_{ku} is the convective heat transfer and the other variables are described above. The convective heat transfer is modeled as thermobuoyant flow of a plate.

By using equations F1, F2 and F3 we were able to determine how raising the temperature of the power supply affects how much heat comes out of the box. According to our analysis if the power supply generates 11 kW of heat, then the box temp raises about 10. Additional equations used for heat analysis are found in Appendix A.

Housing of the Original Bowling Ball Design

The motor is going to be housed inside the bowling ball. However, the bowling ball is a very good insulator. This makes it very hard for the motor to dissipate heat. Over heating of the motor could pose a problem for the system.

The only place that the motor can dissipate heat through is the Plexiglas. The Plexiglas will have slits cut into it so that hot air can rise out of the cavity. A similar analysis was done for the motor that was done for the power supply box. Using equations #, #, and # we have determined that if the motor temp raised 10 °C then the box can dissipate heat at a rate of up to 50 W. Additional equations used for heat analysis are found in Appendix A.