Labor Reducing Piano Regulating Mechanism Using Precise Voice Coil Motor with No Friction

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ME 450: Design and Manufacturing III

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Project 17

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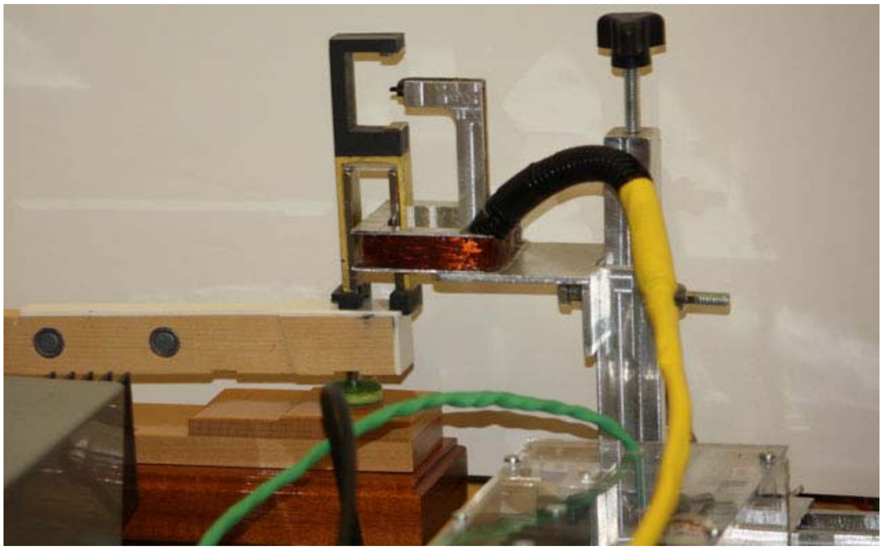

This report contains the description and analysis of a device that balances piano actions. The project was assigned as part of a mechanical engineering course, ME 450, at the University of Michigan.

EXECUTIVE SUMMARY

When balancing the keys of a piano, the goal is to have a consistent feel from key to key so that a pianist can get precise control over the sounds produced and consistent, predictable performance from each key. This consistent feel is produced by regulating the piano so that keys within a specific region have the same up and down weights. Currently this regulation is done manually by a technician, and the up and down weights are iteratively determined using calibrated gram weights. This process is subject to error and time-consuming (15+ hrs / piano). Therefore, it would be worthwhile to develop a product that can automate this process and record the desired data.

Our customer, Professor Grijalva, Director of Piano Technology at the University of Michigan, presented the problem of designing and building a device that can accurately and consistently measure the up and down weights of piano keys and calculate the corresponding friction and balance weights. The device should be compatible with any piano type, be easily reproducible, conform to specifications, and be within budget.

Additionally, the dimensions of the device must allow for it to be operated on a workbench in front of a keyboard. The device must cycle in a short amount of time and must be accurate, precise, repeatable, and of high resolution (±0.5 gram-force). The device must also be able to overcome influences of static friction without the assistance of a technician. All important force measurements must be reported to the technician in a digital display on the device.

In engineering such a device, it was necessary to see what had already been done. A previous ME450 project utilized a pin-supported beam driven by a voice coil motor, but this previous project did not produce accurate measurements due to the team's inability to characterize friction to obtain pure, accurate force outputs. As an attempt to minimize friction, another prototype was generated that contained a flexure bearing driven by a voice coil motor, but performance was frustrated by undesired lateral movements in the flexure bearing. Since friction severely disrupts accuracy and repeatability in low force applications, our team investigated frictionless force applications. After researching and developing several designs, our team determined that the best way to eliminate or reduce friction was to use a voice coil motor. Unlike other prototypes with voice coil motors, our design incorporates the piano action as a part of the voice coil motor and thus, theoretically eliminates the need to characterize friction. To accomplish this, two permanent magnets with a back iron will generate a constant, uniform magnetic field throughout the devices operating range. Then, a non-contacting single coil of wires will pass orthogonally through this field to generate a Lorentz force that is linearly dependent on the applied input current to the wire.

The first full-scale prototype has been developed and has been proven to function according to expectation. With its integrated 3-axis adjustments, power supply, signal amplifier, and microcontroller, the device is capable of actuating white and black piano keys, but does not have a fully developed control circuit and will require further improvement to be able to measure, record, and display force data. The ability of the device to fit properly on a workbench and adjust to accommodate white and black keys has been discussed with and confirmed by Professor Grijalva. Much interest in the device was generated by its display at the University of Michigan Engineering Design Expo, where it became evident that there is a demand for such a device among Professor Grijalva and his colleagues.

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ABSTRACT

Piano technicians currently spend upwards of 15 hours measuring forces on the ends of piano keys to produce the consistent feel and sound expected by pianists. This process is referred to as balancing the action. Technicians manually determine the “up-weight” and “down-weight” on each of the piano’s 88 actions by iteratively adding/removing gram weights from the ends of the keys until a desired velocity is qualitatively observed. A device that would automatically perform these measurements and calculate the balance and friction weights from the up and down weights would greatly accelerate this process and also eliminate qualitative observations to improve repeatability. Existing prototypes have been developed but they have difficulty characterizing friction to eliminate it from torque outputs of the motor yielding pure, accurate force measurements. Consequently, this design attempts to eliminate friction by using a voice coil motor composed of permanent magnets and an electrified coil. Considering previous work and discussing needs with experts, engineering specifications and consumer requirements were defined and guided the design. Through modeling, prototyping, and experimentation this design meets the requirements in a cost-effective manner.

INTRODUCTION

Piano technicians spend upwards of 15 hours balancing piano actions in order to achieve a consistent feel from key to key. This process is done manually using gram weights and qualitative observations where the piano technician observes a “smooth, constant velocity” of the piano key. As a result of the observational judgments, the process is inconsistent among technicians and lacks repeatability. Additionally, the process is lengthy as experienced technicians spend upwards of 15 hours calibrating all 88 piano actions. To meet the demands of the technicians, our team was presented the problem of designing and building an automated, high precision device that can quickly and consistently measure the up and down weights of piano keys to calculate and display the corresponding friction and balance weights. Our primary customer, Professor Grijalva, Director of Piano Technology at the University of Michigan, has had other prototypes designed and our team will build upon these ideas to produce our own device meeting his requirements.

BACKGROUND INFORMATION

This section provides information regarding the current procedure for balancing piano actions and how balance and friction weights are derived. It also provides justification regarding why friction must be minimized from the design in order to precisely measure forces. Furthermore, this section discusses previous research and prototypes.

Current Procedure and Weight Derivations

Understanding of the current balancing procedure was learned while meeting with Professor Grijalva. The current method uses gram weights and is referred to as the “thump and observe” method because the technician must tap the action in order to break the static friction of the piano key allowing the key to move. As one can imagine, tapping is an inconsistent step in the process because different technicians tap at different times, locations on the action, and with varying forces. Furthermore, it is time consuming as the technician must iteratively adjust the weights until a qualitative, smooth speed is observed. Using this method, the down weight, W_{down}, and up weight, W_{up}, of an action are measured and then equations are used to calculate the friction weight, $W_{friction}$, and balance weight, $W_{balance}$. From $W_{friction}$ and $W_{balance}$, a piano balancer knows the quantity and position of lead balancing weights that must be inserted into the piano action arm. This process is repeated for each of the piano's 88 actions and is very time consuming. Additionally, each action must have holes drilled into the side before lead weights are inserted. However, this report only investigates how to more quickly, precisely, and consistently prescribe the weights. Figure 1 below shows a single piano action with the gram weight positioning and lead balancing weights.

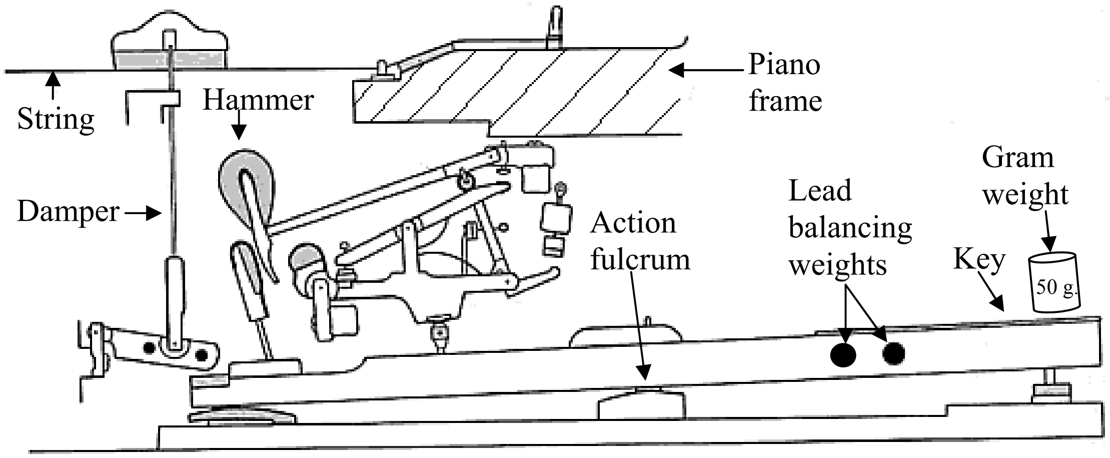


Figure 1: Single piano action of a modern *Steinway & Sons* grand piano

Down and Up Weights: As mentioned previously, W_{down} is found by iteratively placing a gram weight at the end of the piano key as shown in figure 1. During the process, the piano technician lightly knocks or "thumps" the workbench or action to break the static friction. If the action does not move, then more weight is added and the technician "thumps" again. When the piano key moves down with a slow, constant speed (assessed visually), the mass on the end of the piano key is reported as W_{down}. Conversely, if the piano key moves down too quickly, masses are removed until the piano technician observes the un-quantified slow, constant speed that he/she is looking for.

Similarly, W_{up} is found by starting with the key depressed and removing weights instead of adding weights. W_{up} is determined to be the amount of weight that can be placed on a key that still allows the key to return to its original position.

Friction and Balance Weights: Static friction, Coulomb friction, and viscous friction are all present in the piano action. To aid in comprehension of frictional forces acting on the piano action, Figure 2 shows a very simple model of the expected behavior of these frictional forces as a function of angular velocity.

In the current procedure, the technician adds a constant force (gram weight) to the end of the key, "thumps" the action or table to break/eliminate static friction, and then iterates (by adding/removing gram weights) until he/she achieves a prescribed velocity. Figure 2 shows the actions expected frictional forces as a function of velocity assuming Stribeck friction is insignificant and the frictional force is a linear function of angular velocity. In this model, Stribeck friction is neglected since our model will not be traveling at very low velocities. By definition, Coulomb friction results in a constant force at any velocity so it exists during the balancing procedure. Likewise, viscous friction opposes motion and its force is directly proportional to the relative velocity of the piano action so it also has an effect on the weight measurements. Static friction, the force resisting initial motion at zero velocity, is eliminated in the procedure when the balancer "thumps" the piano action. Therefore, the only frictional forces at play during weight measurements are the dynamic (Coulomb) friction and viscous friction.

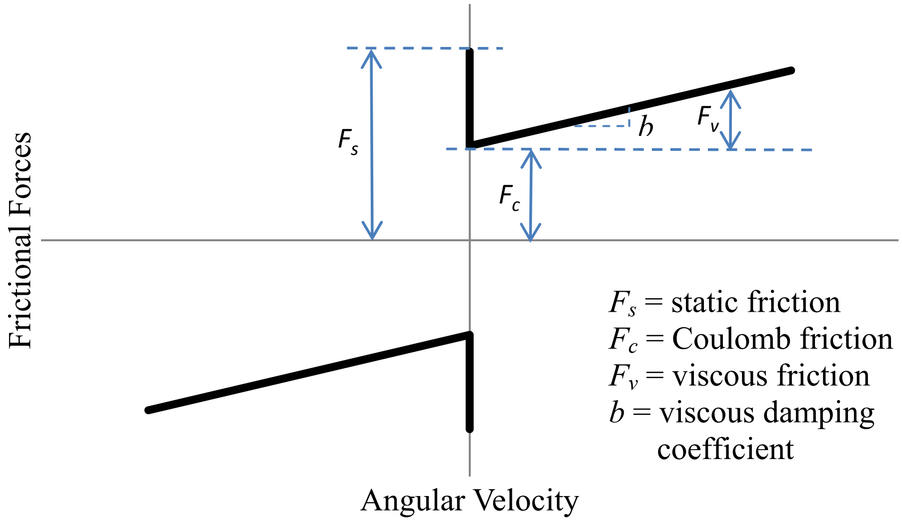


Figure 2: Piano action assumed frictional behavior

More simply, the piano action in figure 1 can be thought of as a simple balance with a single fulcrum and damper as shown in figure 3. In the figure, only dynamic and viscous frictions of the piano action are represented by the damper since they will depend on the piano key's velocity. The balance weight of the action can be thought of as the weight required to balance the system in figure 3. Again, W_{up} and W_{down} are currently directly measured when in the procedure for simplicity and then both $W_{friction}$ and $W_{balance}$ are calculated. However, determining any two weights allows calculation of the other two.

Weight Derivations: $W_{balance}$ is found by first setting the moment about the fulcrum of the balance in figure 3 equal to zero. This is done because the beam will be balanced when there is no rotation/moment. Also, the damper exerts no force on the beam since the force of a damper is a function of velocity and the balance weight is calculated at static equilibrium. Equation 1 equates the sum of moments about the fulcrum to zero, where the balance weight is equal to m_2g.

$$\sum M_{fulcrum} = 0 \;\rightarrow\; W_{balance}L_2 - m_1gL_1 = I\alpha = 0 \;\rightarrow W_{balance} = \frac{m_1gL_1}{L_2}$$

(Equation 1)

Also, the down weight can be calculated by assuming clockwise rotation with constant velocity. This is true because down weight is measured as the beam rotates clockwise and it is measured when the beam qualitatively moves "smoothly with constant velocity." Balancing the moments in figure 3 where the down weight is measured to be m_2g and angular acceleration equals zero due to constant acceleration, equation 2 is derived.

$$\sum M_{fulcrum} = 0 \;\rightarrow\; W_{down}L_2 - m_1gL_1 - b|\omega| = I\alpha = 0 \qquad \text{(Equation 2)}$$

Similarly, the up weight is calculated assuming counterclockwise rotation with constant velocity. Again using figure 3, the up weight is measured to be m_2g and the angular acceleration equals zero due to constant angular velocity or no acceleration. The sum of the moments is shown in equation 3.

$$\sum M_{fulcrum} = 0 \;\rightarrow\; W_{up}L_2 - m_1gL_1 + b|\omega| = I\alpha = 0 \qquad \text{(Equation 3)}$$

Next, balance weight is defined as having no motion so all velocity dependant variables need to be eliminated from equations 2 and 3. This is done by solving for $b|v|$ in both equations 2 and 3 and setting them equal to each other producing equation 4.

$$W_{down}L_2 - m_1gL_1 = m_1gL_1 - W_{up}L_2 \;\rightarrow\; \frac{m_1L_1}{L_2} = \frac{W_{down}+W_{up}}{2} \qquad \text{(Equation 4)}$$

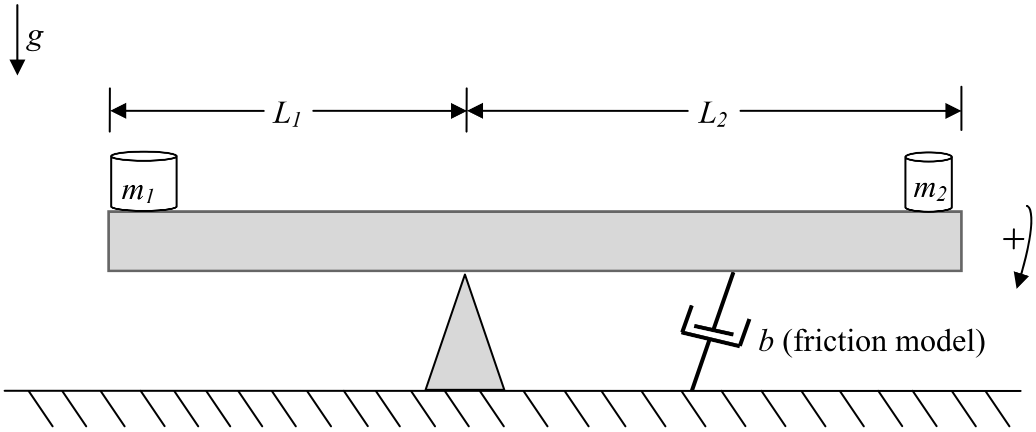


Figure 3: Simplified version of piano balancing with single fulcrum

The result of equation 4 equals the balance weight of equation 1 and is thus defined by equation 5.

$$W_{balance} = \frac{W_{down}+W_{up}}{2} \qquad \text{(Equation 5)}$$

Similarly, we want to determine $W_{friction}$ in terms of the up and down weights so solving equations 2 and 3 for m_1gL_1 and setting them equal to each other gives equation 6.

$$W_{down}L_2 - b|\omega| = W_{up}L_2 + b|\omega| \;\rightarrow\; \frac{b|\omega|}{L_2} = \frac{W_{down}-W_{up}}{2} \qquad \text{(Equation 6)}$$

The friction weight represents the amount of weight which when added to the balance weight causes the key to move slowly downward or when subtracted from the balance weight allows the key to slowly lift. Therefore, it makes sense that it should be the average of the difference of down and up weights and is simply stated as equation 7.

$$W_{friction} = \frac{W_{down} - W_{up}}{2} \qquad \text{(Equation 7)}$$

Justification

Many system models neglect friction because it is poorly understood and often times difficult to model, however it exists in all mechanical systems. Additionally, discontinuous differential terms and friction's non-linear dependence on the device's velocity/position make it complex to characterize [1]. To avoid modeling difficulty, minimal friction is desired to accurately model a system's performance. Sometimes friction is not important to characterize and can be disregarded due to high output tolerances; however in high precision devices friction can significantly disrupt accuracy and result in incorrect results. Studies regarding friction's effect on forward dynamics, particularly with robotics, states that friction can consume up to one third of the motor torque [1].

The first step in compensating friction is to develop a feasible, physically correct model and then identify its parameters [2]. However, it has two major drawbacks. The first is that most models apply only to linear systems and second, all models require prior knowledge of the model structure [2]. Since *Steinway & Sons* piano actions are hand-made, they each have slightly different operational qualities making them very challenging to model and predict accurate parameters. Moreover, due to our team's limited knowledge of the modeling structures with complex control systems, it would be very difficult to compensate for friction in a design. In addition, determining model parameters requires many controlled experiments with expensive equipment [2], beyond our project's $400 budget. Furthermore, as parts wear the friction will likely increase and re-calibration will periodically be required in this application since this particular device must be highly precise. Given the difficulties in obtaining accurate measurements by characterizing friction, our team's limited complex modeling expertise, and limited budget, it is desirable to design a system without friction, as it is a very error-prone objective to attempt even with sufficient funds.

Research and Existing Prototypes

Due to a small market, there is little literature regarding piano balancing devices other than the previously built prototypes designed at the University of Michigan. However, one article by Stanwood [3] describes a method for balancing piano keys using a different strategy in which individual action parts are weighed individually. This method may solve the issue of consistency by removing some qualitative measurements from the technician. However it likely does not decrease time for the technician.

Professor Brent Gillespie has been involved in previously built prototypes and has provided valuable information regarding flaws in existing prototypes and ideas that have previously been attempted. One of the central challenges in constructing a suitable device is to characterize friction so it can be eliminated from the device's known output force which must provide accurate, precise measurements. To resolve this issue, the prototype in figure 4 was built which used a flexure bearing to eliminate nearly all frictional forces from the device during motion by utilizing the bending moments and elasticity of the flexure beams. Unfortunately this device also has flaws. Most notably, there is undesirable lateral motion (into and out of the page) of the device which disrupts optical sensor readings and sometimes results in detrimental rubbing on the housing.

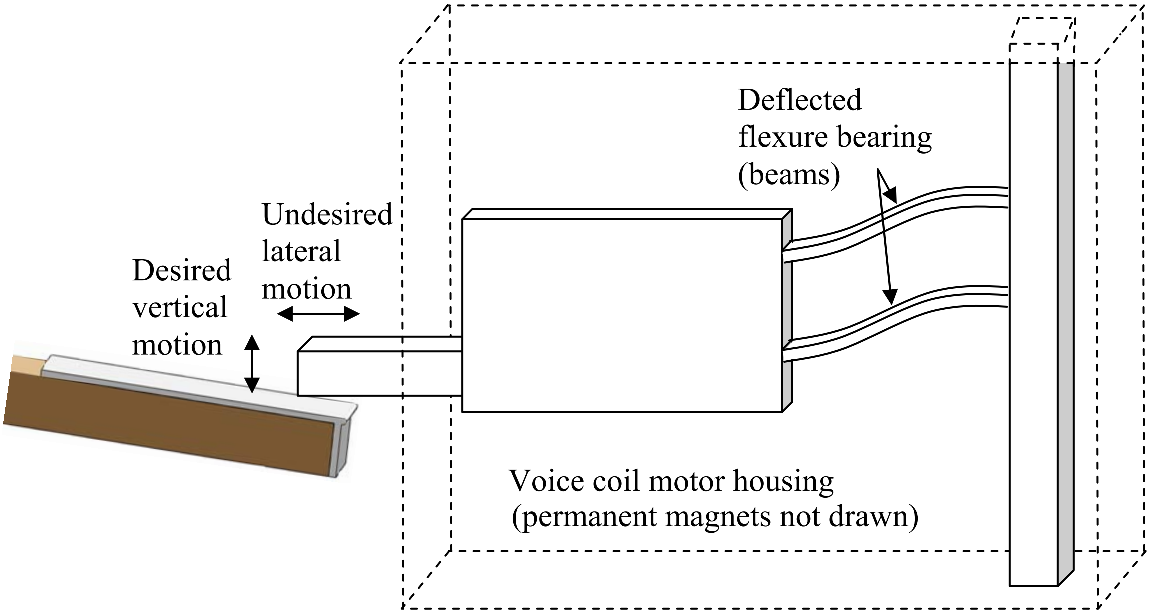


Figure 4: Existing prototype with undesirable lateral motion but successful friction minimization using flexure bearing

Most of the information regarding this project has come from Professor Brent Gillespie and Professor Bob Grijalva. Professor Grijalva has provided nearly all customer requirements as he will be the beneficiary of our device. Professor Brent Gillespie has been involved in previously built prototypes and has provided valuable information regarding their flaws and ideas that have previously been attempted. From Professor Gillespie we have learned that the current prototype needs a flexure bearing with more constrained lateral movement and refinement to produce better consistency and more utility.

We expect to meet with Professor Grijalva frequently throughout the semester to gather information. Professor Gillespie will also provide our team with a great deal of thought and guidance. Other information sources this semester are technical documents regarding components in our system and machine shop advice from Bob Coury and Marv Cressey.

CUSTOMER REQUIREMENTS

The properties of the desired device were discussed with Professors Gillespie and Grijalva. The device must be able to perform the following tasks:

- Quickly and accurately measure the up, down, balance, and friction weights
- Overcome the static friction of the piano keys
- Be compact enough to be portable and fit on a workbench
- Provide consistent measurements
- Reach the white and black keys

ENGINEERING SPECIFICATIONS

Using the customer requirements that were provided by the professors, in conjunction with the information sources that were found, the specifications for the device were prioritized and quantified. System specifications related to the measurement of a single key and the associated requirements are shown in Table 1, below. Secondary requirements not directly related to the primary function (force measurement of a key) are shown in Table 2, below.

Table 1: System Specifications: Primary Function

High Priority	Medium Priority	Low Priority
• Accurate Force Measurements [± 0.5 gram-force] • Fast Measurement Cycle Time [< 5 s] • Excellent Voltage Control [±5 mV]	• Excellent Position Resolution [±0.1 mm] • Limit Coil Temperature [< 5 A coil current]	• Option between manual control and logic controller

Table 2: System Specifications: Secondary Requirements

High Priority	Medium Priority	Low Priority
• Measure and display four parameters [display ±1g] • Easily adjustable to measure white and black keys [<5 kg, 8 cm reach] • Fits on workbench [8.9 cm max depth]	• Easily portable [<10 kg, one package] • Determine the depth travelled by key (±1mm)	• Automatically measure all keys • Store measurements in USB drive (Input Voltage, Measured current, Position, Determined weights)

The high priority specifications include the quick and accurate determination of the up, down, balance, and friction weights with a ±0.5 gram precision. To obtain the ±0.5 g precision, it is estimated that the voltage controller must have a controllable voltage step of ± 5mV. To ensure that the product significantly reduces the time required to balance a keyboard, the measurement cycle time should be < 5s. The device must also have the ability to fit on the workbench and measure both white and black keys. Additionally, the device must be easily adjustable between keys. As we do not plan on implementing an automatic switch between keys, this implies a maximum weight to be easily maneuverable. These functions were deemed high priority because without these features, the device would offer little utility to a piano technician. Specifically, the device will be 0.3 x 0.3 x 0.3 meters to comfortably fit on any workbench, while weighing less than 10 kg. Also, the device would be placed 13 mm from the edge of the white/black key and take at most 5 seconds to make the measurements for each key, which will be displayed on an easy-to-read digital screen. For the device to measure the black keys, it must be able to travel 8 cm into the keyboard.

The medium priority specifications include the device's ease of portability and the ability to measure the depth travelled when the piano key is pressed. These functions are medium priority because while the ideal device would have these features, the general goal of the device will not be compromised without them. For ease of portability, the device will be compact (8.9 cm max depth) and weigh under 10 kg. Additionally, to accurately measure the depth traveled, as well as leave the possibility to calculate velocity, the position sensor(s) must have a resolution of at least ±0.1 mm. To reduce overheating of any design with current flowing in a coil (circular or otherwise), the maximum current should be limited to < 5A.

The low priority specifications include the ability to automatically make the measurements for all 88 keys and store them in a USB drive. These are specifications representing features that can be implemented once the high and medium priority specifications have been met. A motor would have to be implemented to move the device across the keyboard. The data would be saved to a file on the USB drive, which would be accessible on any computer. Additionally, a low priority option is to allow the choice of either a manual control or a control algorithm.

CONCEPT GENERATION

Figure 5 shows a functional decomposition of the device. An input current is supplied to drive a motor which will lower/raise the key. The movements of the key are measured by two Hall effect sensors to verify to eliminate errors, and this information in conjunction with the known current is used to calculate the weight values. These weight values are displayed on a LED screen. Parallel lines from the energy input indicate other functions that require energy to operate.

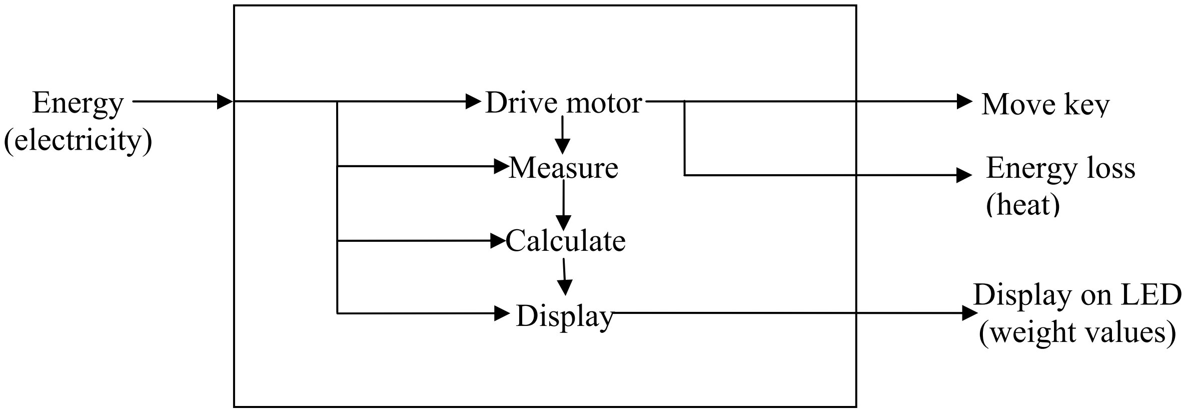


Figure 5: Functional decomposition of force measurement device

In generating concepts, it was necessary to analyze what had already been done. A previous project utilized a pin-supported beam driven by a voice coil motor, but this project did not produce accurate measurements and was very bulky. Additionally, a prototype was generated that contained a flexure bearing driven by a voice coil, but this was unsuccessful due to undesired lateral movements in the bearing which resulted in inaccurate measurements.

The shortcomings of the previous designs included lack of reproducibility and manufacturability. Consequently, simplicity and manufacturability are important goals for this design. New ideas were investigated in the area of force generation and application. Implementing rotary electric motors was considered, but was quickly deemed unfeasible because of the extra friction associated with converting rotational motion to linear motion. This friction manifests itself in the screws, gears, or pulleys that are driven by the motor. To avoid introducing friction to the system, a water-displacement system was considered because it was a frictionless, easy to measure way of applying a force to the keys. However, this idea was rejected because of pianos' sensitivity to liquids and the chance of water escaping the system during operation. From this point, linear force generation methods were investigated, including solenoids and voice coil motors.

The research showed that for a constant force to be generated across the device workspace (depression distance of the key), a uniform magnetic field is required wherever a coil interacts with that field. A solenoid is a variable reluctance device that is difficult to use for producing a constant force across a device workspace. The voice coil motor uses a permanent magnet to generate a uniform magnetic field. A magnetic field is generated within the coil when current is applied to the wires, and this field interacts with the permanent magnetic field yielding controlled motion of the coil via Lorentz forces, which is the force on a point charge (current) due to an electromagnetic force. Thus implementing a voice coil motor was determined to be the best way to apply the force to the key because as long as the constant, uniform permanent magnet magnetic field lines are perpendicular to the current running through the wire, the resulting force should be a linear function of current as defined by Lorentz forces.

Next, methods to measure the applied force and position of the actuator were investigated. To measure the applied force, the two options discussed were using a load cell (strain gauge) at the end of actuator to measure the force at the contact point on the key or using the current-force relationship to calculate the force based on the input current. The load cell would be very accurate, but is a very costly device, and the current-force relationship would be easy to calculate, but is easily tainted by the presence of friction or mechanical impedance in the system. The challenge then became generating concepts that would stabilize and linearize the motion of the voice coil and implementing the calibration. After further brainstorming, three different approaches were determined to achieve the desired results:

(1) <u>Contact Bearings/Bushings</u>: Implementing a system with ball bearings or bushings would successfully achieve a linear motion, but would introduce friction to the system. This friction would result in a difference between the input force and output force applied to the key, so a strain gauge would be required to measure the force at the key.

(2) <u>Flexure Bearing/Spring</u>: Implementing a system with a flexure bearing or spring would eliminate the friction of the motion, but introduce the element of internal mechanical impedance since flexure bearings work by bending to cause motion. In order to overcome this impedance, an input force larger than the up and down weights would be required, so the impedance would need to be characterized. For consistent, accurate measurements the impedance should be the same every time the device is operated.

(3) <u>Noncontact Voice Coil</u>: Implementing a system with the voice coil orientated in way to eliminate the need for springs or a flexure bearing would eliminate friction and impedance. This can be achieved by placing the voice coil directly on the key rather than having it suspended. The necessary weights could be determined by relating the coil's input current to the force generated by the magnetic field.

Taking these three approaches into account, several concepts were designed. Since one of the main objectives for our device is to create a zero friction mechanism, the report body focuses on design approach 3, implementing noncontact voice coils. Therefore concepts A, B, and C are shown and discussed in Appendix A because these designs are based on the first 2 design approaches which require friction characterization.

Concept D

This concept, shown in figure 6 on the next page, embodies the third design approach by placing the coil of the voice coil motor directly on the piano key. By doing this, the need for bearings or springs is eliminated as the piano key acts as the "bearing," so friction and internal mechanical impedance are eliminated. Flat permanent magnets would surround the coil, which would be placed on top of a pedestal that is on the key. This pedestal also ensures that the entire coil remains inside the uniform magnetic field during the motion to guarantee linearity of applied force. The magnets' base plates are attached to the base through a post. The post can be adjusted vertically to accommodate the height of the black keys. The base moves on two rails that contain several notches, so that the voice coil can reach the depth of the black keys. The magnets are secured in place by locks on the base and post. Since there is no friction or internal mechanical impedance is this concept, the force can be directly calculated from the input current. A disadvantage of this design is that the wire leads from the coil may resist motion. Although the resistance would likely be small, it is unacceptable because it could significantly alter readings due to this devices low-force operating range.

Concept E

This concept, shown in figure 7, also embodies the third design approach of no friction via the voice coil motor. It is very similar to Concept D in that it is composed of two major components, the permanent magnets and the coil. However in this case, the magnets rest on the piano key with the coil suspended by a rigid base. This would produce the same effect as Concept D, with the added advantage that the wire leads would not be able to interfere with the measurements. As a result, this concept theoretically eliminates all sources of friction or motion resistance within the device and will give a pure force reading.

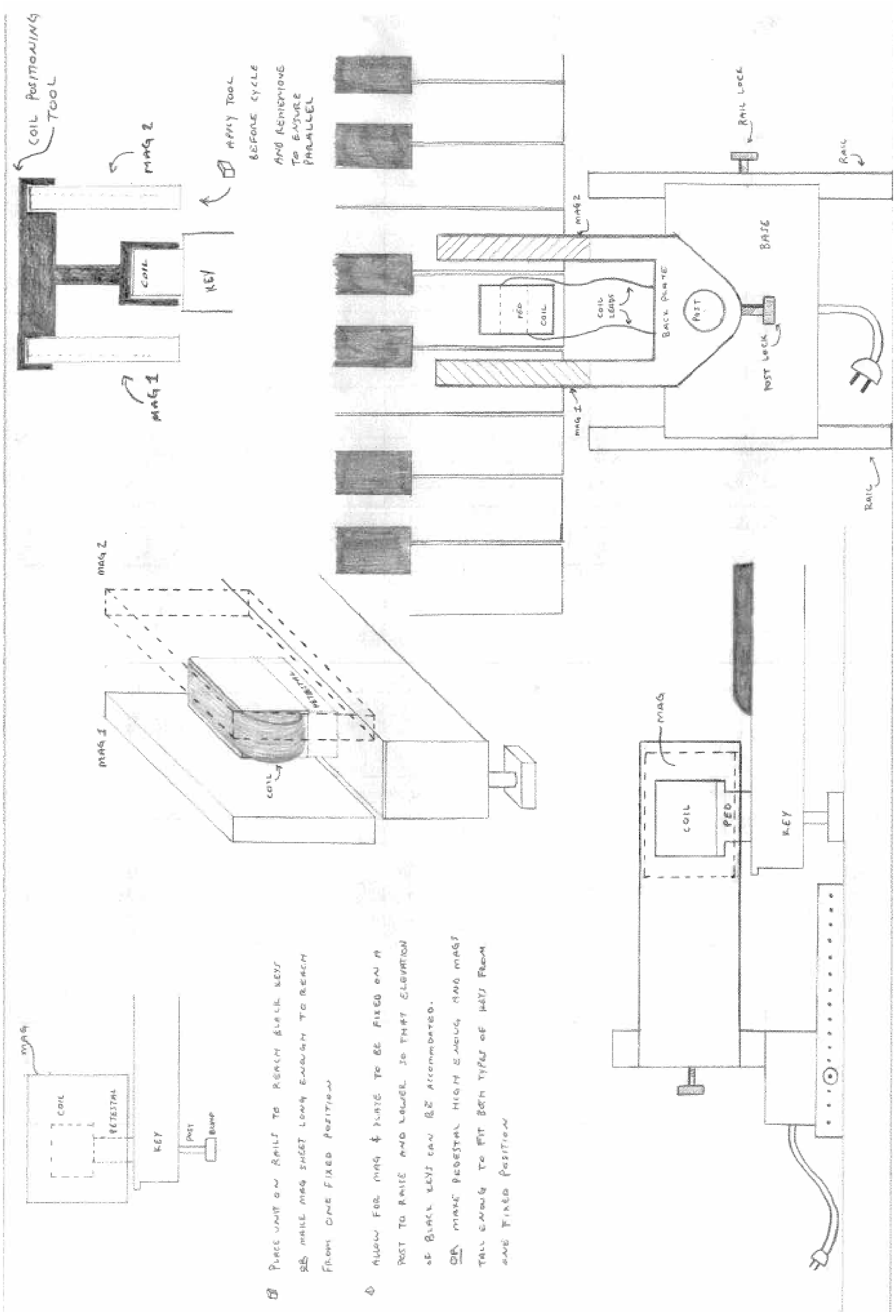


Figure 6: Concept D with coil resting on key and magnets suspended by workpiece.

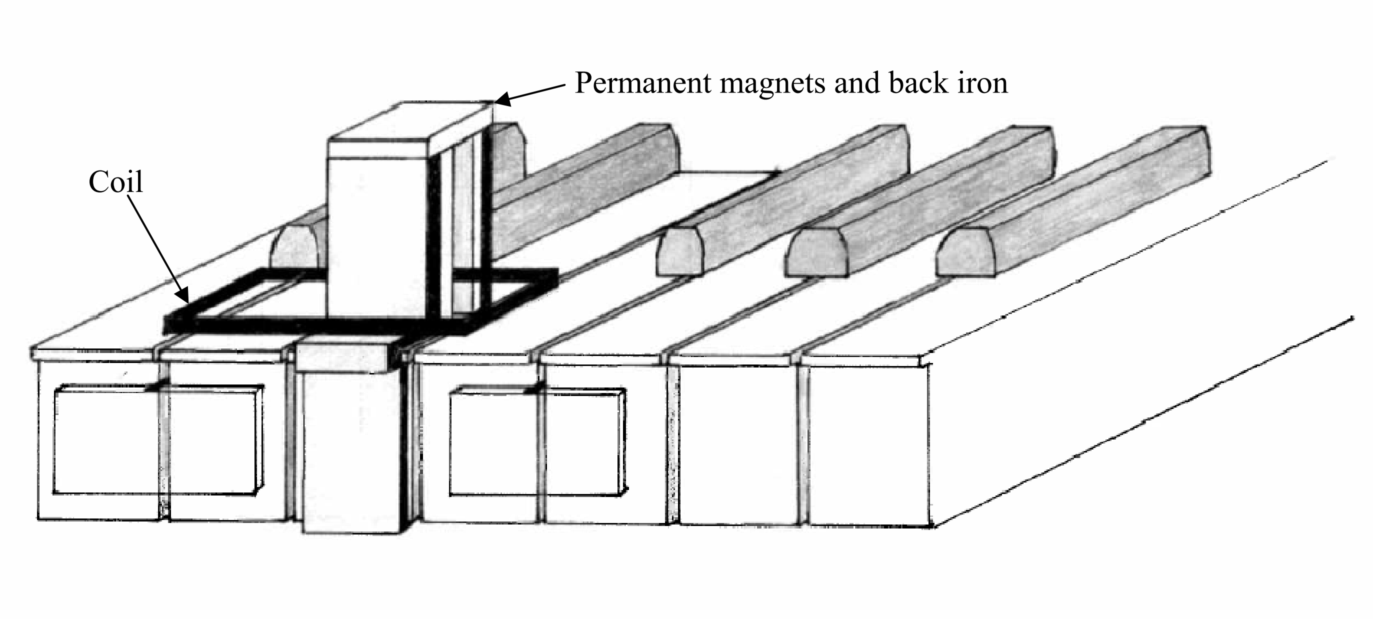


Figure 7: Concept E with permanent magnets resting on key and coil suspended by a rigid base (rigid base suspending coil not shown)

CONCEPT SELECTION

To assist in the selection of possible design concepts it was necessary to determine the advantages and disadvantages associated with each concept. When determining advantages and disadvantages, the focus was on internal friction, internal mechanical impedance, linearity of motion, constancy of force, manufacturability, adjustability, and size. The results of this analysis are shown in Table 3, below.

Table 3: Concept advantages and disadvantages

Concept	Advantages	Disadvantages
A	• Precisely constrains motion of actuator • Simple manufacturing • Compact • Easily adjustable to accommodate black and white keys • Applied force is constant	• Force gauge measurements must be made to account for friction • Strain gauge costly • Nonlinear force
B	• Force characterized by current only • Applied force is constant, linear • Spring support force can be characterized • No internal friction • Easily adjustable to accommodate black and white keys	• Concentricity may be difficult to manufacture • May have inconsistent internal mechanical impedance
C	• Simple manufacturing • No internal friction • Easily adjustable to accommodate black and white keys • Force characterized by current only • Applied force is constant	• Undesired lateral movement in flexure bearing • Nonlinear force • Not compact
D	• No internal friction	• Positioning tool required to

	• No internal mechanical impedance • Accounts for the natural arc in key depression • Eliminates friction at contact point • Easily adjustable to accommodate black and white keys • Force characterized by current only • Constant, uniform magnetic field	center coil • 2-3 main components • More complex manufacturing • Coil leads may resist motion and skew readings • Hall effect position sensors may be affected by existing magnetic field
E	• No internal friction • No internal mechanical impedance • Arc in key depression does not affect force • Eliminates friction at contact point • Easily adjustable to accommodate black and white keys • Force characterized by current only • Constant, uniform magnetic field	• Positioning tool required to center coil • 2-3 main components • Hall effect position sensors may be affected by existing magnetic field

A quantitative valuation method was then used to facilitate the selection of the concept that best satisfied all design requirements. The method chosen is commonly known as a *Pugh Chart*. In this method, each design goal is given a value determined by its importance to the success of the design. Concepts that satisfied the requirement were marked with a "+", those that were neutral received a "0", those that did not satisfy the requirement received a "-". Multiple marks were given to indicate to greater degree satisfaction or dissatisfaction. Valuations for each concept were totaled and properly weighted to reveal a more detailed comparison of how each concept satisfies design requirements. Table 4 shows the results of the *Pugh Chart* method.

Cost is weighted most heavily in the comparison, given three out of a possible three points, because expensive gauges and sensory equipment can be easily purchased, but do not allow the device to be developed or sold at a reasonable price of $200. Market demand for a device such as this is predicted to be fairly low, so manufacturability is only given one point out of three. Size is given two points out of three because it is important that the device fit in the work area where it is being used, but further development of concepts will allows for size to be reduced. Concepts that are deemed practical are those whose function and operation are simple and can easily be understood by an unfamiliar user and will be weighted with two points out of three. As an important requirement of the device to ensure high quality results, precision will receive 3 points out of three. If a device easily incorporates a position sensor, one point out of three will be given because there are many different position sensing devices that could be used in all concepts.

Table 4: Pugh Chart analysis

Design Goals	Weight	Concept A	Concept B	Concept C	Concept D	Concept E
Cost	3	- -	+	+	+	+
Manufacturability	1	0	0	0	-	-

Size	2	0	+	-	+	+
Practicality	2	+	0	0	+	+
Precision	3	+ +	0	0	+	++
Easily incorporates position sensor	2	+	+	+	0	0
Total		+2	+3	+1	+3	+5
Weighted total		**+4**	**+7**	**+3**	**+9**	**+12**

The results of the *Pugh Chart* analysis show that Concept E best satisfies the design requirements and will be considered for further development. Concept D looked second highest with just a small difference compared to Concept E. Due to high cost requirements, Concept A scored relatively low and was eliminated. Concept C scored the lowest and was therefore quickly eliminated.

Further analysis of valuation is given in “Concept Selection” descriptions in Appendix A for Concepts A, B, and C. Concepts D and E are further analyzed in the following subsection.

Concepts D and E

These concepts utilize a flat voice coil in which the permanent magnets with a back iron are held on both sides of a key, allowing the coil to be between the permanent magnets, which acts as the “bearing.” Due to the absence of contact between the coil and the rest of the device, no contact friction will exist in using either device, however in Concept D the coil wire leads may resist motion and cause inaccurate readings since the forces of this device are so low. Concept E resolves this issue by setting the magnets on the key instead of the coil and attaches the coil to the base as shown in figure 8. The wire leads coming off the coil in Concept E do not have an effect on the motion or force reading since they will just be attached to the stationary base.

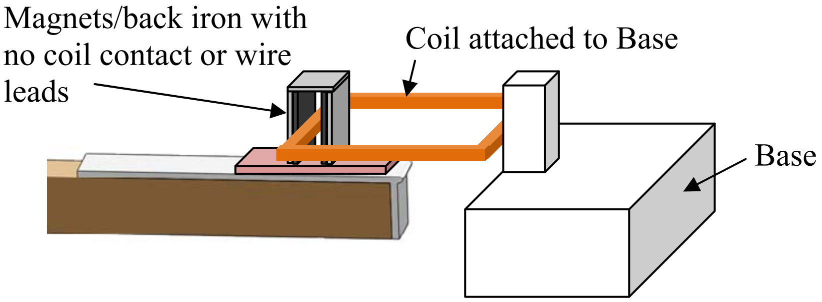


Figure 8: Concept E showing 2 piece frictionless mechanism due to no wire leads resisting motion on key and no contact between magnets and coil

The only negative valuation given to these designs is for manufacturability due to their adjustability on two axes of motion. By necessity, this design must be able to adjust height to accommodate black keys. The only criterion that received a neutral mark was in regard to the position sensor as this concept does not yet include a sure method to measuring the position of the key during travel and will have to be verified after prototyping through experimentation.

Hall effect sensors readings could be distorted by the existing magnetic field from the other permanent magnets and coil. Due to high valuation, this concept will continue to be developed.

FINAL DESIGN CONCEPT DESCRIPTION - FLAT VOICE COIL MOTOR, CONCEPT E

This section provides a description of the alpha design. Figure 9 shows how the voice coil actuator works. It simply uses the basic physics equation $\vec{F} = (I\vec{l} \times \vec{B})N$ in which the permanent magnets create uniform magnet field vectors and the coil (shown in red) passes current perpendicular to the magnetic field thereby maximizing the force magnitude. Since the coil is fixed, it will not move so the magnets/back iron exert an up or down force on the piano key which will only be proportional to the direction and magnitude of current in the coil. Furthermore, the coil never comes into contact with the magnets so the device achieves no friction.

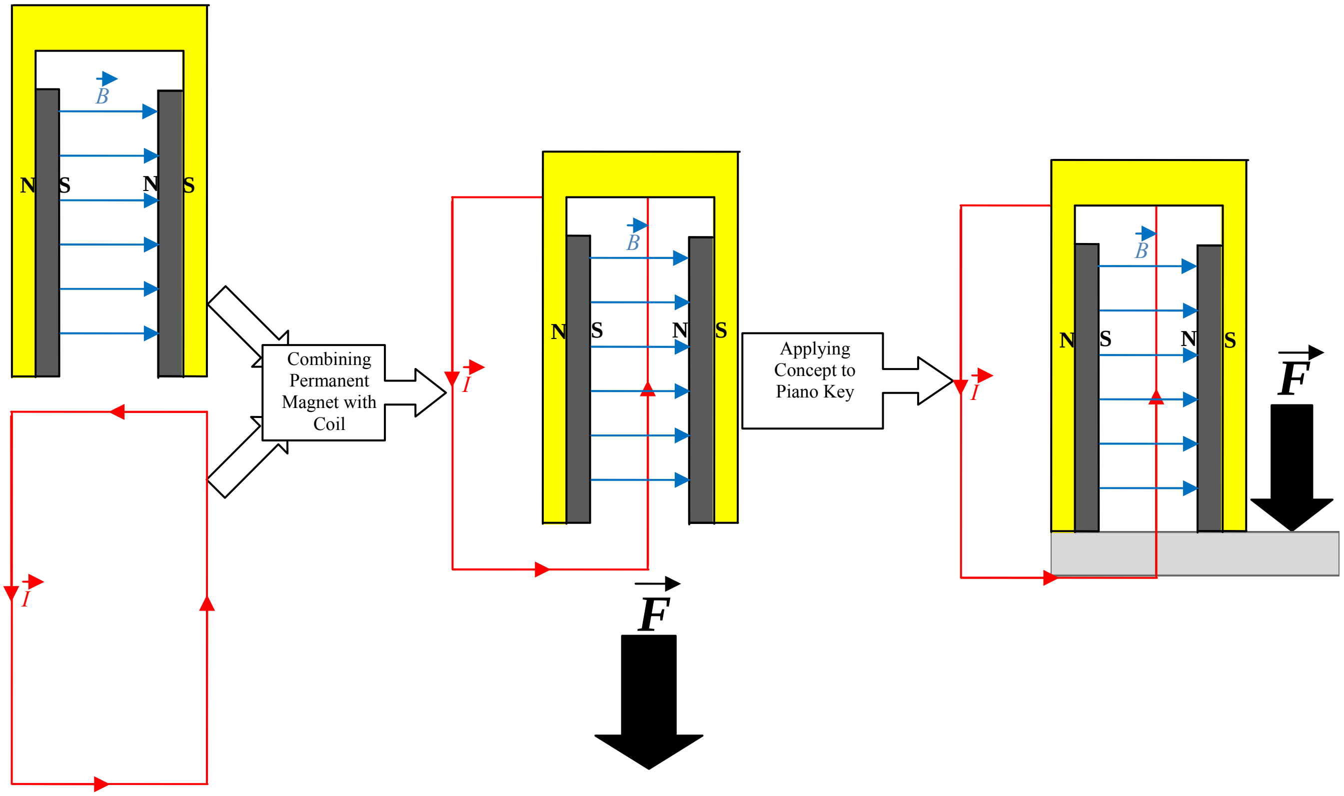


Figure 9: Voice coil force application concept description

PARAMATER ANALYSIS

A detailed description of design analysis is provided which helped assess the required components and dimensions of the design.

Concept Refinement and Parameter Description: Design parameter selection began with analyses of major components from a "big picture" point of view, beginning with force generation. Due to the small forces that are to be measured with this device, an actuation method free from friction and other mechanical impedances was desired to ensure the accuracy of measurement. Thus, the first parameter of design was an actuation method with no internal mechanical impedance. A voice coil motor was selected as a suitable method of applying force to piano keys, which, in its most simple description, is a coil of wires placed between two permanent magnets. Concept generation efforts prior to Design Review 2 focused on a voice coil that allowed for the magnets to be supported by a rigid structure and the coil to be placed directly onto the surface of the piano key so that no other support would be necessary.

The placement of the coil on the key would require loose wires to connect the coil to the power supply, which would move with the coil as the key is depressed and could generate mechanical impedance as well as misalignment of the coil. To avoid this impedance, the concept was changed so that the magnets are supported by the key, and the coil is supported by a rigid structure. The second design parameter was defined in this perspective of using the key to support the magnets: items placed on the key must fit within the surface dimensions of a single (white) key. Therefore, the magnet apparatus can be no wider than the key width of 22.6 mm and should be located in the first 25.4 mm (1 inch) of the key depth from the front edge of the key to allow for weight placement during the balancing process.

In contrast to the current method of measuring up and down weights with gram weights of various sizes, this device will place a magnet of constant weight on the key and vary the applied force by adjusting voltage to the voice coil motor. This means that the output force by the motor must be strong enough to depress keys as well as lift the magnet, thereby introducing another design parameter. Typically, down weight is measured before up weight since the key naturally sits in the "up" position, allowing for weight to be added until the key falls and then taken off until the key rises. The same method can be used with this device by increasing current in small increments until the key falls and then decreasing it until the key rises. However, this method will only work if the constant weight of the magnet apparatus is smaller than that of the down weight. If the magnet is heavier than the down weight then the process must begin by applying current until the key rises and then decreasing it until the key falls again. By the equation $\vec{F} = (I\vec{l} \times \vec{B})N$, we see that greater forces are produced by increasing current, magnetic field strength, or number of wire turns. This directly implies that if a larger force is required these terms can be changed accordingly to achieve the necessary force.

Other parameters on the system design are driven by the amount of heat that is allowed to develop while the device is operating. As current passes through the coil, heat is generated and can be damaging if left uncontrolled. One parameter will therefore be to ensure that the heat generated be kept below the point of causing injury to the user and damage to the product. Circuit controls can be implemented to prevent current from passing when temperature inside the coil reaches dangerous levels. Additionally, sufficiently limiting the heat production during operation will allow the device to operate uninterrupted. Material selection of the coil armature will also influence the affects of heat in the coil as some materials dissipate heat better than other. Therefore, another parameter driven by heat in the coil is the selection of armature material that is highly heat dissipative.

Once the methods of force application and measurement are decided upon, all necessary components that support these methods must be fit together into a single packaged unit. Therefore, the last parameter that must be considered is the limitation of the overall size of the complete device package. The overall package includes the coil, armature, armature support, and base unit. Within the base unit are all of the electronic components, including the power supply, signal amplifier, and processors. When all of these components are placed into their final package, the package must fit on the piano technician’s workbench when the entire keyboard is in its proper position.

Magnetic Field Strength: *Vizimag* was used to obtain the field strength as a function of distance from the top of the magnets (through the center line). A plot of this can be seen in figure 10, below. *Vizimag* shows that the field strength decreases slightly linearly under our operating range. This should be relatively simple to “calibrate out” in our final design.

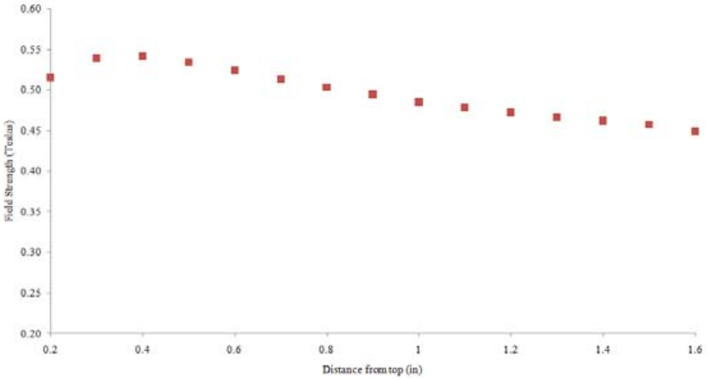


Figure 10: Field strength along centerline of magnets

Vizimag was also used to obtain the magnetic field strength as a function of the total gap between magnets. An example graph showing the field lines can be seen in figure 11. The field strength was given in the *Vizimag* program. By varying the gap between the magnets, and recording the field strength, we obtained a log fit of the curve for use in our analysis. The resulting curve can be seen in figure 12, below. It should be noted that the value taken for each point was the maximum field strength (for example, see figure 10, above).

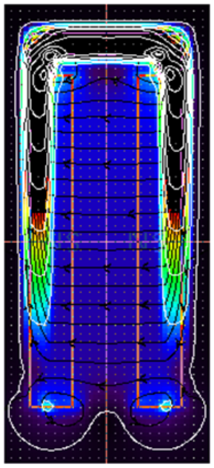


Figure 11: Example *Vizimag* plot

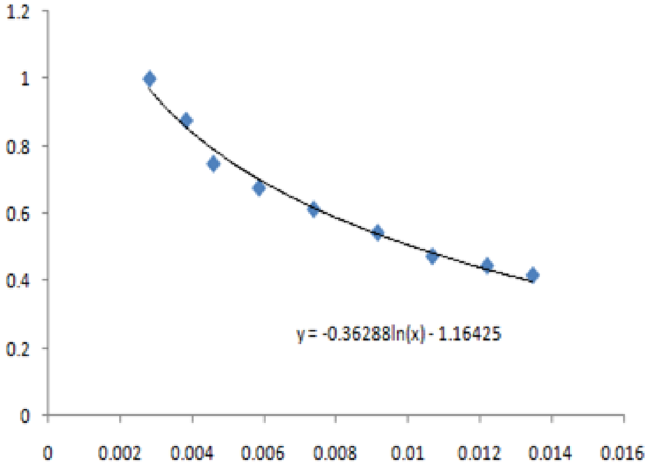


Figure 12: Field strength as a function of gap width

It should be noted that this function and all of our subsequent analysis assumes the magnetic field strength “into the page” is completely uniform. This is likely to not be the case. However, extreme derivations are not expected, and will implement a sufficiently large "force safety factor" to account for this and other unexpected deviations from theory in our design.

Parameter Analysis: Heat Dissipation: As mentioned above, the heat generated during device operation is a primary concern for our project. Thus, the following analysis was performed to minimize heat and maximize force under heat generation and geometric constrains. Basic qualitative experiments determined that the coil should not produce more than 8W, and our customer requirements stated that the base plate should not extend more than approximately 1" from the edge of the black keys. It was assumed that this maximum of 8 W would translate roughly to our final design. After speaking with our customer, we were provided with some leeway (approx ±0.2").

With C, ratio between armature coil cutout height and depth, N, number of turns, l magnet width, I, current, ρ, resistivity, A, wire area, d, wire diameter, Q, heat generated, P, average coil perimeter, and w, armature coil cutout depth.

$$\vec{F} = \left(I\vec{l} \times \vec{B}\right)N \qquad \text{(Equation 8)}$$

$$R = \frac{P\rho N}{A} \qquad \text{(Equation 9)}$$

$$A = \pi d^2 \qquad \text{(Equation 10)}$$

$$\dot{Q} = I^2 R \qquad \text{(Equation 11)}$$

$$N = \frac{Cw^2}{d^2} \qquad \text{(Equation 12)}$$

It was assumed that a reasonable packing efficiency was achieved (one wire was packed into every square the size of its diameter). Higher packing efficiencies could be achieved by laying the wires in the gaps formed from the previous layer. Lower packing efficiencies would result from extra gaps or "passes" not running parallel to previous layers.

Note that the field strength, B, is also a function of w. These equations reduce to the following representation of the heat generation:

$$\dot{Q} = \frac{4\rho P F^2}{\pi C l^2 B^2 w^2} \qquad \text{(Equation 13)}$$

A 3D plot of this result as a function of the force, F, and the armature coil cutout depth, can be seen in figure 12, below. In this graph, C = 1.6, chosen to be reasonable for our design.

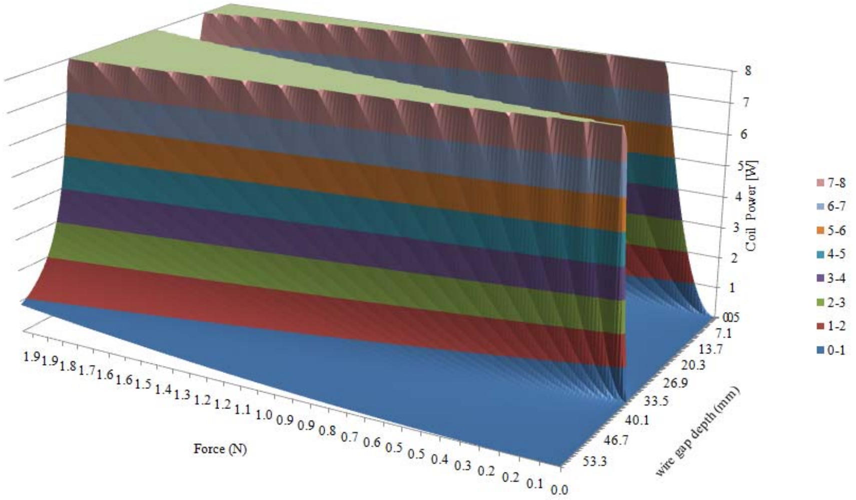


Figure 13: Producible force as a function of cutout depth

As can be seen by the shallow section in the middle, there is a clear optimal value in choosing the cutout depth. As increasing the cutout depth increases the magnet spacing by the same amount, which takes up more space along the key, we are limited to a maximum cutout depth. Limiting the graph to this maximum cutout depth, seen in figure 14, we see that choosing the maximum cutout depth possible maximizes our allowable force output under our specified allowable heat dissipation.

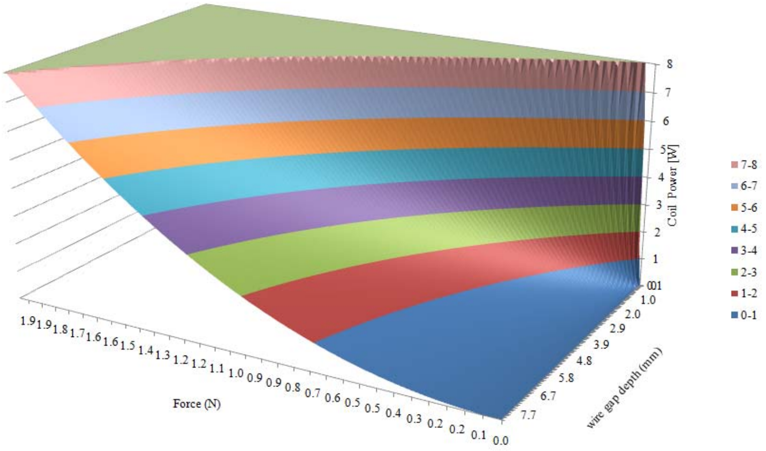


Figure 14: Producible force, limited to maximum allowable cutout depth

Assuming operation under the maximum allowable force output, with this armature cutout depth, and a corresponding average coil perimeter of 119mm, we obtain a result of 775 turns with 27 gauge wire, resulting in a current of 0.54 A. Assuming the: magnetic field strength is consistent with our analysis, a maximum on-key weight of 100 grams, and a minimum up weight of 20 grams (resulting in 80 gram-force of required force), the device is operating under a "force safety factor" of 2.4, and results in a required maximum current of 0.23 A, and a maximum heat dissipation of 1.3 W.

Cambridge Engineering Selector (CES), SimaPro, and Designsafe: These three software programs were used to aid in the selection of proper materials, evaluate environmental impact, and assess potential safety hazards and risks of this device. The most beneficial program was *CES*. We learned that 2024 aluminum was a much better thermal conductivity than wood which is a very important item to minimize in our design. Additionally, we found that AISI 1010 annealed steel was a suitable back iron material since it has a high permeability and low reluctance. *SimaPro* showed us that wood is environmentally much better to use than aluminum. However, since we are using such small quantities of aluminum we determined that was the better choice. Likewise, steel is worse than cast iron environmentally however it has a lower permeability and we need to maximize this quantity so we chose steel. *Designsafe* brought many potential hazards to our attention. For example, high voltage requirements made us design a box around the power supply so the piano regulator cannot touch it and be shocked. Furthermore, we tried to design the prototype with limited extension beyond the workbench so it will not fall off and injure people. More detailed analysis is provided in Appendix E and the Safety Report.

FINAL DESIGN DESCRIPTION

As previously described, the goal of our device is to measure and report the up, down, friction, and balance weights of a piano key, using the interaction between current-carrying wires and magnetic fields known as the Lorentz force. Our device can be broken up into several distinct categories: On-key mechanical components, Off-key mechanical components, and electrical sensors, controls, and power.

A CAD drawing of our design, with the electronic components represented by the big box, can be seen in Figure 15, below.

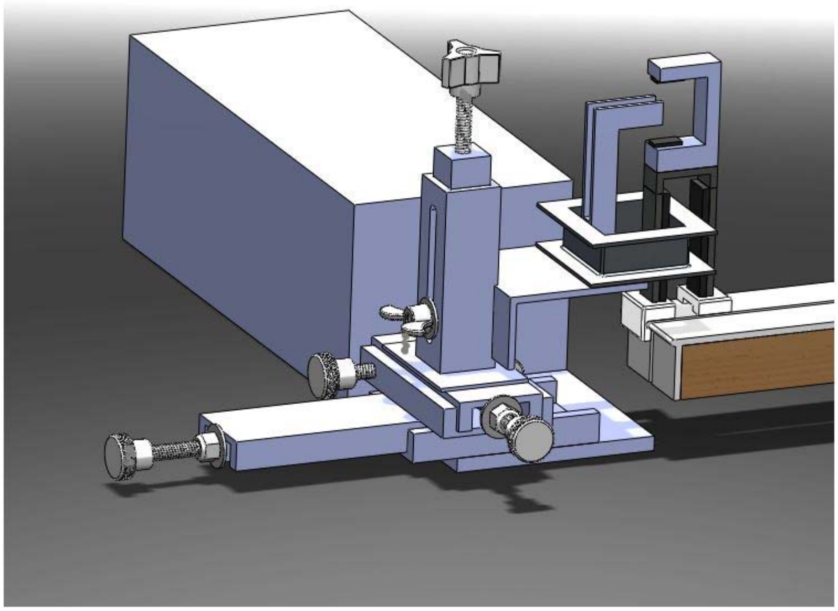


Figure 15: Final design excluding base and electronics.

On-key mechanical components: The on-key mechanical components consist of the base plate, back iron / magnet combination, hall-effect magnet attachment, and hall-effect magnets. The drawings of these components can be seen in figures 16-18, below. The back iron and all components can be seen in Appendix G. The magnets are not shown in these figures. The primary magnets are 2” x 0.5” x 0.125”, and the hall-effect magnets are 0.5” x 0.25” x 0.125”. The function of the base plate is to conform to the key’s shape, and provide a secure base for the primary magnets / back iron. The back iron serves to increase the uniformity of the magnetic field between the magnets. The on-key components move with the key during its motion.

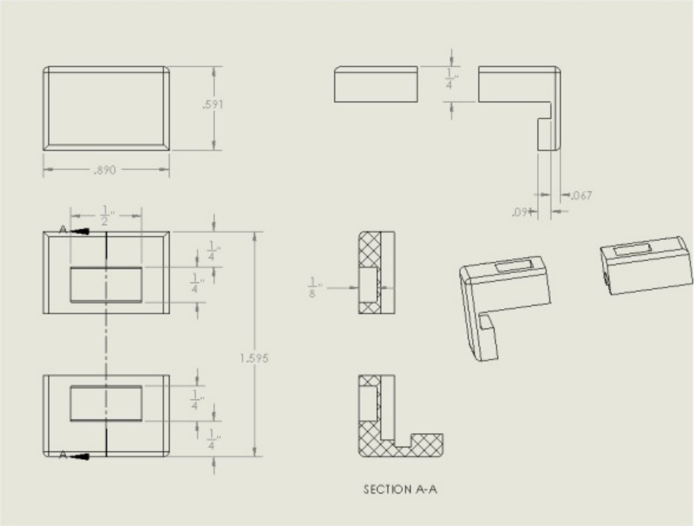
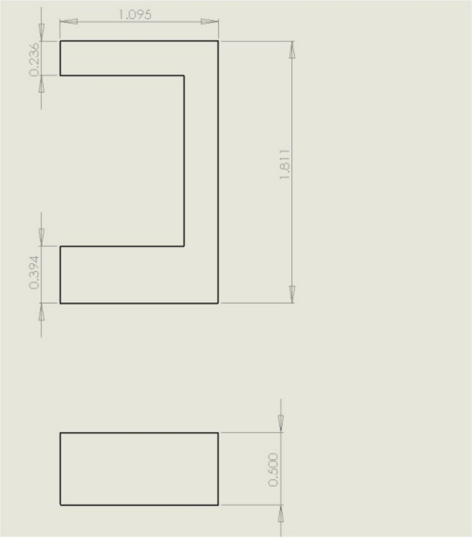


Figure 16: White/black key base plate (epoxy)



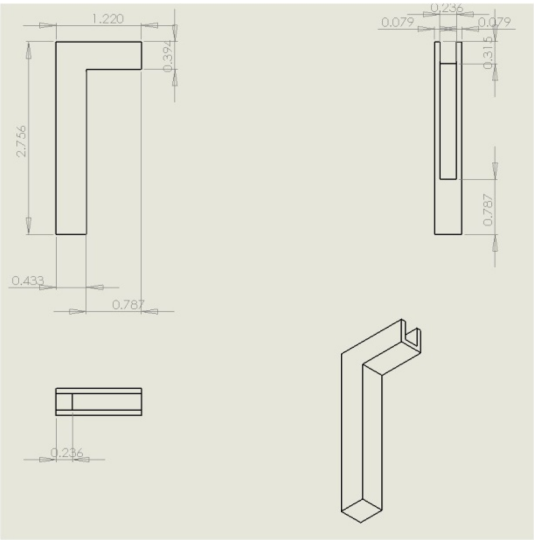


Figure 17: Hall-effect magnet bracket (epoxy) **Figure 18:** Hall-effect bracket (epoxy)

Off-key mechanical components: The off-key mechanical components include the hall-effect sensor bracket, the armature and wire, the base, and the (manual) multi-axial positioning system. The positioning consists of a 3-axis table that was built specifically for this application.

Purchasing such a table is very expensive, so we built a simple table to suit the need of this project. The hall-effect bracket can be seen in Figure 18, above. The off-key mechanical components remain stationary during operation, when current is pumped through the windings around the armature. Using the positioning system, the setup is brought into the correct position prior to operation.

Electrical components – control circuitry: The control circuitry components include the hall-effect sensors, microprocessor, amplifier, and power supply. The purpose of these components is to measure the position and velocity of the key during its travel, and adjust the force provided to the key through the Lorentz interaction accordingly. A TDK-Lambda ZWS150PAF-24 power supply is used in conjunction with an Arduino microcontroller and a PWM signal amplifier to deliver and control voltage to the system.

Electrical components – informational circuitry: These components include the LCD screen, LED’s for alignment, and any interactive buttons / informational LED’s. These components are currently in the selection process.

Calibration: After production but prior to operation the device would be calibrated against a set of known weights to determine the specific devices current-force relationship. This relationship would be stored in memory. The hall-effect sensors are calibrated with their position-voltage output, and this information is stored in memory.

Description of complete device operation: The following is a description of how a typical measurement would be done for a white or black key:

(1) The base of the machine is positioned flush with the base of the keyboard
(2) The armature is positioned to an approximate position over the desired key
(3) The magnet with attached base plate is placed over the armature and positioned on the key surface so that the base plate catches on the leading edge of the key
(4) The multi-axial system is used to fine-tune the position.
(5) The system is powered on. White/black key measurement is selected, position is selected.
(6) Using the dual hall-effect sensors and informative LED lights, it is possible to correctly position the armature.
(7) Position is unselected, and measure is selected.
(8) The microprocessor ramps up the current until the key moves upward.
(9) The microprocessor determines the velocity of the key from the hall-effect sensor output, and controls the current to maintain the velocity, compared against a standard value.
(10) Based on the current input required, the microprocessor determines the up-weight of the key.
(11) The microprocessor decreases current and allows the key to fall, similarly determining the down-weight.
(12) The microprocessor determines the balance weight and outputs this information to the user.

INITIAL FABRICATION PLAN

Similar to other sections in this report, the following section will encompass the initial fabrication plan for the final design by describing each component of the device individually.

With all components accounted for, a description of the final assembly process will also be included.

Machining: The magnet apparatus consists of 2 magnetic plates and a back iron that holds them at a fixed distance apart. The magnets are 2 x 0.5 x 0.125 inches and are purchased from *K&J Magnetics, Inc*. The back iron is machined from a piece of 0.5 inch mild steel, first cut to a 6.125 x 3.125 inch size using a band saw at 85 ft/min. Using a 0.625 inch four-flute end mill at 397 revs/min, 0.0625 in. will be taken off the top and bottom to level both sides and leave 6 inches in height. The same process will be applied to both sides of the work piece until they are level and it is 3 inches wide. Although the back iron will end up being much smaller than this, the extra material is used to provide rigidity to the work piece when the gap area is machined out of the center. Without extra material while machining the gap space, the force of the vice will flex the gap closed, causing too much material to be removed from the lower area of the gap walls. Therefore, the next machining operation is to use a 0.25 inch four-flute end mill at 993 revs/min and machine a 0.845 inch wide gap in the center of the work piece that will extend 2.25 inches up from the bottom. Once the gap is completely machined, 3.25 inches of material can be cut off from the top and 0.75 inches off both outside walls using the band saw. This will put the work piece closer to its final dimensions so the finishing milling process does not take very much time to complete. Finally, a 0.625 inch mill bit will be used to mill 0.192 of material from both sides of the work piece and 0.25 inches off the top of the work piece. After the milling processes is finished, all edges of the work piece will be sharp and have burrs that should be filed until safe and smooth using a hand file. Once all machining is finished, the back iron will be painted and the magnets can be inserted in the back iron gap space so that opposite poles of the magnets are facing each other with the bottom of the magnets aligned with the bottom of the back iron. See figure G1 in Appendix G.

Material selection for the coil armature was based on the strength and heat dissipation qualities of different materials. Using *Cambridge Engineering Selector*, commercial-purity aluminum showed the best compromise between strength and heat conductivity, which was selected to be the armature material. From a 0.75 inch thick sheet of commercial aluminum,0.0625 inches are taken off the top and bottom surfaces to bring the block to proper thickness. Then a 2.5" x 2.5" piece is removed using a band saw at 375 ft/min. Using a 0.625 in. two-flute end mill running at 1200 revs/min, 0.25 inches are removed from all four sides of the rectangle so that final dimensions of 2.25" x 2.25" are achieved with level and parallel sides. A 1.4375" x 1.4375" rectangle will be removed from the middle of the armature, which will leave a 0.75 x 0.375 rectangular portion at the front of the armature to be inserted between the magnet plates. Along the entire perimeter of the armature, a 0.5 inch thick and 0.3125 inch deep trench will be machined out of the side edge using a 0.5" two-flute end mill at 1000 revs/min to provide space to wrap the coil windings. The coil will be comprised of 775 turns of 27 gauge magnet wire. Two 0.0625" holes are drilled into one of the back corners on the top surface to allow for the leads of the coil to reach away from the armature safely. Once the magnet wire is wound and enough length is left for each lead, epoxy is used as potting around the coil trench to protect the coil from damaging contact. See figure G6 in Appendix G.

A base plate that attaches to the magnet and back iron is then made to ensure that the magnets sit at the appropriate distance from the edge of the keys and remains stable during the motion of the key. This plate is made from a a block of PVC as shown in figure G5 and the bottom is milled out to leave a small lip at the front which will be used to align the magnet on the white keys. All milling is done with a 0.125” two-flute end mill at 600 revs/min. Two slots that are sized to fit the legs of the magnet and back iron are machined 0.25” deep at the appropriate spacing with the first slot 0.03125” in from the front edge and centered along the length of the plate. In the center of the bottom surface of the plate a 0.4” x .125” trench is made down the entire length of the plate. This trench fits snugly over the surface of a black key and will be used to maintain stability of the magnet when it rests on the black key. In order to contour the sloped face of the black keys, an actual black key was taken and tape was placed over its sloped front. The base plate was placed on top of the key, the two were turned upside down, and epoxy was poured over the area of the trench that came to the front of the key, thus providing a sloped surface to make contact with the sloped key face. After the epoxy is cured, a band saw is used to cut the plate into two pieces by cutting 0.03125 inches to the center of the inside edge of each magnet leg slot. This leaves two pieces that can then be glued to its respective leg using epoxy.

Attached to the top of the back iron will be a “C” shaped bracket that will hold the magnets used in the Hall Effect sensor. The bracket is started by cutting a 1.095” x 1.811” x 0.5” block of PVC on a band saw. Using a 0.125” 2-flute end mill, a (1.181” x 0.859”) cavity is removed through the entire width of the bracket, giving the bracket its “C” shape. This cavity is started (Z”) from the bottom to ensure that the magnets of the Hall Effect sensor are far enough away from the voice coil magnets and back iron that they will not interact and produce false readings in the sensor. See Figure G11 for a dimensioned figure of this component.

The Hall Effect sensor will be fixed to separate bracket that attaches to the Z-axis table. This bracket will be machined from commercial aluminum so that it will be rigid and will not disturb the magnetic fields of either the Hall Effect sensor or the voice coil motor. This bracket will be built in the shape of an upside down “L” so that the sensor can reach into the space between the two Hall Effect magnets. Starting with a block of aluminum, material will be removed as shown in figure G12 from the bottom right corner using an 0.125” 2-flute end mill to leave the basic “L” shape. A 0.315” deep trench is machined out of the top and half way down the back of the “L” so that the sensor and its wires can be placed in the trench and potted for protection.

The 3-axis positioning system consists of 3 separate linear movement tables in the X, Y, and Z dimensions. The X-axis table is composed of three main parts: table, base, and lead screw. The table is machined by cutting a block of commercial aluminum on a band saw at 275 ft/min. The edges are made square using a 0.625” 2-flute end mill at 1200 rev/min, bringing the block to final dimensions shown in figure G4. The bottom surface of the table will interface with the base, so a cavity is removed shown in figure G4. This block was drilled with a #8 drill bit at 800 revs/min and threaded with a ¼-20 tap. This block receives the lead screw so the table can slide across the surface of the base. The base shown in figure G2 is started by cutting a block of commercial aluminum on a band saw and brought to the final dimensions using a 0.625” 2-flute end mill at 1200 revs/min. The top of the base interfaces with the table, so a cavity is removed from the surface except for two blocks that are centered at either end of the table. These blocks are drilled through their center with a 0.25” inch drill bit at 800 revs/min and will act as the support for the ends of the lead screw. The lead screw is 8” of ¼-20 threaded stock and is run through the length of the table so the extra length protrudes only from one side. At both ends of the lead screw where they exit the table a 7/16 ¼-20 nylon-insert locking nut is threaded until snug after a nylon washer is slipped over the end. These nuts prevent the lead screw from traveling through the base. A brass knob is attached to the long end of the lead screw that gives leverage to drive the lead screw.

The Y-axis table is composed of three main parts: table, base, and lead screw. The table is machined by cutting a block of commercial aluminum on a band saw at 275 ft/min. The edges are made square using a 0.625" 2-flute end mill at 1200 rev/min, bringing the block to final dimensions shown in figure G4. The bottom surface of the table will interface with the base, so a cavity is removed shown in figure G4. This block was drilled with a #8 drill bit at 800 revs/min and threaded with a ¼-20 tap. This block receives the lead screw so the table can slide across the surface of the base. The base shown in figure G3 is started by cutting a block of commercial aluminum on a band saw and brought to the final dimensions using a 0.625" 2-flute end mill at 1200 revs/min. The top of the base interfaces with the table, so a cavity is removed from the surface except for two blocks that are centered at either end of the table. These blocks are drilled through their center with a 0.25" inch drill bit at 800 revs/min and will act as the support for the ends of the lead screw. The lead screw is 8" of ¼-20 threaded stock and is run through the length of the table so the extra length protrudes only from one side. At both ends of the lead screw where they exit the table a 7/16 ¼-20 nylon-insert locking nut is threaded until snug after a nylon washer is slipped over the end. These nuts prevent the lead screw from traveling through the base. A brass knob is attached to the long end of the lead screw that gives leverage to drive the lead screw.

The Z-axis table is comprised of several parts: shaft, tube, base, table, and knob. The square shaft shown in figure G9 is a solid piece of commercial 2024 aluminum that fits inside the square tube shown in figure G10. Using a 0.25" drill bit, a hole is drilled through the thickness of the slide. A 0.25" slot is cut down the center of the front and back of the tube at 0.5" from the top and bottom of the tube. The table is made from a piece of 90° angled aluminum shown in figure G7. To coordinate with the holes in the slide and tube, a 0.25" hold is drilled through the center of one side of the table so that to protruding side is above the side butted against the tube. The table will slide up and down the height of the tube, so a 0.0625" deep groove as wide as the outside of the tube is machined along the side of the table that received the hole to guide the motion of the table during motion. With all of the 0.25" holes aligned with the slots in the tube, a 3.5" ¼-20 piece of stock is slid through all. The side of the screw protruding from the table receives a locking nut that wedges against the top of the table and prevents the table from tilting. The end of the screw that protrudes from the back of the Z-axis table receives a nylon washer, a metal washer, and a wing-nut for hand tightening and loosening. The center of the top surface of the slide receives a #8 hole that is threaded with a ¼-20 tap, into which a 2.5" piece of stock is threaded and topped with a plastic knob. This will serve as the handle for pulling up on the table. Finally, a base plate for the table is made by cutting a piece of aluminum and removing material from the surface to leave a square that the bottom of the tube fits tightly around as shown in figure G8. The tube is fixed to its base using epoxy, thus completing the Z-axis table.

The last remaining component of the final design that requires fabrication is the body. An acrylic base was made using 0.224" thick acrylic. Also, the power supply was enclosed by a box 3.5" in depth so it fits on the workbench. Cutting was performed with the laser cutter using *Solidworks* and a program that is compatible with the laser cutter called *BobCAD.* In this program, each piece of the body will be draws and will include all features that will be machined, including

Assembly: Assembly begins by first fastening each electronic component to the inside of the body. With all circuitry double checked, the walls of the body can then be assembled except for the top sheet, which will be fastened into place at the same time as the armature. The LCD screen will then be fastened to the surface of the top body sheet after all the walls are brought together with 6-32 screws.

The magnet configuration should then be assembled using the two plate magnets, back iron, Hall Effect sensor bracket and magnets, and base plates. The magnets should be fixed to the inside of the back iron gap space so that the surfaces of the magnets that face each other are of opposing poles. They will be permanently fixed using epoxy. The Hall Effect sensor bracket should then be fixed to the outside of the back iron using epoxy. Only non-ferrous materials can be used to attach the Hall Effect bracket so that the magnetic field of sensor magnets is not altered. Once the bracket is fixed, the sensor magnets can be adhered to the bracket. When the device is in use, either a white or black key base plate will be placed under the magnet after the coil is aligned. This step in the assembly will actually be performed each time the device is used, but should be noted in this section.

Next, 600 turns (775 originally but only 600 fit) of 27 gauge magnet is wrapped inside the perimeter ditch of the armature. Plenty of lead length should be left on both ends of the coil are attached to the power supply inside the body. The armature can now be glued to the top of the Z-axis table, and the wires for the coil and Hall Effect sensor can be connected to their appropriate places in the circuit. Once the wires are connected, they can be potted into the Hall Effect sensor bracket after the bracket is glued to the surface of the Z-axis table, on the inside of the rear wall of the armature.

The armature and Z-axis table assembly are then placed on top of the X-axis table so the base of the Z-axis can be glued to its surface. The Z-axis base is pushed forward (toward the keyboard) to allow for the maximum reach over the end of the X-axis table.

The armature, Z-axis, and X-axis assembly are then placed on top of the Y-axis table to the forward most edge of the Y-axis table where they are glued together. With all of the adjustable components together, they are all placed on top of the extension of the box floor and is glued I place. The front edge of the Y-axis base is positioned inside the edge of the acrylic box floor so that the edge of the box can be pushed up to the edge of the key board and serve as the horizontal alignment datum.

Finally, all wires that lead away from the device and into the box are collected inside of shrink-wrap tubes and heated to keep the wires in a single bundle, thus preventing tangling and potential damaging.

VALIDATION RESULTS

To validate our design and analysis, the following experiments have been performed to characterize the design and compare it to our initial analysis and assumptions.

Heat output: During lab testing, the device was operated at its highest output voltage for an amount of time that is much greater than what is expected of it during typical operation. The voltage to the coil was cycled to the maximum positive and negative values for approximately 30 minutes uninterrupted, after which time the coil was determined to be in a warm state that is not damaging to the device or harmful to human contact.

Maximum force: Considering the maximum heat output mentioned above, the maximum force produced was measured using a simple scale. We measured the force to be 81.1 grams which is under the 192 grams we designed for, but this was done using a conservative signal strength so more in-depth validation should be done. 81.1 grams is still enough necessary force to regulate piano's so we are fortunate to have designed with a large "safety factor."

Geometric constraints: To verify that the prototype met all geometric constraints, it was taken to the workshop of Professor Grijalva and was set up on his workbench in front of a keyboard placed in the repair position. The device was then moved through all required movements and adjustments to verify that it fit geometric constraints of the workbench through all prescribed procedures.

Electronics Package: At this point, the device is responsive to a programmed adjustment of voltage provided from within the Arduino microcontroller. Lab testing has shown that the force output by the device is directly responsive to the varied voltage by the microcontroller in both magnitude and direction but does not maintain a constant velocity since the Hall Effect sensor has not yet been incorporated into the control circuit. Also, without an electronic display incorporated into the circuit, the device is not yet capable of displaying weight values. Essentially, the device is fully capable of its mechanical requirements, but is not yet properly configured to be fully controlled by the microcontroller.

Safety: Safety issues with the device focus on heat generated in the coil, exposure to circuit components, and pinching between magnets. During lab testing and workbench testing with Professor Grijalva, use of the device was determined to be safe with regards to heat and circuit exposure. Use of the device at the maximum voltage proved to be of little concern and the acrylic case in which the power supply was contained proved to be very effective protection. While no failure analysis regarding magnet separation was made in lab or workbench testing, it was proven during assembly that when the magnets are separated from the back iron or are jolted, they tend to attract quickly to the back iron due to magnetic attraction. This behavior shows itself to be quite good and suggests that if the magnets were to separate or shatter that they would quickly collect themselves on the back iron.

Aging: Calibration of the device has not yet been complete, therefore no determination regarding the affects of age on the accuracy of force readings have been made at this time.

DISCUSSION

This section discusses the strengths, weaknesses, and suggests improvements for future designs.

Strengths: The highlight of this design is its ability to actuate white and black piano keys using a frictionless voice coil motor, in contrast to the several previous prototypes that proved to be unsuccessful due to the presence of mechanical impedances within the device and its functions.

Although this device does not yet satisfy every customer requirement, its development has overcome the main challenge of producing a device that can: actuation of piano keys without any kind of mechanical impedance introduced by the device. Through careful design and analysis, linear and consistent forces can be produced by the device, which only require calibration of the output force to an input voltage to deliver gram force measurements. This ability is crucial to the success of the device as an accurate and precise measurement tool.

This device is also capable of adjusting the armature position in three dimensions to accommodate any kind of keyboard on any workbench. While a simple method of adjustment would be to create elevation platforms that can be placed under the device and removed when necessary, we included simple adjustment tables in three dimensions that can be easily manufactured and will accommodate any keyboard.

Weaknesses: Since every aspect of this device has not been finalized and tested, we can only critique the portions that are done and have been verified. Currently, the mechanical functions of the device required to actuate piano keys have been verified to work properly. Although frictionless actuation has been achieved, there are some improvements that can be made to ensure repeatability and ease of use. The first improvement to be considered is the stability of the magnet on the key surface during its upward movement. The weight of the magnet exceeds that of any key's down-weight, causing the key to begin each cycle in the "down" position. This requires that the coil be used to pull the key upward to measure the up-weight. Pulling the magnet upward, noting that it is not fastened to key surface, causes the magnet to tilt toward the armature when the current increases faster than the upward key movement can support the magnet. This behavior is undesirable as it would require more time to cycle slowly and restart cycles.

Another possible improvement lies in the design of the magnet's base plate. The current base plate design is comprised of two separate parts that are permanently attached to each foot of the magnet. This plate is preferable because it accommodates both white and black keys, but is slightly unstable when sitting on the black keys. Due to the lack of surface are that protrudes above the surface of the white keys when the black keys are depressed, stabilizing the magnets on the black keys is very challenging. With some improvement its features can be made to perform better.

RECOMMENDATIONS

Better performance of this device can be achieved by implementing some recommended adjustments to its functions. The first recommendation for improvement is to slightly redesign the sizes of the magnet, back iron, and armature to allow for a lighter magnet and back iron. The importance of reducing the weight of the magnet and back iron is shown by the way it will change the order in which the up- and down-weights will be measured. As previously mentioned, the excessive weight of the magnet and back iron keeps the key in a naturally depressed position and demands that the coil be used to pull the magnet upward, causing issues of instability. If the weight is reduced to the point that the key sits in a naturally elevated position, then the force produce will be used to push the magnet against the key surface, thereby providing stability during movement. Using this method, the input voltage will only need to be reduced to bring the key back to the starting position so that the force generated will always be in the down position, thereby maintaining stability of the magnet on the key.

In regards to the unfinished aspects of this design, specifically the functions of the control circuit, there are several improvements that can be made to their intended functions. After speaking with Professor Grijalva and his associates, it has been made clear that this device has great potential to be a diagnostic tool during the balancing and regulation processes. The ability of the device to measure the travel distance of the key means that it can be used to measure not only the stroke distance traveled during the balancing process, but it can be used to measure full stroke distances, including "after touch" distances. Knowing these values aids the regulation process by introducing fast and accurate measurements.

CONCLUSIONS

Our goal with this project is to develop a product to reduce piano regulation time. To do this, we have developed a method which analytically is reproducible, has a resolution of 0.5 gram-force, and experiences no or negligible friction to avoid inconsistencies, complex characterization, and maintain a high level of precision.

We chose a force-application method which uses a voice-coil motor due to the linear force-current relationship and high likelihood of eliminating friction. From this we chose to use a flat voice coil motor with the permanent magnets resting on the key and the coil suspended by a base. We have verified that the device mechanically functions according to expectation, is of low safety hazard, and can be easily manufactured. With no time left to develop the electronic aspect of the device, we have prepared a list of needed improvements before the device can be released.

Our next steps are to:

- Complete the design of feedback control circuit
- Include Hall Effect sensor
- Generate operational programs for microcontroller
- Calibrate prototype

Aside from delivering an autonomous device that is capable of automatically cycling and displaying up-, down-, balance-, and friction-weights, we have achieved our goals by designing and manufacturing a device that is mechanically capable of actuating piano keys with a frictionless voice coil motor.

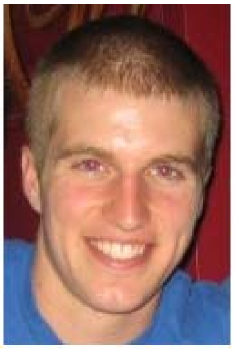
REFERENCES

[1] Dupont, Pierre E. "The Effect of Friction on the Forward Dynamics Problem." *International Journal of Robotics Research*. 12.164 (1993): pp 164-179.

[2] Craig T., Johnson. "Experimental Identification of Friction and Its Compensation in Precise, Position Controlled Mechanisms." *IEEE Transactions on Industry Applications*. 28.6 (1992): pp. 1392-1398.

[3] Stanwood, David C., 1996, “Methods for Inertial Balancing of Piano Key Mechanisms,” United States Patent, Patent Number 5585582.

BIOGRAPHIES



David Boehmer

I am a senior Mechanical Engineer from Marshall, MI graduating in April 2010. Throughout my life, I have always had a strong interest in math and science so I decided to become an engineer. I chose mechanical engineering because I have very diverse interests, enjoy large systems, and working with my hands. Upon graduating, I will be working in Seattle on naval ships and submarines. I really enjoy IM sports and unfortunately, have little experience or knowledge about pianos. However, this problem seems challenging and I am excited to use my creativity and technical knowledge to help design a marketable and functional product.

Phil Eklem

I am a senior Mechanical Engineer from Dearborn, MI. I plan on graduating in May 2011 with a concentration in manufacturing and a minor in mathematics. I chose to pursue mechanical engineering because it fits my generally analytical perspective and mechanical inclinations while also providing broad career options. I am a very hands-on learner and worker, but I also enjoy the logical and theoretical aspects of engineering in general. My post-graduate intentions are to either be working or attending graduate school for either engineering or patent law. I have some experience playing the piano and I am eager to apply my knowledge and perspective toward developing a useful product.

**Vijay Venkataraman**

I am a senior Mechanical Engineer from Princeton, NJ with a concentration in energy and a minor in mathematics. Upon graduating in May 2010, I will either immediately pursue a Masters in Mechanical Engineering or Energy Systems, or enter industry with the hope earning my Masters a few years down the line. My primary interest is alternative energy, and I choose Mechanical Engineering because of its prevalence in the design and manufacturing process of various alternative energy approaches. Though I am not very knowledgeable on pianos, I am very eager take on this unfamiliar challenge because I feel that I will learn a great deal about mechatronics, controls, and programming, which will be very useful for me in my future.

**Michael Werries**

I am a senior in Mechanical Engineering originally from Midland, MI. I have a strong passion for Mechanical Engineering and enjoy the combination of theoretical and hands-on experience that Michigan allows. After graduating in May of 2010, I plan on either continuing at Michigan for my Masters in Mechanical Engineering, or working in industry for a few years before returning for Graduate school. My primary interests are robotics, power generation, combustion engines, and turbines. I am excited about our project as it will provide an interesting and challenging opportunity to gain more experience in mechatronic systems and controls beyond the level offered in our current coursework.

APPENDIX A – Initial Concepts

Concept A

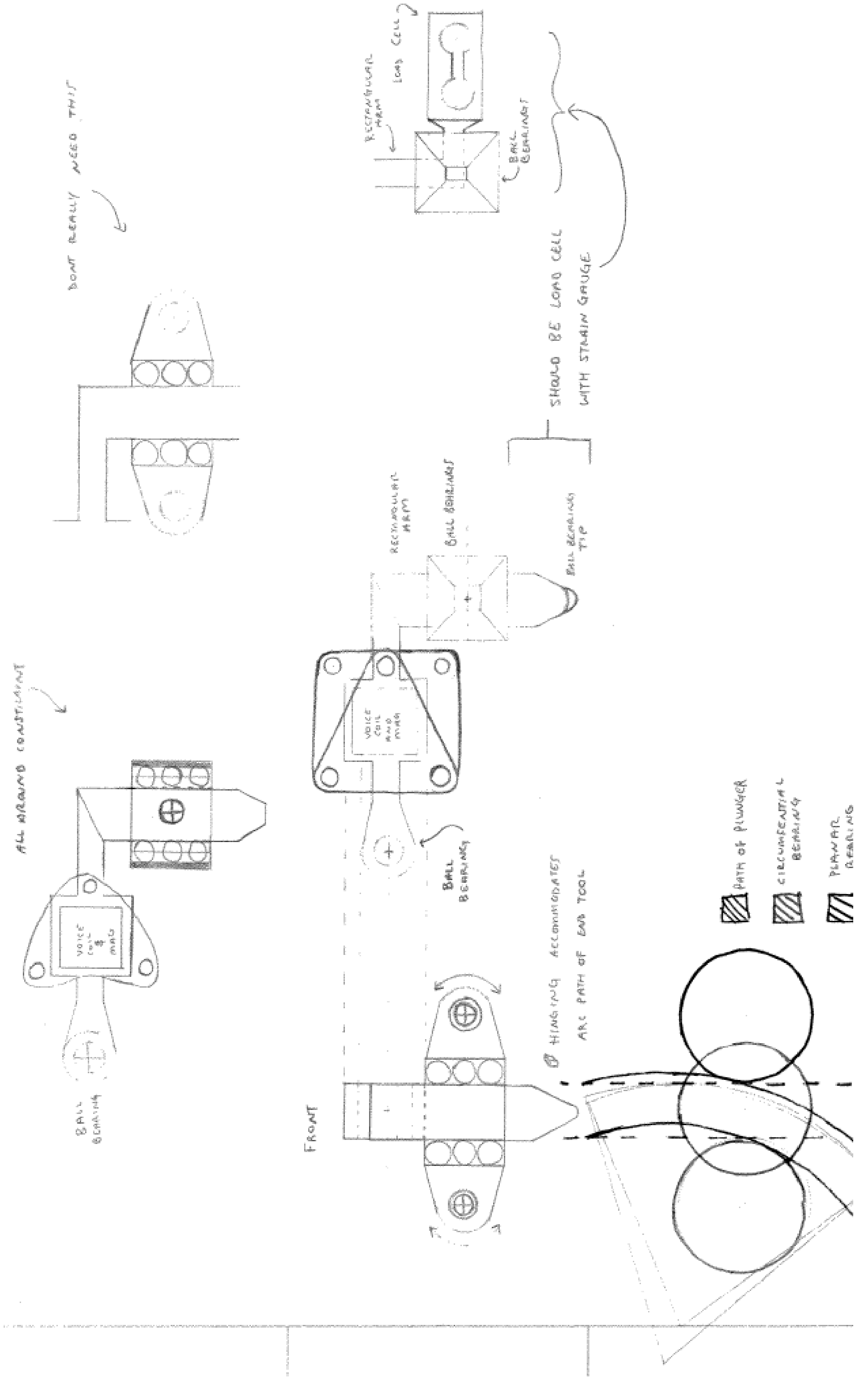
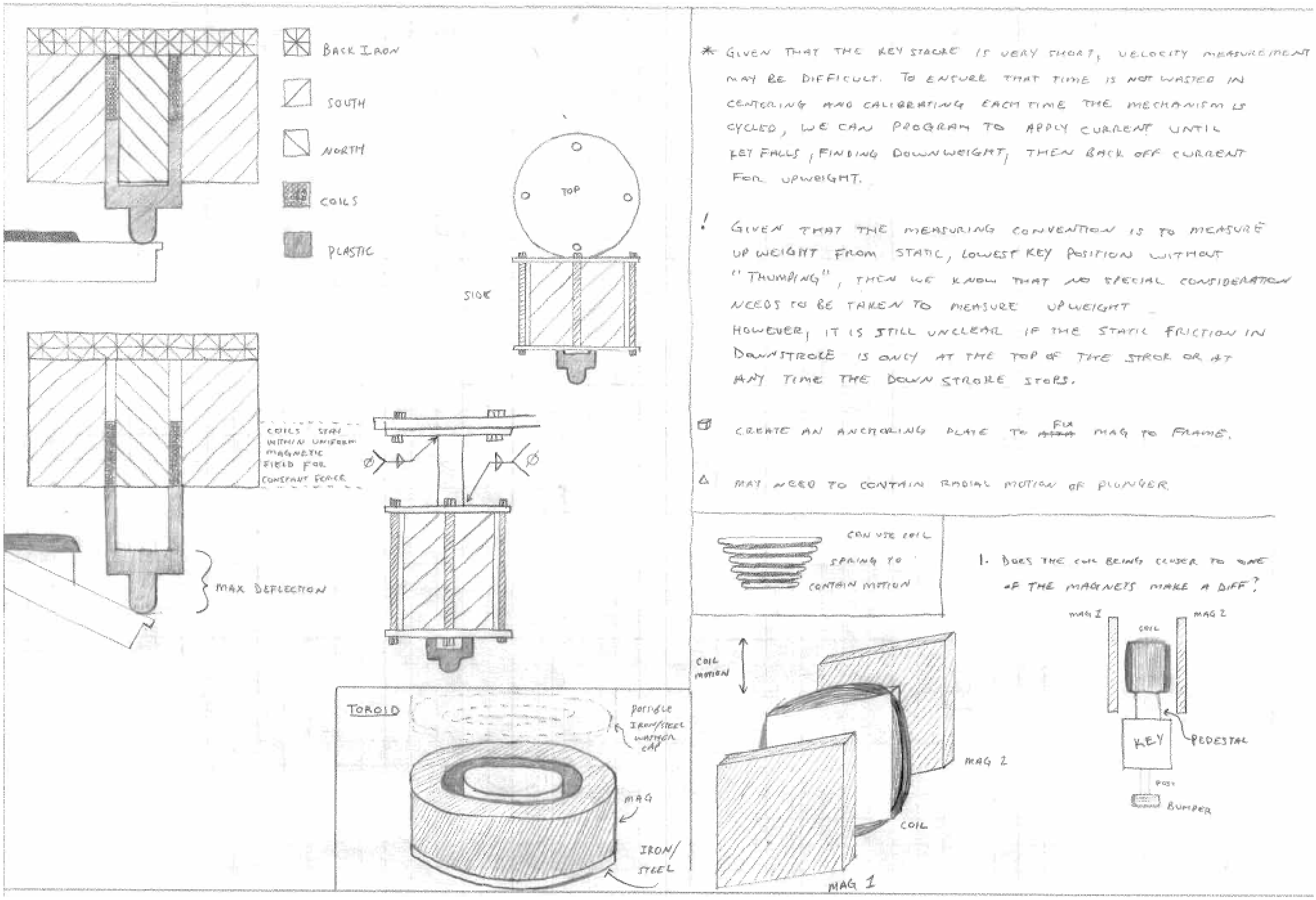


Figure A1: Concept A using first design approach, contact bearings/bushings

Description: Concept A embodies the first design approach by utilizing contact bearings to support and stabilize the actuator. A circular ball bearing is incorporated at the pin support of the actuator arm. The square hole half way down the actuator arm houses the coil that, when energized, interacts with the permanent magnet, represented by the triangular outline. A square outline is also included in one of the iterations to signify the possible use of a square magnet. Although only one is shown in the drawing, two magnets will be required; one on each side of the coil. Below the ninety-degree bend in the actuator arm, another bearing is implemented to prevent lateral motion of the arm. One type of bearing configuration uses a cylindrical ball bearing that hinges at the center of its length, allowing for the tubular arm to move in a circular path. Since undesired motion only occurs in the lateral direction, another configuration shows the use of two independently mounted ball bearing sheets or strips that are positioned on both lateral sides of the vertical portion of a rectangular arm. The use of two separate bearings reduces friction by only contacting the arm at the lateral sides, whereas the cylindrical bearing contacts the entire surface area of the arm. The end of the actuator arm, which contacts the piano key, is shown in multiple configurations as well. The first configuration utilizes a ball bearing tip to reduce the friction associated with the circular path of the arm striking the flat surface of the key. However, allowing friction in the system means that the input current will reflect forces needed to overcome friction as well as push the key, thereby yielding inaccurate results. To eliminate this problem, another configuration of the end of the arm replaces the bearing tip with a load cell that measures force with a strain gauge.

Concept Selection: The main factor leading to the elimination of this design concept was its cost requirement. Incorporating the use of multiple bearings meant that contact friction would exist within the mechanism, which is inconsistent and difficult to account for and quantify by measuring input current to the motor. Therefore, this design utilized a load cell with strain gauges to measure the force applied by the device at the point where it contacts the key. While this method is highly accurate and unaffected by inconsistencies of friction, it is very costly to acquire load cells with properly mounted strain gauges.

Concept B



* GIVEN THAT THE KEY STROKE IS VERY SHORT, VELOCITY MEASUREMENT MAY BE DIFFICULT. TO ENSURE THAT TIME IS NOT WASTED IN CENTERING AND CALIBRATING EACH TIME THE MECHANISM IS CYCLED, WE CAN PROGRAM TO APPLY CURRENT UNTIL KEY FALLS, FINDING DOWNWEIGHT, THEN BACK OFF CURRENT FOR UPWEIGHT.

! GIVEN THAT THE MEASURING CONVENTION IS TO MEASURE UP WEIGHT FROM STATIC, LOWEST KEY POSITION WITHOUT "THUMPING", THEN WE KNOW THAT NO SPECIAL CONSIDERATION NEEDS TO BE TAKEN TO MEASURE UPWEIGHT
HOWEVER, IT IS STILL UNCLEAR IF THE STATIC FRICTION IN DOWNSTROKE IS ONLY AT THE TOP OF THE STROK OR AT ANY TIME THE DOWN STROKE STOPS.

▢ CREATE AN ANCHORING PLATE TO FIX MAG TO FRAME.

△ MAY NEED TO CONTAIN RADIAL MOTION OF PLUNGER

CAN USE COIL SPRING TO CONTAIN MOTION

1. DOES THE COIL BEING CLOSER TO ONE OF THE MAGNETS MAKE A DIFF?

Figure A2: Concept B using second design approach, flexure bearing/springs

Description: Concept B embodies the second design approach by utilizing a voice coil motor and a spring to support the coil and plunger. This concept focuses on eliminating friction between the coil and magnet while stabilizing the vertical motion of the coil and plunger. A toroid (donut shape) magnet with concentric iron plates at its top and bottom and a concentric center post provides a permanent magnetic field. The tubular coil sits within the air gap between the inner wall of the magnet and the outer surface of the center post. Friction is avoided between the magnet and coil and the post and coil by leaving the air gap wide enough to ensure no contact occurs. Increasing the air gap decreases the power of the permanent magnet, so a spring is implemented to keep the coil concentric with the magnet and post while preventing any angular displacement from the centerline, so that the gap can be minimized. By measuring the input current, the force generated by the voice coil actuator can be measured. However, the mechanical impedance of the spring requires more current to overcome, therefore calculations of force must account for force used and applied by the spring. Since the force requirements of a spring can be easily calculated with knowledge of the displacement and spring constant, strain gauge measurements are not necessary for this configuration.

A common style of voice coil motors is found in most stereo speakers. They function by placing a coil of wire, wrapped around a tubular structure, inside the magnetic field of a toroid, or doughnut-shaped, magnet. Such a magnet is designed by placing iron plates on the top and bottom surfaces of the toroid magnet that is magnetized across its axis. The top place is open at the center to expose the center of the toroid, which has an iron post at its center that connects to the bottom plate. The tubular coil is then aligned concentrically with the magnet and iron core. When current is passed through the coil, a magnetic field is induced around the windings of the coil. This induced magnetic field interacts with the field of the permanent magnet to produce a Lorentz force on the core in the upward or downward direction based on the direction of the current. The direction of the force is determined by the cross product of current and magnetic field: $\vec{F} = \vec{I}l \times \vec{B}$. Figure A3 shows how the toroid magnet and coil are oriented and the direction of the force produced.

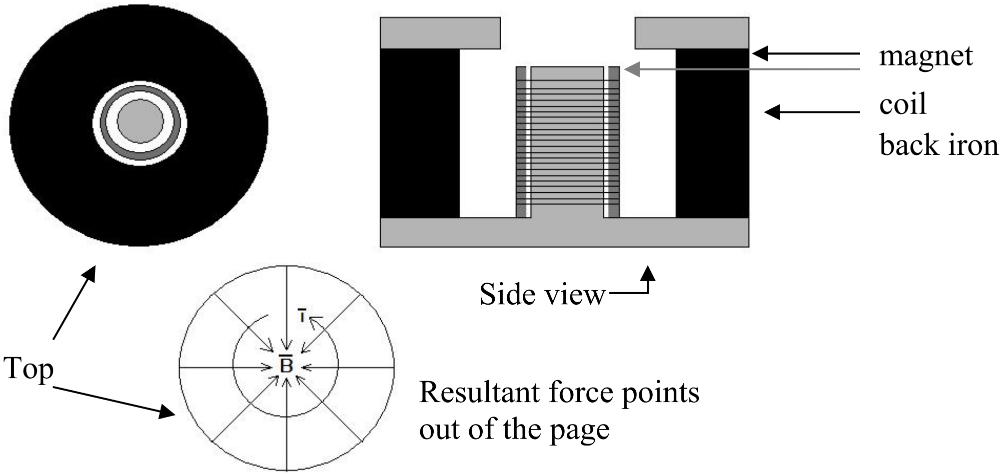


Figure A3: Toroid magnet configuration and resultant force

It is very important to know that the successful performance of this type of voice coil is contingent upon the windings of the coil remaining within the uniform region of the permanent magnetic field. The field generated by a toroid magnet is pictured below. Back iron and a center post are added to concentrate the field inside the magnet. However, this magnetic field is only uniform in the air gap between the inner wall of the magnet and the outer surface of the center post. Due to this constraint, a proper magnet will be one that is designed to have a uniform field over the entire stroke of the coil. Ensuring a uniform magnetic field will guarantee that the output force will be constant when the current is constant.

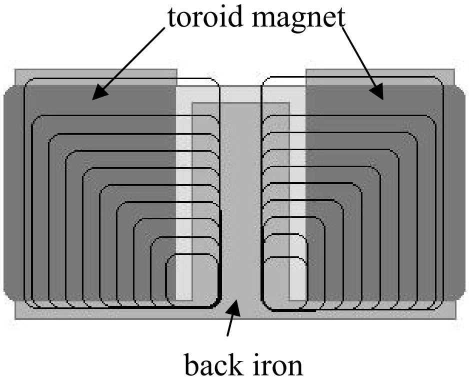


Figure A4: Linear toroid with back iron magnetic field lines

Since the direction and magnitude of the current dictates the direction and magnitude of the resultant force, a controlled linear force can be applied to the piano keys by manipulating the direction and magnitude of the input current. A calibrated relationship can then be determined between the input current and the resultant force so that a desired force output can be reached by simply adjusting the current to a known value.

The next step in developing this idea is finding the best combination of current, magnet, and coil. Each of these components plays an important role in the performance of the device. Increasing current will increase the resultant force as will increasing the strength of the magnet. The magnitude of the induced magnetic field is also dependent upon the number of turns in the coil's wire. When the number of turns is increased, more magnetic field is induced, which increased with current. However, when the strength of the permanent magnet is increased, less current is required to produce the same force. The equation, $F = (ILxB)N$, summarizes these relationships. F is the resultant force, I is the current magnitude, L wire length of a single turn, B is the magnitude of the magnetic field, and N is the number of turns in the coil. From this equation it can be seen how increasing any of the variable on the right side will increase the resultant force. Through some basic experiments, it has been discovered that when too much current is delivered to the coil, it can become extremely hot. This is why balancing the relationship between the magnet, coil, and current is crucial to the performance of this device.

As depicted in figures A6-A9, this device is adjustable in height by fixing the voice coil to some type of collar than can be slid up and down on a post that is attached to the base of the device. Since the surface of the black keys is higher than the white keys, it is essential that the height of the device be adjustable. In order to reach the depth of the black keys, the base of the unit is to be slid forward from the point used to reach the white keys. The following figure demonstrates the general way that this device will approach the key. Unfortunately, the force output will not be pure since the coil leads will resist motion when the device is moving.

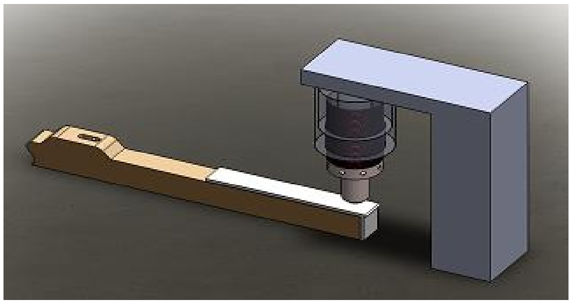


Figure A5: Configuration of Concept B

Some challenges that are foreseen in further development of this concept include the orientation of the coil and preventing friction during the coil stroke. One option for the coil orientation is to keep it contained inside the magnetic field at all times, allowing it to hang freely when the coil is not energized. The problem with this orientation is that the coil must be kept away from the inner wall of the magnet to prevent friction during the coil stroke. One way to keep the coil centered is to implement a return spring that will keep the coil concentric with the center post and return it to a starting position. This will then require that the force of the spring be accounted for in calculating the force delivered to the key. To do so will require knowing the displacement of the spring, thus will require an accurate position sensor to provide displacement data. Another orientation of the coil would be to place it on the key and lower the magnet over the coil. Performing this procedure will be somewhat difficult since it is necessary to eliminate friction between the coil and magnet in this orientation. To assist with this procedure, the air gap between the inner magnet wall and the outer surface of the center post can be increased, but will decrease the strength of the permanent magnetic field. As discussed before, a magnet that is strong enough or adjustments to the other variables can be made to compensate for the air gap. As this concept is further developed, an appropriate solution to these problems will be found.

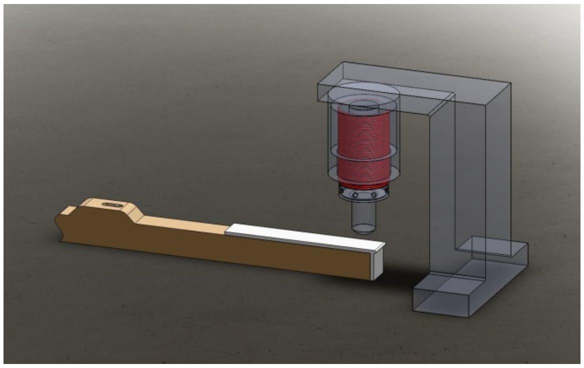


Figure A6: Concept B drawing

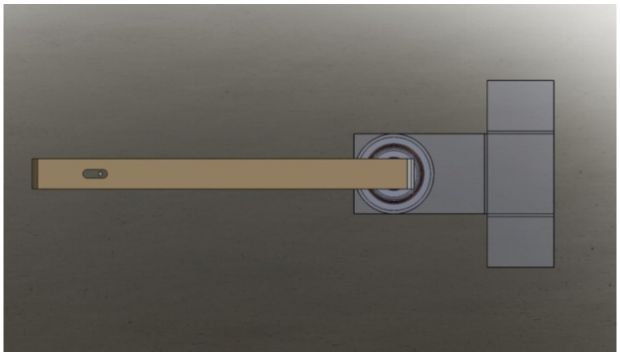


Figure A7: Concept B drawing

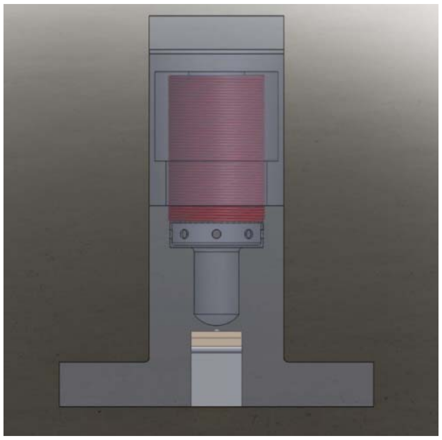


Figure A8: Concept B drawing

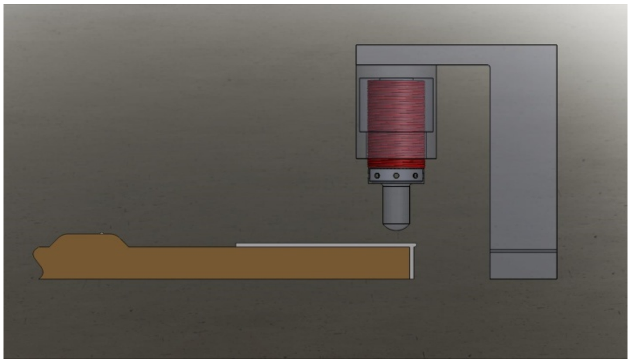


Figure A9: Concept B drawing

Concept Selection: Using a toroid magnet and cylindrical coil, this concept embodies the same voice coil principle as a speaker. Its high valuation is contributed to its low cost and small size. In order to avoid friction, this concept must utilize a spring or other type of flexure support so that contact is not made between the coil and magnet. Doing so will require the use of an accurate position sensor and calculation capability within the device. Also, the key travels in an arc path, which means that the horizontal component of displacement can alter the vertical force application by introducing friction that develops as the key surface slides past the tip of the plunger. For this reason, this concept did not receive positive valuation for precision and practicality. Since its valuation remains high, this design concept will continue to be developed.

Concept C

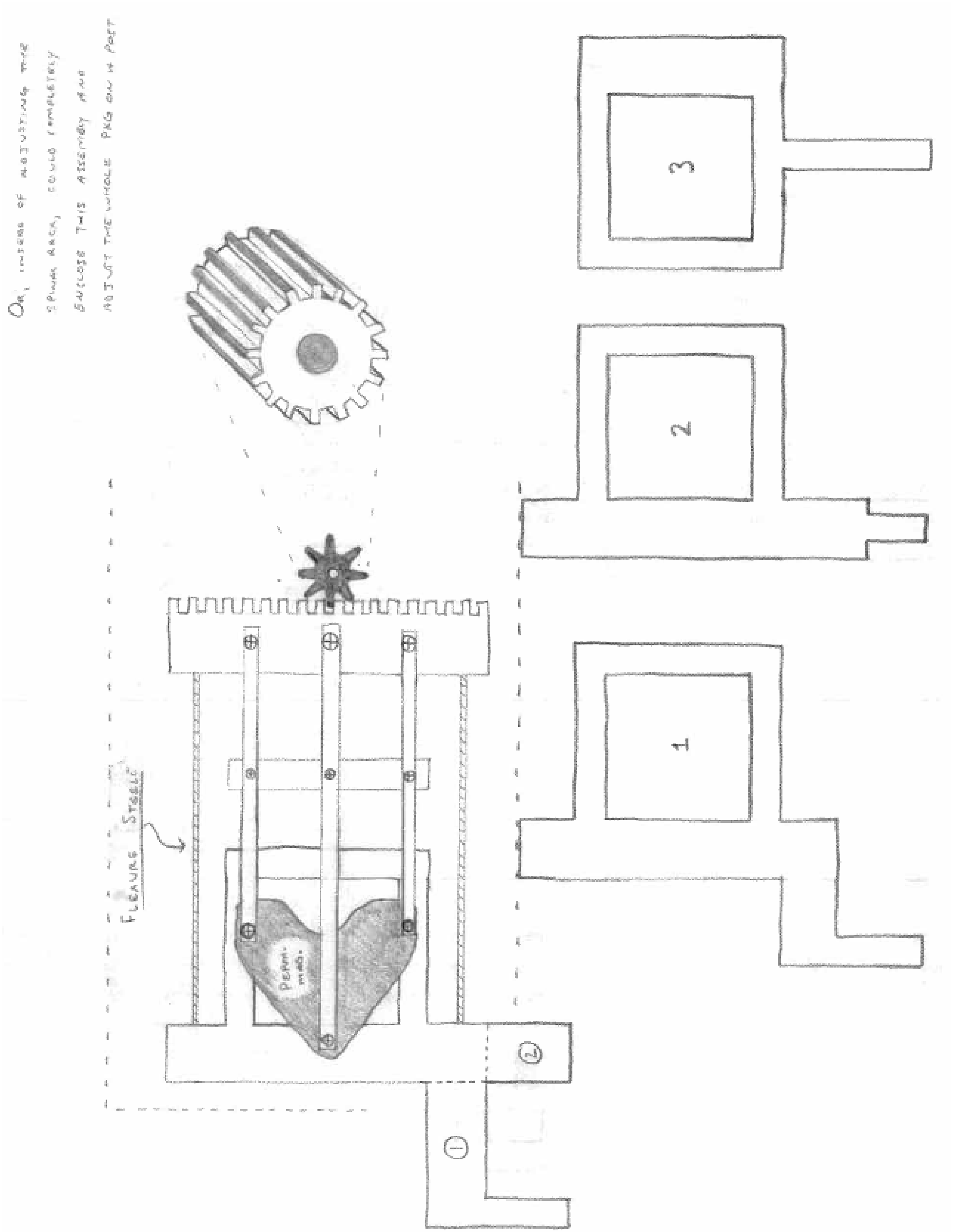


Figure A10: Concept C using second design approach, flexure bearing/springs

Description: Concept C also embodies the second design approach by using a flexure bearing to support the voice coil motor. A flat voice coil motor, which involves surrounding the coil with flat magnets, would be used instead of the toroid magnet mentioned in concept #2. By suspending the coil on the flexure beams, we can support the actuator arm and guide its motion linearly while preventing surface contact, much like the spring's purpose in the concept #2. Internal mechanical impedance exists, and can be characterized by performing calculations based of the flexure of the beams when their length and deflection are known. Since this impedance can be accounted for, a strain gauge is not necessary to determine the applied force to the keys. The force can be calculated by using the known input current.

Concept Selection: Scoring the lowest valuation, this concept was quickly eliminated. A flat voice coil is supported by a flexure bearing in this design, which requires a minimum length of the flexure beam to allow for flexure at modest forces, which increases the necessary length of the device. To avoid using costly load cells, this design allows for the flexure of the beam to be characterized and accounted for through calculation of the applied force. Due to the complexity of its design, this concept did not score positively in manufacturability, practicality, or precision, and thus was eliminated.

Concept D

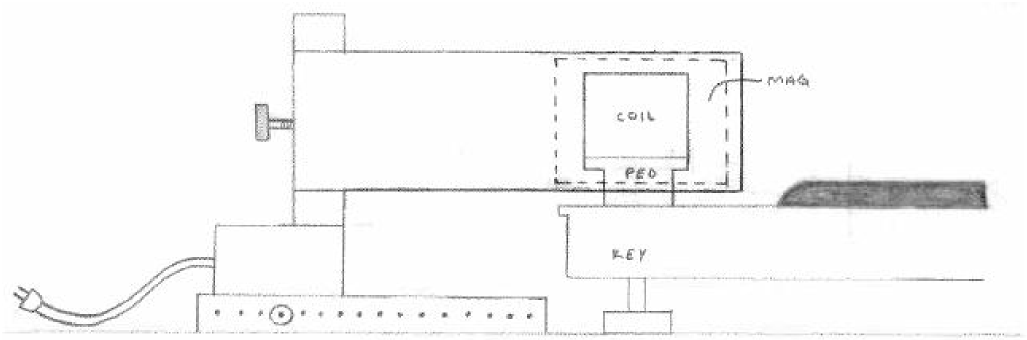
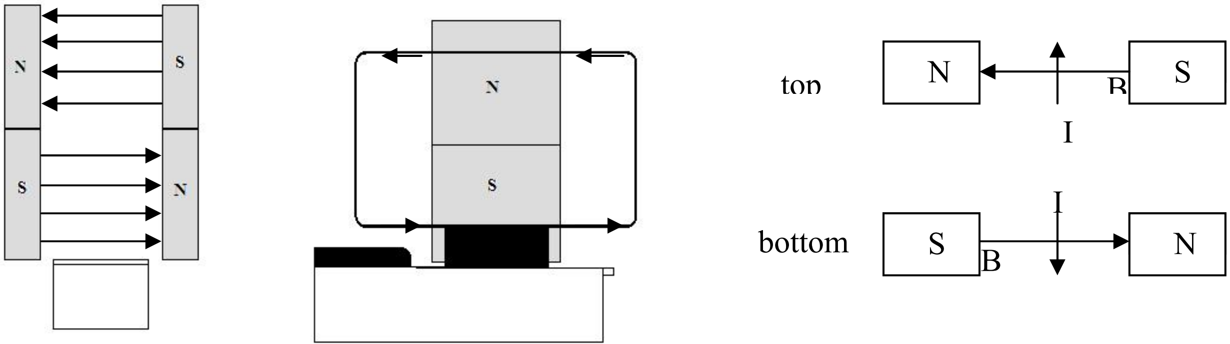


Figure A11: Adjustability of Concept D on two axes

The concept is very similar to the toroid voice coil (described in Appendix A, Concept B), but is oriented differently to achieve the same kind of linear motion. In this design, two plates of magnets are placed parallel with the piano key so that the plates face each other from opposite sides of the key as shown in A12. The poles of each plate are different from top to bottom and are opposite between the plates. The coil for this concept will need to be wound in a rectangular shape so that the long stretch is parallel with the key. Full resultant force occurs when the current path is exactly parallel with the magnetic field lines. By creating field lines that flow in opposite directions from top to bottom, resultant forces in the same direction can be generated from both top and bottom wires of the coil. The figure below shows how this configuration will work. The direction of the resultant force follows the equation $\vec{F} = \vec{I}l \times \vec{B}$.



Resultant force at top and
bottom is out of the page (up).

Figure A12: Flat voice coil configuration and resultant force

When we consider how the vertical components of the coil interact with the magnetic field, we see that $\vec{F} = \vec{I}l \times \vec{B}$ shows the forces to reinforce one another.

Since the magnetic field between the plates is uniform, we are able to place the coil anywhere between the plates and achieve constant resultant force when the current is constant. When the key acts as the coil support or “bearing”, contact friction between the coil and magnets is totally eliminated. The pedestal that the coil sits on in Figure A11 allows for the descent of the key while keeping the coil totally within the uniform magnetic field. With further development, the pedestal can incorporate a feature to help locate the coil to be perfectly parallel with the depth of the key and perpendicular to the permanent magnetic field. This is important to ensure that the resultant force is of constant strength each time the device is used. The governing equation of the resultant force is $F=(ILxB)N\sin(\theta)$, where θ is the angle between the magnetic field and current path. When the magnetic field and current are perpendicular ($\theta = 90°$), the force is at its greatest magnitude. The resultant force decreases as the angle decrease and becomes zero when they are parallel ($\theta = 0°$). Since the magnitude of the force depends on the angle between the magnetic field and current path, it is necessary to keep the angle constant to maintain a constant relationship between the resultant force and the applied current. Figure A13 depicts the difference between these two situations.

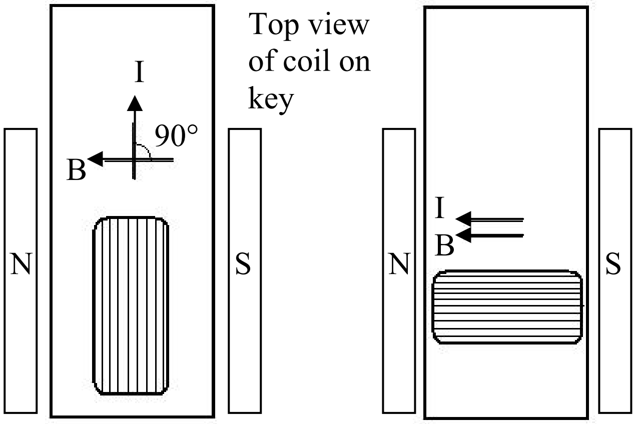


Figure A13: Coil orientation

The magnetic plates in this configuration are ideally positioned very slightly above the height of the key surface to require minimal pedestal height when accounting for the distance of key stroke. Since the surface of the black keys is higher than the white keys, the device must be adjustable in height to accommodate all keys. Figure A14 shows how the magnetic plates are attached to a collar that is adjustable on a post. The post is mounted to the base, which is also adjustable on two rails.

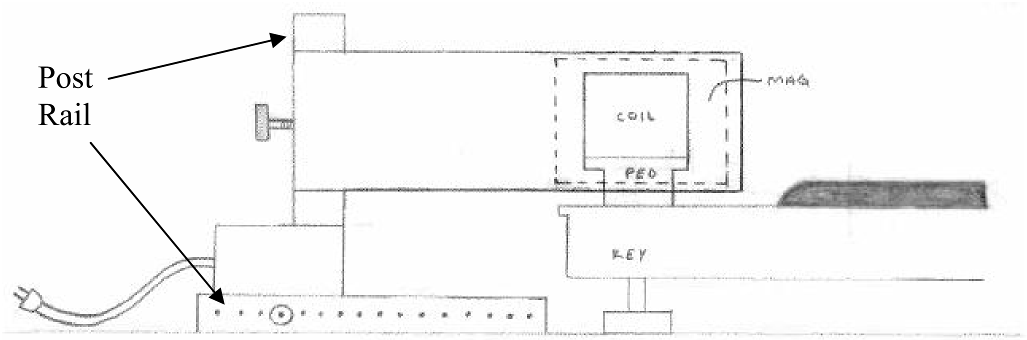


Figure A14: Adjustability of Concept D on two axes

In order to help maintain a constant orientation angle between the permanent magnetic field and the coil, a square or rectangular post can be used to ensure that the orientation angle of the magnets relative to the base never changes. This will allows to operator to configure the device the same way each time it is moved from key to key.

Some challenges that are foreseen in further development of this concept include balancing the affects of the permanent magnet, coil, and current, configuring the coil to remain in the uniform magnetic field, and creating a light and effective coil. As stated in the previous section, it is very important to balance the relationships between the magnets, coil, and current to achieve favorable performance. But when the key acts as the coil bearing, the weight of the coil becomes more of an important issue. If the coil is too heavy, heavier than the lowest expected down-weight, it will cause the key to depress without applying current. However, if the thickness of the wire becomes too small for a given amount of turns, the coil can become extremely hot and could fail. The probability of failure due to heat increases as the angle between the magnetic field and current path decreases since the force is weakened, requiring more current to deliver the necessary force. It is therefore that most of the difficulty in developing this concept further will focus on generating the most suitable coil.

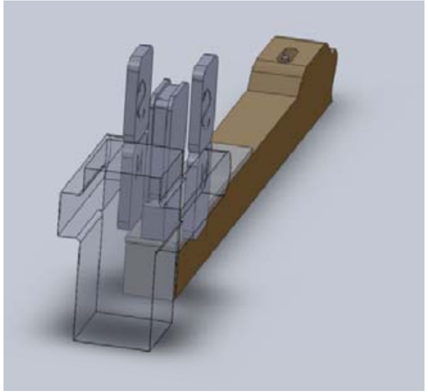


Figure A15: Concept D drawing

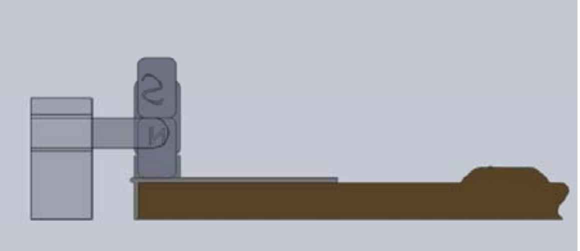


Figure A16: Concept D drawing

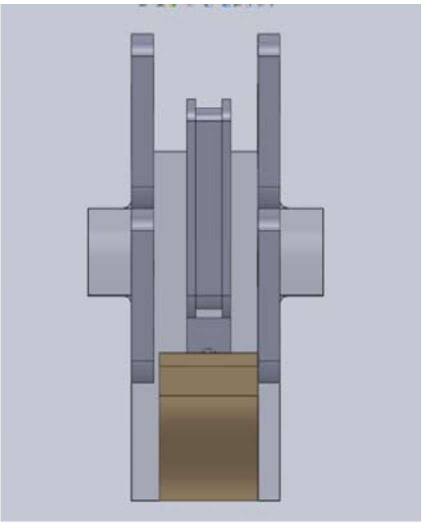


Figure A17: Concept D drawing

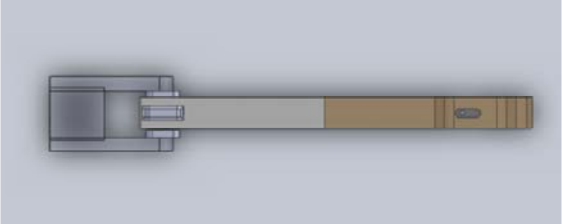


Figure A18: Concept D drawing

APPENDIX B – Bill of Materials

Table B1: Prototype bill of materials

Item	***Quantity***	***Source***	***Catalog Number***	***Cost***	***Contact***	***Notes***
18” x 24” x 0.22” clear acrylic	1	Home Depot	1AG2123A	$15.57	homedepot.com	
1/4”-20 12” steel threaded rod	1	McMaster-Carr	98790A320	$0.58	mcmaster.com	Right hand
1/4”-20 8” steel threaded rod	2	McMaster-Carr	91565A567	$6.47 / 10	mcmaster.com	Right hand
1/4”-20 threaded knob	2	McMaster-Carr	6121K22	$3.02 each	mcmaster.com	Right hand
1/4”-20 threaded stud with knob	1	McMaster-Carr	57715K84	$1.02	mcmaster.com	Right hand
1/4” screw size flat washers	2	McMaster-Carr	91081A129	$2.32 / 100	mcmaster.com	
1/4”-20 nylon-insert locknuts	5	McMaster-Carr	90630A110	$3.25 / 25	mcmaster.com	Right hand
1/4”-20 steel wing nut	1	McMaster-Carr	90876A150	$7.71 / 5	mcmaster.com	Right hand
1” cutout aluminum square tube	1’	McMaster-Carr	6546K341	$5.95	mcmaster.com	
1” x 1” square aluminum bar	1’	McMaster-Carr	9008K141	$9.44	mcmaster.com	
1/4” nylon washers	5	McMaster-Carr	90295A150	$8.98 / 100	mcmaster.com	
4” x 4” 90º aluminum bracket	3”	McMaster-Carr	88805K67	$55.76 / 8’	mcmaster.com	
27 AWG amber magnet wire	1600’	Tech Fixx	170473284040	$18.70	techfixx.com	Insulated
4” x 4” x 1” aluminum plate	1	McMaster-Carr	89155K971	$33.78	mcmaster.com	
20 x 4 LCD character display	1	Modern Device	-------	$19.95	moderndevice.com	
General purpose wire 22 AWG	5’	McMaster-Carr	7587K931	$8.22 / 100’	mcmaster.com	Insulated
1/2” x 1.25” x 12” steel plate	1	McMaster-Carr	8910K934	$8.70	mcmaster.com	
1/2” x 6” x 6” PVC plate	1	McMaster-Carr	8747K635	$3.45	mcmaster.com	
Gorilla epoxy	1	Home Depot	100670610	$4.97	homedepot.com	
Super glue	1	Home Depot	SGH24J	$1.97	homedepot.com	
2” x 1/2” x 1/8” Nd magnets	2	K&J Magnetics	BY082	$3.35 each	kjmagnetics.com	
1/2” x 1/8” x 1/4” Nd magnets	2	K&J Magnetics	B824	$0.53 each	kjmagnetics.com	
Arduino USB board	1	Solarbotics	50450	$29.95	solarbotics.com	
ZWS150PF24 power supply	1	PLCCenter	390075936942	$60.00	plccenter.com	
Small solderless breadboard	1	Fun Gizmos	36	$4.50	fungizmos.com	
Hall effect sensor	1	Digi-Key	62012351-ND	$3.99	digikey.com	

The prototype was built and powered using mostly the available scrap materials in the G. G. Brown machine shop and electronic equipment available in the X50 lab and Professor Gillespie’s lab. However, table B1 provides pricing for all materials required to build this prototype. Adding the prices gives a total cost of $329.03. Prototype fabrication was performed using only simple hand tools, a drill press, a band saw, and a mill in the machine shop. Ultimately, this device will operate with a single power supply and embedded software which we were unable to write. Therefore, some electronic equipment (at the end of the table) may change and some small, inexpensive electronics have been omitted from this table such as transistors, resistors, and small capacitors.

APPENDIX C- Description of Engineering Changes since Design Review #3

While the general concept established in Design Review #3, there were a few changes and additions made.

Armature/coil: Due to space limitations within the armature's cavity, only 600 turns of the wire were made instead of the optimal 775 turns. Despite this 175-turn reduction, we still obtained the necessary forces while keeping the heat production to within safe limits since we originally designed this system to output higher than necessary forces. Also, the coil was potted with epoxy to create a safety barrier between the user and the current passing through the coil. Additionally, the potting provides stability for the coil as it keeps all the turns in-line, which adds to the long-term repeatability of the device.

Magnet/back iron: The part of base plate of the permanent magnets that is between the magnets was removed to create two separate base plates. By doing this, we were able to epoxy a base plate to each leg, and eliminate the step in the procedure where the piano technician would have to put the magnet over the armature and place it in the base plate. Now the piano technician can just place the magnet over the armature and directly onto the key. The bottom of the Hall Effect senor bracket was made thicker to create a greater distance between the magnetic fields of the Hall Effect sensor and the permanent magnets in the voice coil motor. Minimizing or eliminating the interaction of these fields ensures that the device will perform as expected. An arm was manufactured to place the Hall Effect sensor between the Hall Effect magnets.

Key-to-key adjustment: The major addition to the prototype was the manufacturing of a 3-axis table to enable the movement of the device into, across, and above the keyboard. The implementation of this table allows the piano technician to easily change the position of the device to make measurements on the black keys in addition to the white keys which was a customer need.

APPENDIX D - Experimental Alpha Prototype Description

For purposes of validating the functions of the final design, a prototype will be generated that will perform to the full capacity of the final design. The prototype will be built to perform in a laboratory setting, thereby requiring only the main functions of the device to work to scale. The main functions to be validated with this prototype are the force production in the voice coil and the heat generated in the coil. Therefore, the prototype described will incorporate the components required to test only theses functions. The following describes the prototype through a breakdown of each necessary component.

The magnet apparatus to be used in the prototype must be exactly the same as that of the final design. Since each aspect of the magnet apparatus, the magnet type, magnet dimensions, back iron material, and back iron dimensions, are critical to the performance of the device, they must all coordinate to the requirements of the final design. Therefore, the magnet apparatus of the prototype will include two neodymium N42 magnets that are spaced 0.595 inches apart. The magnets will be 2 inches tall, 0.5 inches wide, and 0.125 inches thick and will be surrounded on the sides and top by the back iron made of mild carbon steel. The back iron will have the same thickness and width of the magnets but will be 0.25 inches taller so that a 0.125 inch gap will exist between the top of the magnets and the top of the gap cavity in the back iron. A single piece of mild carbon steel will be cut from a piece of bar stock and machined to the final dimensions of 2.375 inches tall, 0.5 inches wide, and 0.125 inches thick. The cavity for the magnets to be placed in will be machined out of the center of the back iron and will have dimensions of 2.150 x 0.595 x 0.5 inches. The magnets will then be placed inside the back iron cavity so that opposite poles of the magnets face each other. The magnets should also be fixed to the lowest point of the back iron wall so that the maximum gap exists between the top of the magnets and top of the cavity in the back iron.

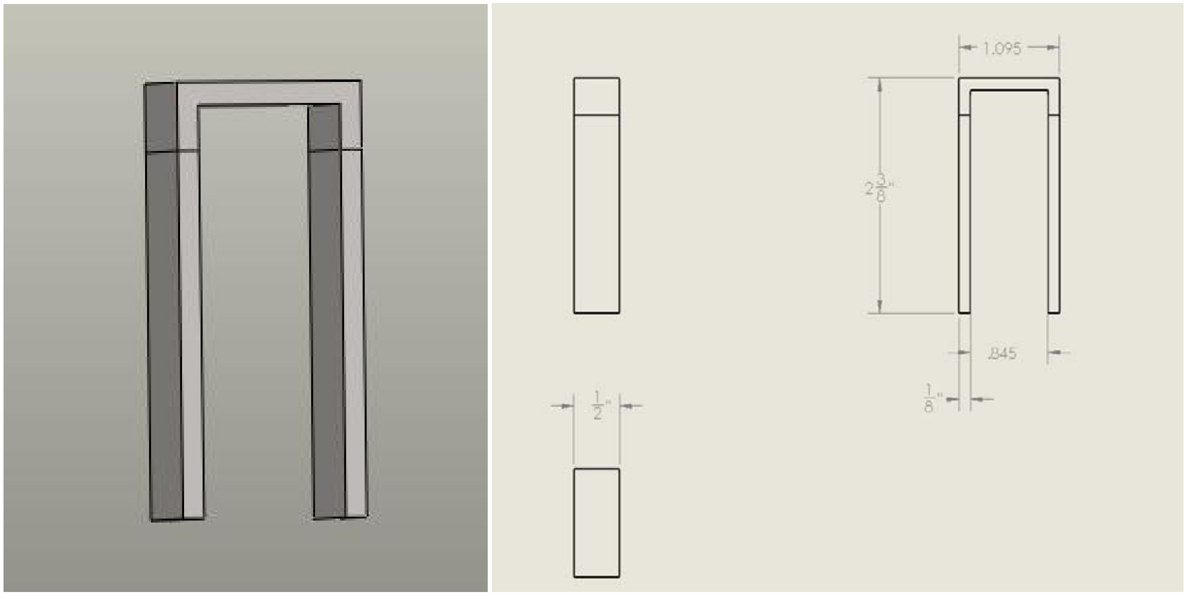


Figure D1: Back iron drawing (steel)

It is also imperative that the coil armature be made to the exact specifications of the final design since the size of the armature will affect the properties of the coil and the heat dissipated during operations. Both of these aspects are critical to the performance output of the device and must model the final design as best as possible. Thus, the armature will be machined from a 0.75 inch thick aluminum plate to the dimensions of 2.25 x 2.25 inches. A 0.1875 inch square will be removed from the inside of the armature leaving a 0.4375 inch wide bar that will fit between the magnet plates. The armature will contain the windings of the coil in a 0.3125 x 0.5 inch trench along its entire perimeter. With sufficient winding of 27 gauge magnet wire inside the armature, the trench will be covered with plastic tubing.

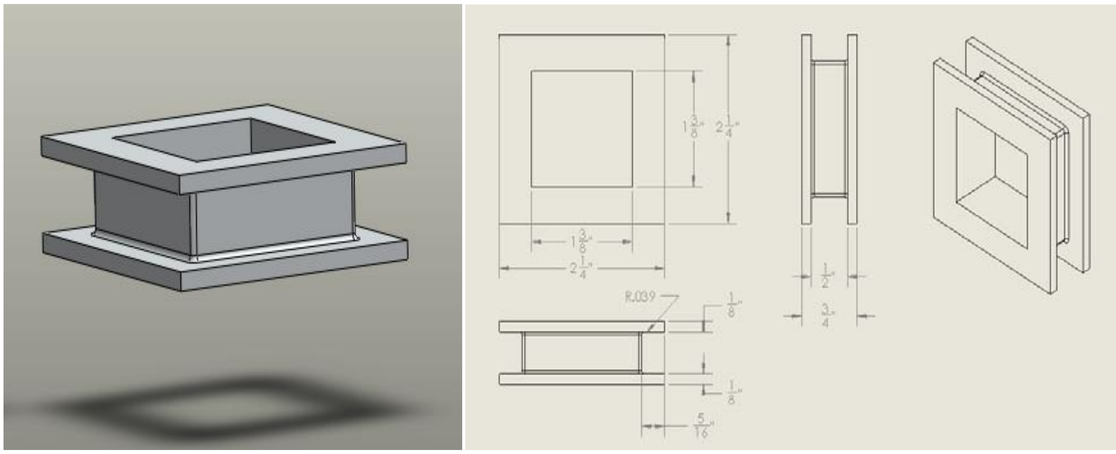


Figure D2: Armature drawing (aluminum)

Two 90° angle brackets will be fastened to the surface of the armature to provide anchoring points for the armature's support arms. Holes will be drilled through the thickness of the armature over the location of the brackets so that they can be attached using nuts and bolts. Support arms made from flat aluminum stock will have holes drilled through their thickness at their ends. These support arms will be fasted to the brackets on the armature using nuts and bolts and on their opposite ends to a rigid structure that is set up so that the armature will remain is specific position during testing and validation. In the final design the armature support arms will be fixed to an adjustable post to accommodate the height difference between white and black keys and Hall Effect sensors, but will simply be fixed to a rigid frame for prototype purposes. The prototype device will be pushed forward on the workbench and raised by re-anchoring the support bars or placing a block under the structure to reach the black keys.

The rigid structure that the armature support arms will attach to will likely be framed with 90° angled pieces of aluminum or steel. This type of material has holes pre-drilled along its length, which will allow adjustments for reaching different keys easily. The frame will be fixed to a wood base that is sized to fit on the workbench. The wood base will likely be bigger than necessary so that there is space to clamp it to the workbench. Since the prototype will only serve to test the primary functions of the device, it does not need to be easily adjustable in any axis nor contain any power supply or computational components. The power supply will sit adjacent to the device on the workbench with the signal amplifier. These components will have wires that connect to a computer, which will be used to calculate and display data in place of an included microprocessor and LCD screen.

APPENDIX E – Design Analysis

This appendix discusses material selection process for the coil armature and the back iron.

Functional Performance

There are two major components of the prototype which require the use of *Cambridge Engineering Selector* (CES) to choose the optimal material. The coil armature needs to be strong so it does not move or flex when a current is applied to the coil and forces are generated. However, it must also be non-magnetic so it does not disrupt the magnetic field produced by the permanent magnets which will be in close proximity during operation. The back iron material also needs to be carefully selected since we want to maximize the magnetic flux through it to get the strongest possible field between the permanent magnets. Therefore, a material with a low reluctance is desired. Furthermore, it must be strong enough to hold the magnets apart. Due to the $400 budget of this project, the materials for both the coil armature and back iron must also be affordable. Table E1 quantifies these constraints.

Table E1: Constraints for both components

	Constraint	*Limit*
Coil Armature	Price	< $5 per lb
	% Fe	< 1%
	% Ni	< 1%
	% Co	< 1%
Back Iron	Price	< $20 per lb

Coil Armature: The material indices used for the coil armature were thermal conductivity and Young's modulus. Thermal conductivity is a measure of the materials ability to dissipate heat. This is important since we would like to keep the coil as cool as possible so no measurement inconsistencies occur while operating with a hot vs. cold coil. Young's modulus is the ratio of stress over strain so a high modulus is desired to minimize any armature flexure under load. Figure E1 shows the results of the CES software for the coil armature.

The top five material choices for the coil armature are listed below. We elected to use Aluminum 2024 given our time constraint and its availability in the machine shop. It is also a very common material to use for heat fins so we were confident of its effectiveness.

- High conductivity copper-chromium
- Aluminum 2024, wrought
- Chromium, >99% purity
- Kaneelhart wood
- Bamboo

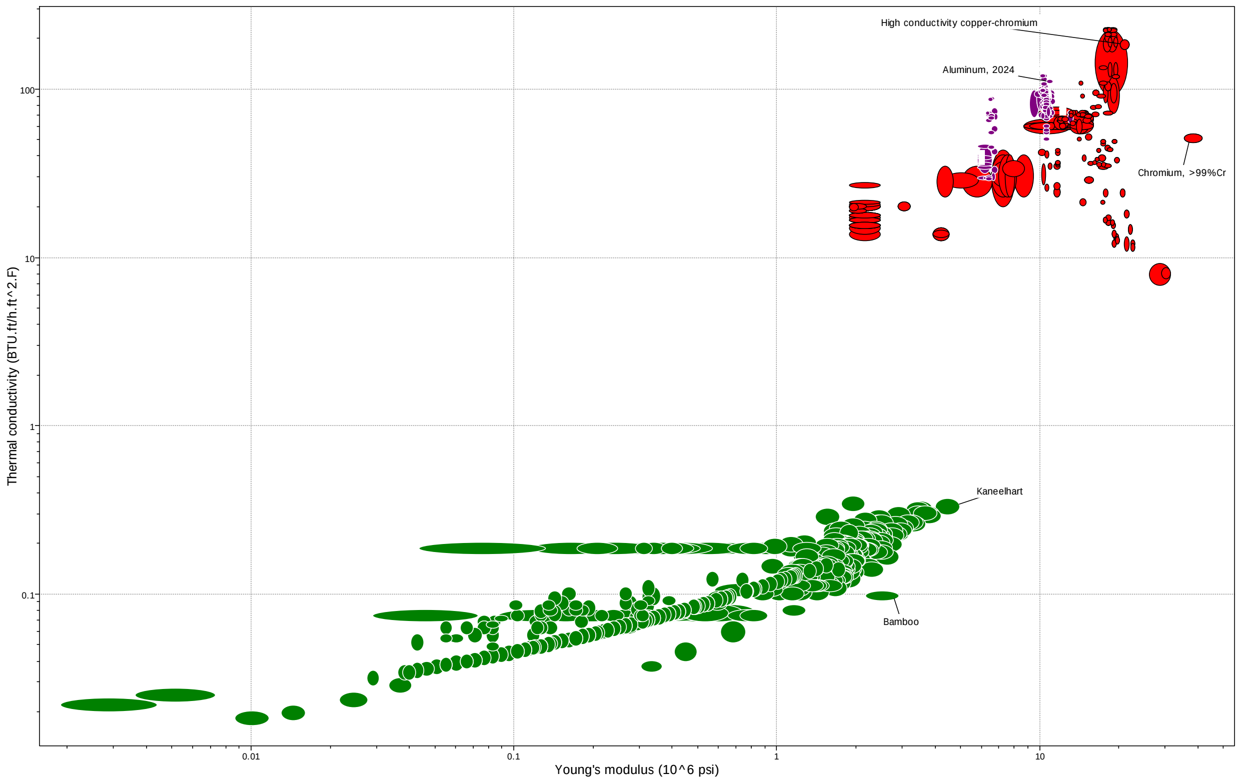


Figure E1: Coil armature CES output showing high conductivity copper-chromium and aluminum 2024 as ideal materials given the constraints. Woods are green and metals are red.

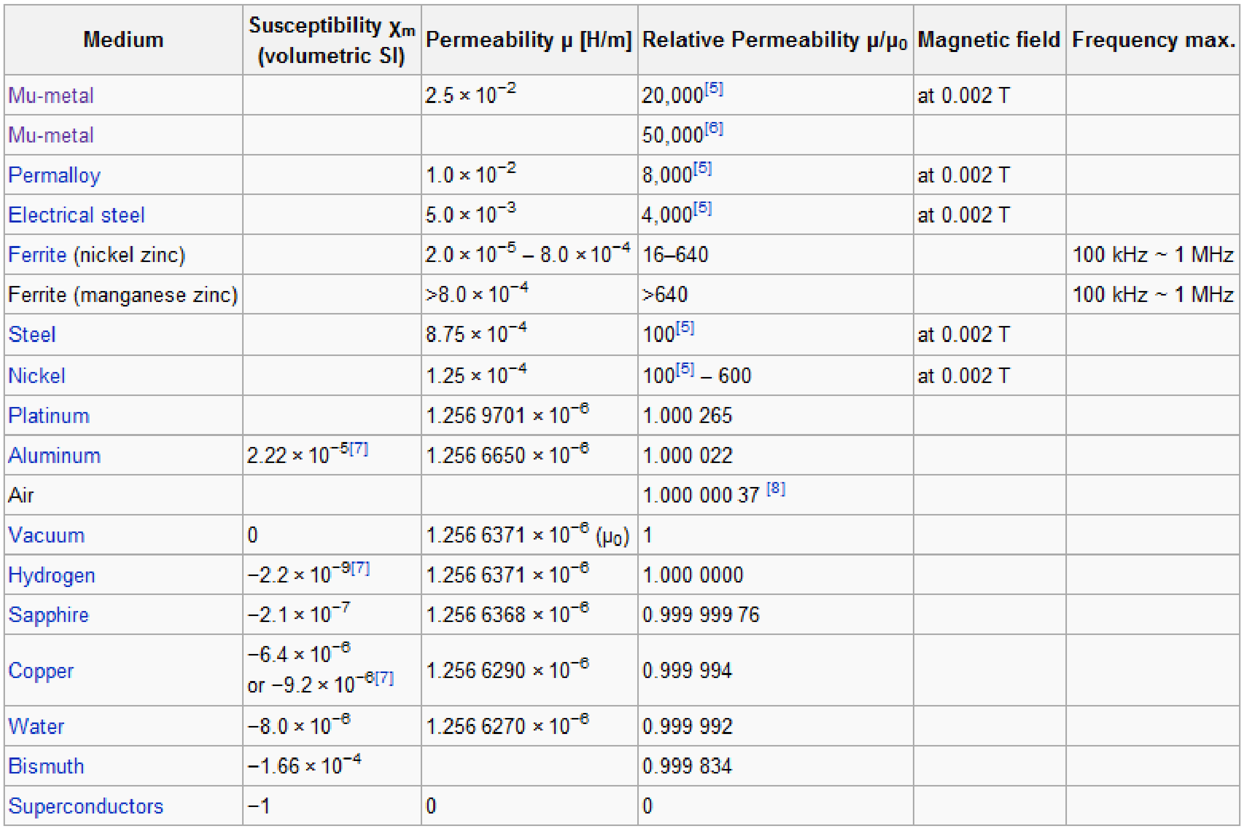
Back Iron: The back iron was more difficult to plot using the CES software since magnetic properties of all materials were not provided so appropriate materials had to be first selected for the program to plot permeability. Reluctance is given as equation E1 where μ_0 is a constant known as the permeability of free space and μ_r is the relative magnetic permeability of the material.

$$Reluctance = \frac{(circuit\ length)}{\mu_0 \mu_r (Area)} \qquad \text{(Equation E1)}$$

For a low reluctance, we need a high value of μ_r. Looking at table E2 from wikipedia.org we selected the values with the highest μ_r and listed them below (the table only lists values of μ but $\mu = \mu_0 \cdot \mu_r$ so the highest values of μ are desired since μ_0 is a constant).

- Mu-metal (approximately 75% nickel, 15% iron, plus copper and molybdenum)
- Permalloy
- Nickel
- Aluminum
- Steel
- Copper

Table E2: Highest μ gives the lowest reluctance as desired.



Medium	Susceptibility χ_m (volumetric SI)	Permeability μ [H/m]	Relative Permeability μ/μ_0	Magnetic field	Frequency max.
Mu-metal		2.5×10^{-2}	20,000[5]	at 0.002 T	
Mu-metal			50,000[6]		
Permalloy		1.0×10^{-2}	8,000[5]	at 0.002 T	
Electrical steel		5.0×10^{-3}	4,000[5]	at 0.002 T	
Ferrite (nickel zinc)		2.0×10^{-5} – 8.0×10^{-4}	16–640		100 kHz ~ 1 MHz
Ferrite (manganese zinc)		$>8.0 \times 10^{-4}$	>640		100 kHz ~ 1 MHz
Steel		8.75×10^{-4}	100[5]	at 0.002 T	
Nickel		1.25×10^{-4}	100[5] – 600	at 0.002 T	
Platinum		$1.256\,9701 \times 10^{-6}$	1.000 265		
Aluminum	2.22×10^{-5}[7]	$1.256\,6650 \times 10^{-6}$	1.000 022		
Air			1.000 000 37 [8]		
Vacuum	0	$1.256\,6371 \times 10^{-6}$ (μ_0)	1		
Hydrogen	-2.2×10^{-9}[7]	$1.256\,6371 \times 10^{-6}$	1.000 0000		
Sapphire	-2.1×10^{-7}	$1.256\,6368 \times 10^{-6}$	0.999 999 76		
Copper	-6.4×10^{-6} or -9.2×10^{-6}[7]	$1.256\,6290 \times 10^{-6}$	0.999 994		
Water	-8.0×10^{-6}	$1.256\,6270 \times 10^{-6}$	0.999 992		
Bismuth	-1.66×10^{-4}		0.999 834		
Superconductors	−1	0	0		

These and similar materials with high permeability and low reluctance were plotted with magnetic permeability on the vertical axis and Young's modulus on the horizontal axis. Young's modulus needs to be high to prevent the strong magnets from bending the back iron when they are arranged close together and magnetic permeability needs to be minimized to obtain the strongest magnetic field between the magnets.

The top 5 material choices for the back iron are listed below. Due to our limited time and eagerness to begin programming the prototype, we decided to use AISI 1010 steel which was available in the shop. Of the listed materials, it is not the ideal choice but through testing, we verified that the magnet field was still strong enough to produce the necessary force outputs from the voice coil motor.

- Nickel-magnetic alloy, annealed (79Ni-4Mo-Fe)
- Nickel-magnetic alloy, annealed (75Ni-5Cu-2Cr-Fe)
- Iron, annealed (>99.9% Fe)
- AISI 1010 steel, annealed
- Stainless steel, wrought, annealed

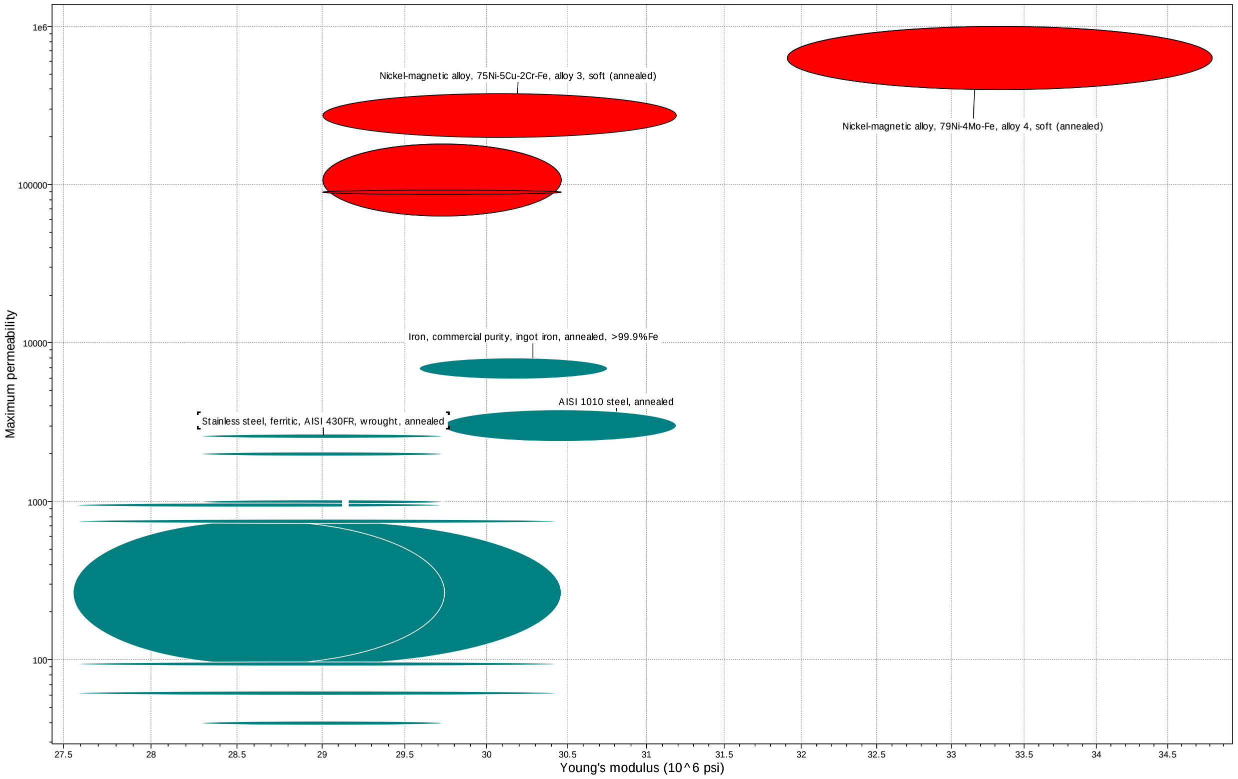


Figure E2: Back iron CES output showing highly permeable, strong materials.

Environmental Performance

Using *SimaPro*, we were able to compare the environmental impacts of the materials we were considering for the armature and the coil. Using the estimated required mass of each material, four figures were generated by *SimaPro* to aid with this analysis:

1. Total emissions across four categories (Raw, Air, Water, and Waste)
2. Relative impacts in disaggregated damage categories
3. Normalized score in *Human Health*, *Eco-Toxicity*, and *Resource* categories
4. Single score using *SimaPro*'s point system

***Armature*:** For the armature, we compared aluminum 2024 and red oak, with required masses of 664 g and 180 g, respectively. In general, the aluminum has a far greater environmental impact that the red oak. The emissions analysis (figure E3) shows that the aluminum has more emissions in all four categories, with the raw emissions being the greatest by a large margin. The relative impacts in disaggregated damage categories (figure E4) shows similar results. Both materials produce no radiation and the only category where the red oak caused more damage was in land use. For all other categories Aluminum has the same, greater environmental impact. Based on the normalized analysis (figure E5), the category that has the greatest importance on is "resources". The other two categories do not have a significant importance, though the red oak has a greater ecosystem quality impact. The single score comparison (figure E6) reflects what the other three figures already indicated: Using the aluminum 2024 for the armature will much more detrimental to the environment than the red oak. Also, there is no reason to believe that the environmental impact of the red oak to overtake the aluminum when considering the greater life cycle because of the large discrepancy (~3.2 points) in the single score comparison.

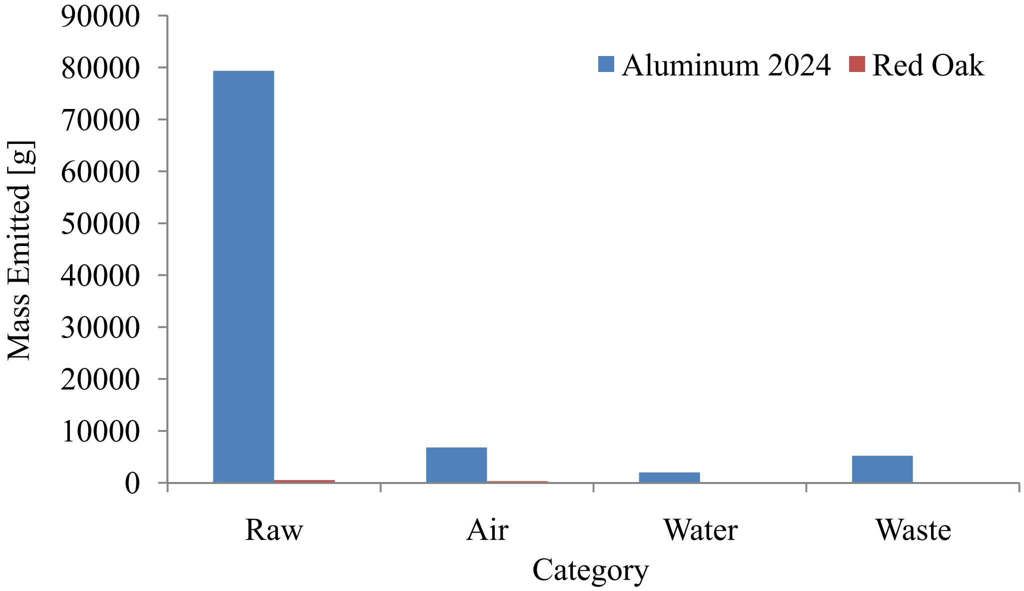


Figure E3: Emissions comparison for armature material selection

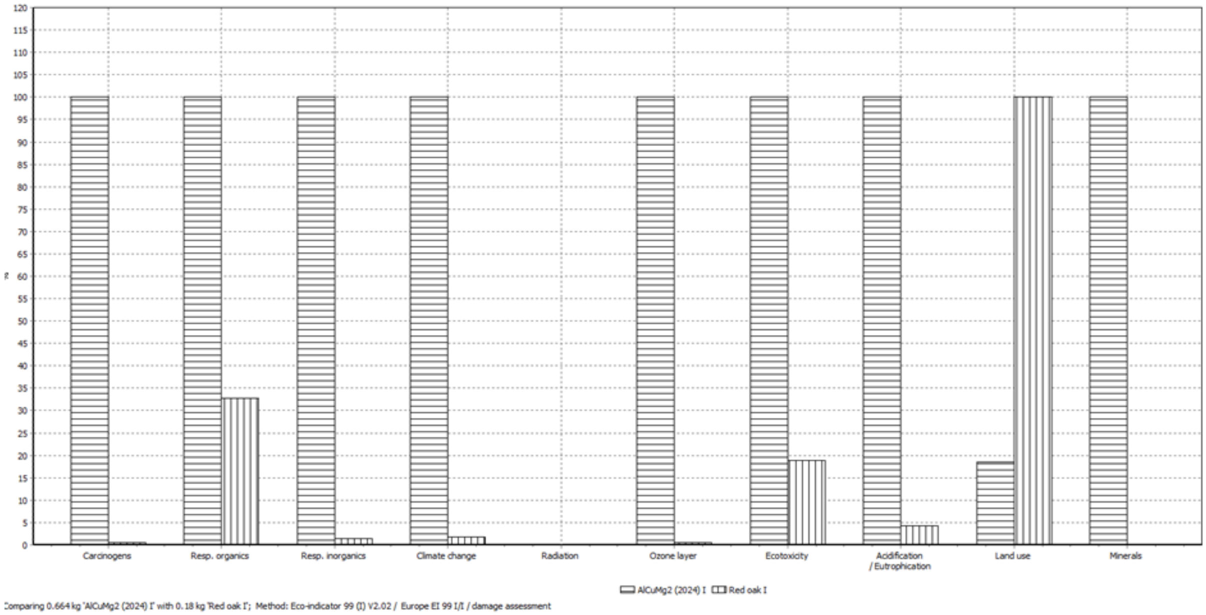
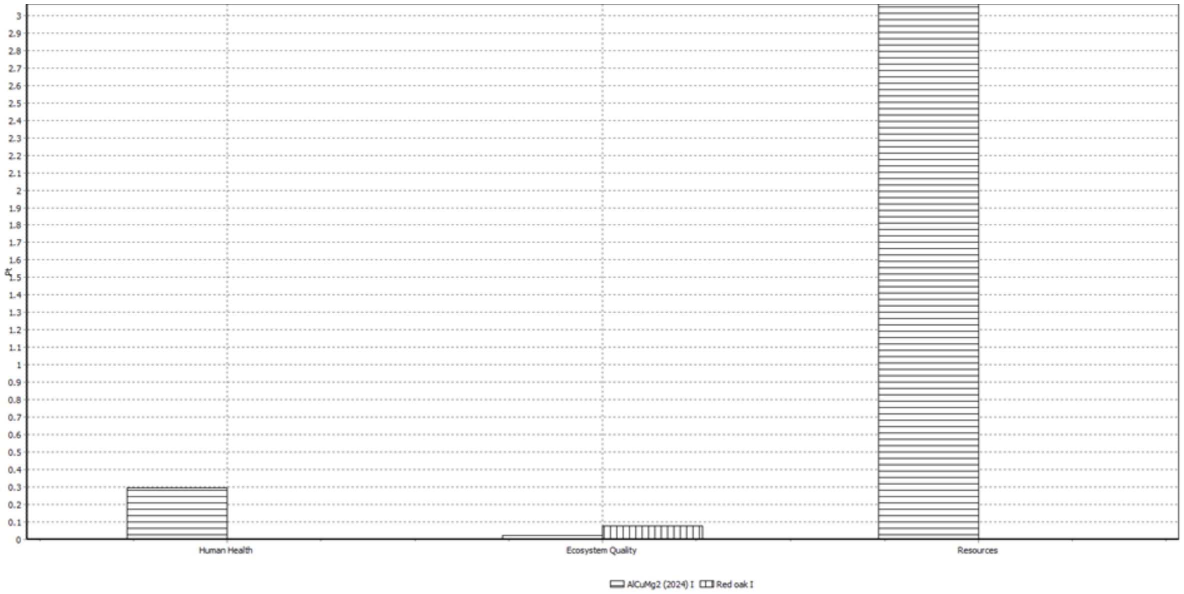
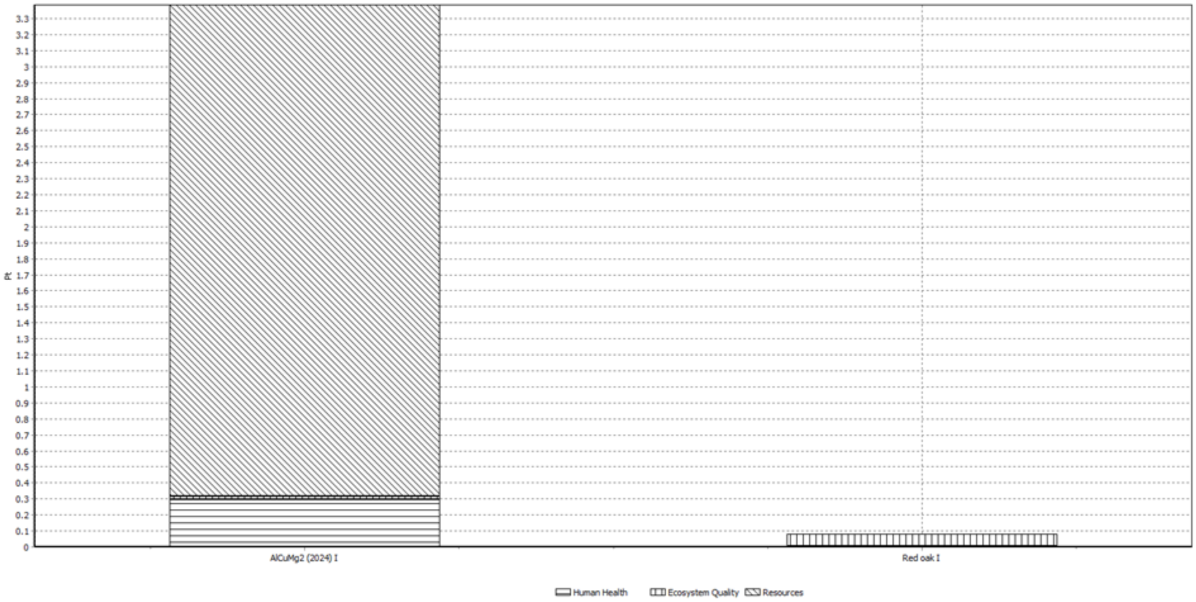


Figure E4: Comparison of relative impacts in disaggregated categories for armature material selection



Comparing 0.664 kg 'AlCuMg2 (2024) I' with 0.18 kg 'Red oak I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / weighting

Figure E5: Normalized comparison for armature material selection



Comparing 0.664 kg 'AlCuMg2 (2024) I' with 0.18 kg 'Red oak I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / single score

Figure E6: Single score comparison for armature material selection

Back iron**:** For the back iron, we compared A514 steel and GG15 cast iron. It must be noted that that the steel we actually were considering was 1010 annealed steel, but A514 was the closest match *SimaPro* offered. The required masses for the steel and the cast iron were 45 g and 40 g, respectively. Overall, the steel has a much greater environmental impact than the cast iron. The emission analysis (figure E7) indicated that the steel has more emissions in all four categories. The waste and water emissions are minimal, while the raw and air emissions are large for both materials. The steel was determined to cause more damage in the relative impacts in disaggregated damage categories (figure E8). The steel causes the same, greater impact in all the categories but radiation (both have zero radiation impact). Like with the armature, the ‘resources’ category is of the greatest importance in the normalized analysis (figure E9) and the other two categories are of negligible importance. Again, the steel causes more damage than the cast iron for all three categories. The single score analysis (figure E10) agrees with the three other figures as the steel has a much higher (~8.4 points greater). Like with the aluminum, the life cycle impact of the steel should remain much greater than the cast iron due to this large single score difference.

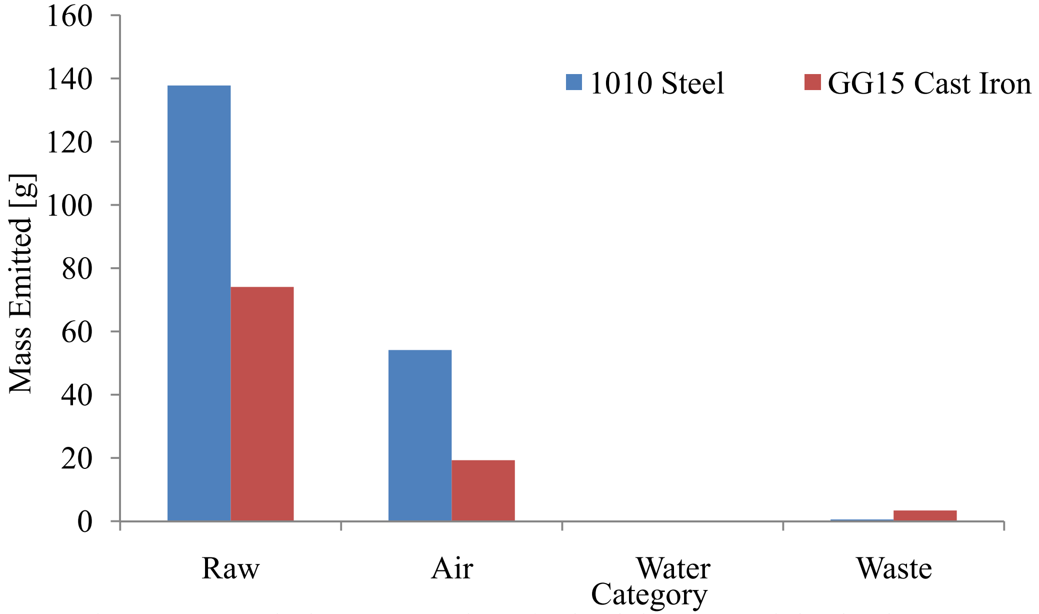
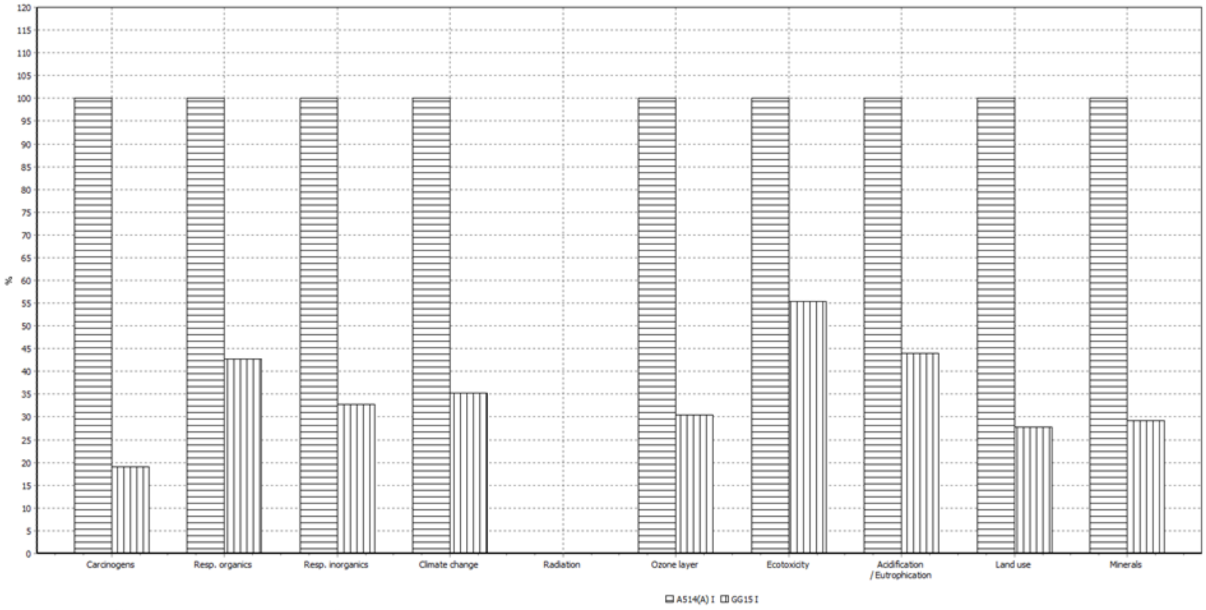
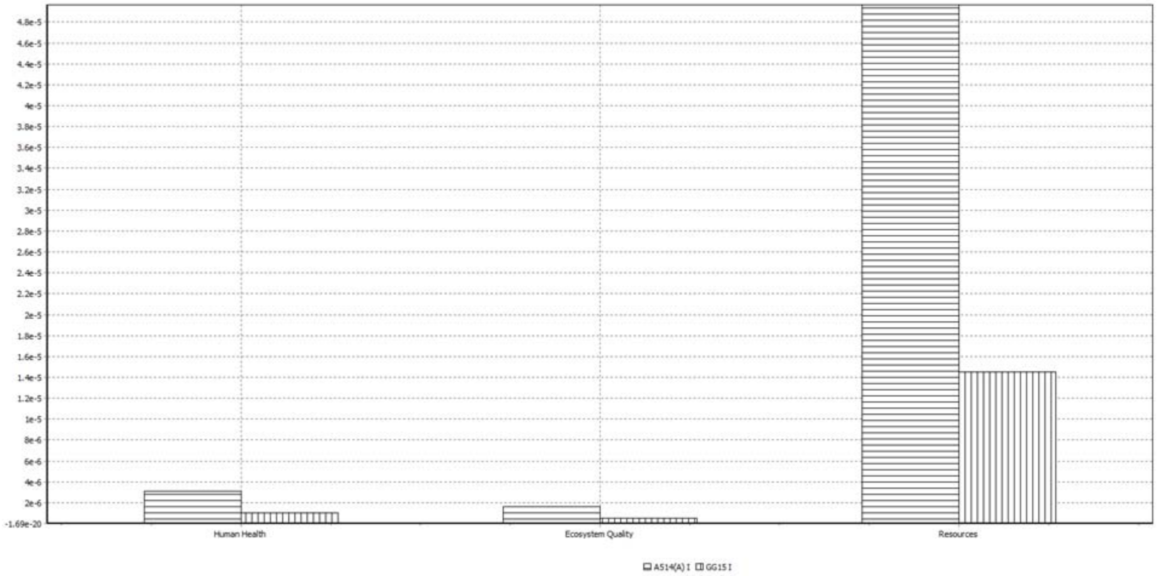


Figure E7: Emissions comparison for back iron material selection



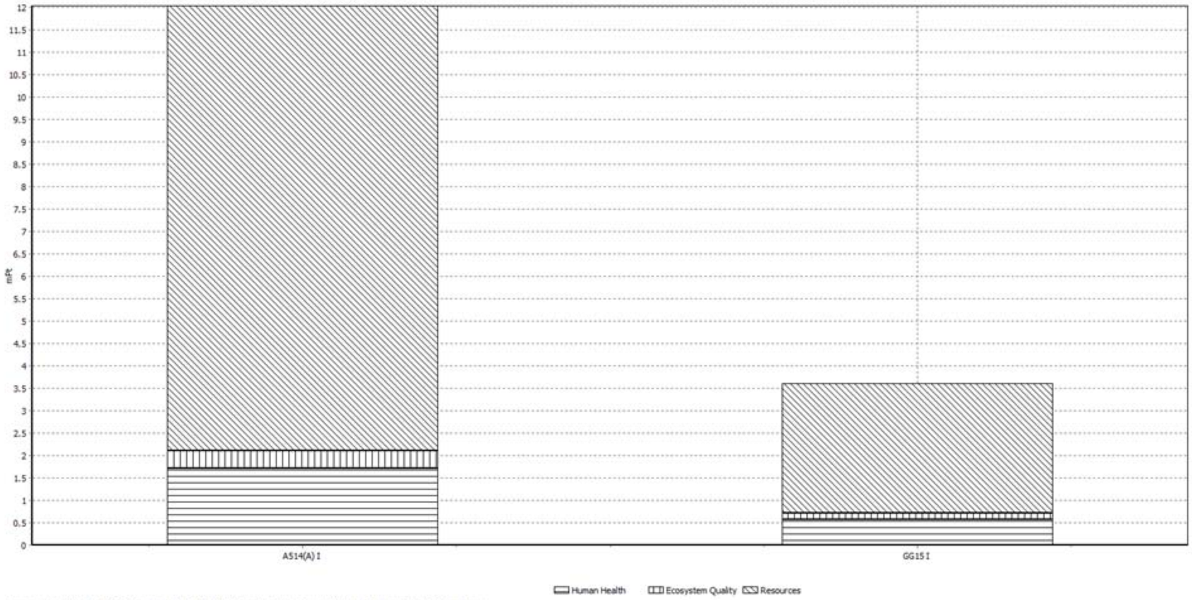
Comparing 0.0451 kg 'A514(A) I' with 0.0404 kg 'GG15 I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / characterization

Figure E8: Comparison of relative impacts in disaggregated categories for back iron material selection



Comparing 0.0451 kg 'A514(A) I' with 0.0404 kg 'GG15 I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / normalization

Figure E9: Normalized comparison for back iron material selection



Comparing 0.0451 kg 'A514(A) I' with 0.0404 kg 'GG15 I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / single score

Figure E10: Single score comparison for back iron material selection

Manufacturing Process Selection

It was important to investigate the full-scale production of our device because it is very likely other piano technicians in the United States and the rest of the world may use such a tool. Since few piano technicians would utilize the device frequently enough to justify purchasing it, we estimated there to be a need for only 2-3 devices per state. This results in the production of 100-150 units for distribution in the United States. Globally, there may be a need for an additional 800 units, so a total production of close to 1000 units. In the future, if the device is successful and does result in large time savings, more units may be required because people may consider balancing their pianos more frequently.

Manufacturing Process Selection: Using the *CES* software, aluminum 2024 was selected as the best material for the coil armature while AISI 1010 annealed steel was chosen as the best material for the back iron. These materials are advantageous over the other good candidates given by *CES* software because they are very common, cheap metals that have relatively simple manufacturing processes, minimize environmental impact, and require no uncommon tooling or manufacturing processes. There was also plenty of stock available in the machine shop.

Since only 240,000 mm^3 of aluminum 2024 is needed per device (0.24 m^3 for 1000 devices) and there is a small demand, it would be best to buy blocks of aluminum and hire someone to mill out the required material. This aluminum is soft and can be easily machined with no special tools or machinery. The raw material is inexpensive ($0.26-$0.31 per pound according to *CES*) and is recyclable so it is not imperative to minimize waste material. Aluminum 2024 is also landfill safe so if some is disposed of, it will not hurt the environment dramatically. Unfortunately, the manufacturing process creates 0.958-1.21 lb CO_2/lb aluminum. While these numbers are not staggering, to be environmentally conscience we should attempt to minimize waste material in mass production (1000 units maximum). With the exception of the x-y table, the components of this device are not complex and do not require high tolerances so it is very probable that most parts could be easily made by a company at an inexpensive price that minimizes waste. The x-y table will likely be purchased externally as many already exist so manufacturing should not be a problem. Furthermore, there has been some discussion regarding the need for an x-y table. The final design might only need to be set on blocks and thereby, reduce the final cost of the device significantly since x-y tables are expensive.

Since only 5735 mm^3 of steel is needed per device ($5.7 \cdot 10^{-3}$ m^3 for 1000 devices) and there is a small demand, it would be best to buy an AISI 1010 annealed steel plate and mill out the required material. No special end mill bits or machinery are required to cut this steel and it is actually better to have rounded inside corners (proved with *Vizimag*) so complex machining is not required. The device will have to be calibrated before use so tolerances do not need to be extremely precise which reduces cost and manufacturing time. Inevitably there will be some waste material but since this type of steel is very common and inexpensive ($0.75-$0.83 per pound according to *CES*), it should not dramatically impact the budget. Furthermore, this steel is recyclable so waste can be sold back to manufacturing plants or scrap yards for money. Also, this steel is landfill safe so it does not pose a huge risk to the environment. One negative consequence of using steel is the annealing process which requires sustained heat treating and leaves a CO_2 footprint (0.66-0.73 lb CO_2/lb steel). Unfortunately, this is an outcome of most metal working and must be accepted.

APPENDIX F – Final Design Images

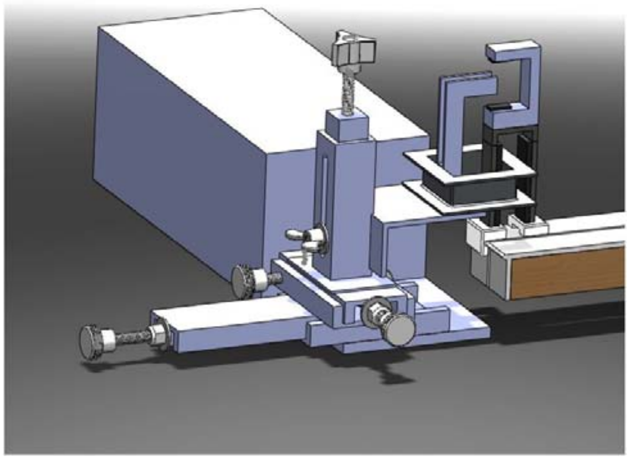


Figure F1: Final assembly

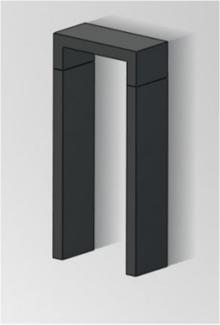


Figure F2: Back iron

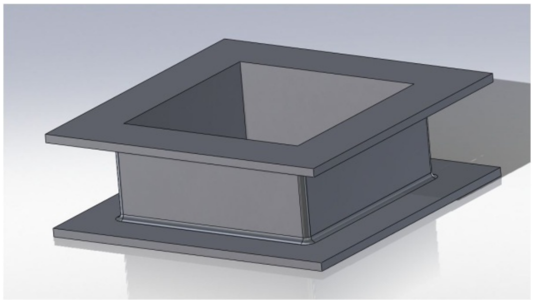


Figure F3: Armature

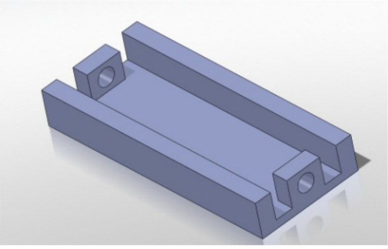


Figure F4: X-axis table base

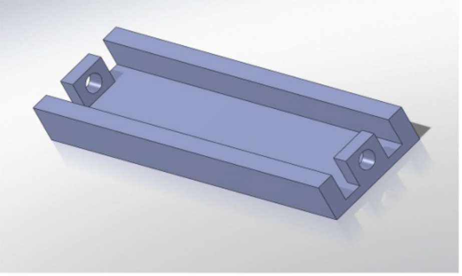


Figure F5: Y-axis table base

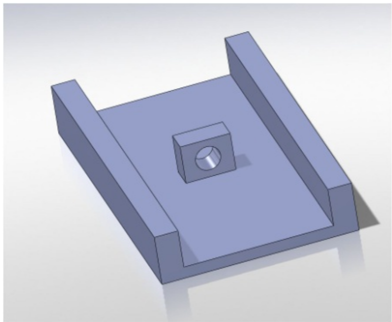


Figure F6: X- and y-axis table top

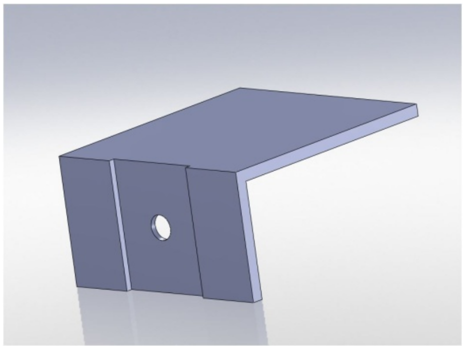


Figure F7: Z-axis table plate

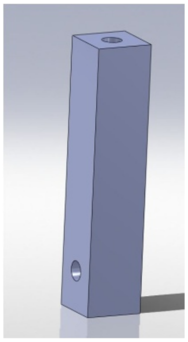


Figure F8: Z-axis table shaft

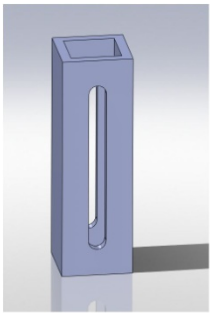


Figure F9: Z-axis table tube

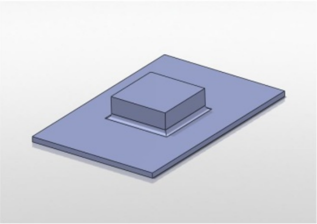


Figure F10: Z-axis table base

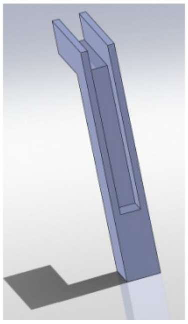


Figure F11: Hall effect sensor bracket

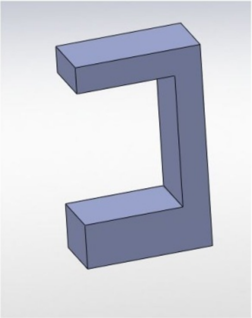


Figure F12: Hall effect magnet bracket


Figure F13: Hall effect magnet


Figure F14: Voice coil magnet

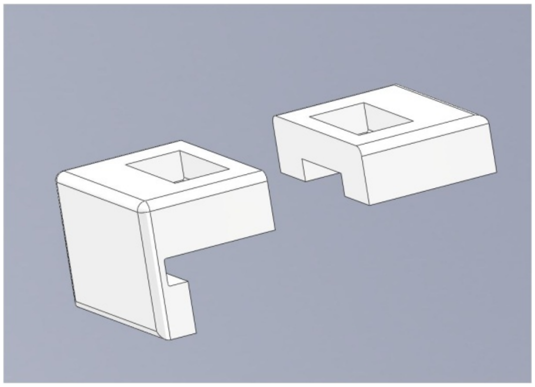


Figure F15: Magnet base plates

APPENDIX G – Dimensioned Drawings

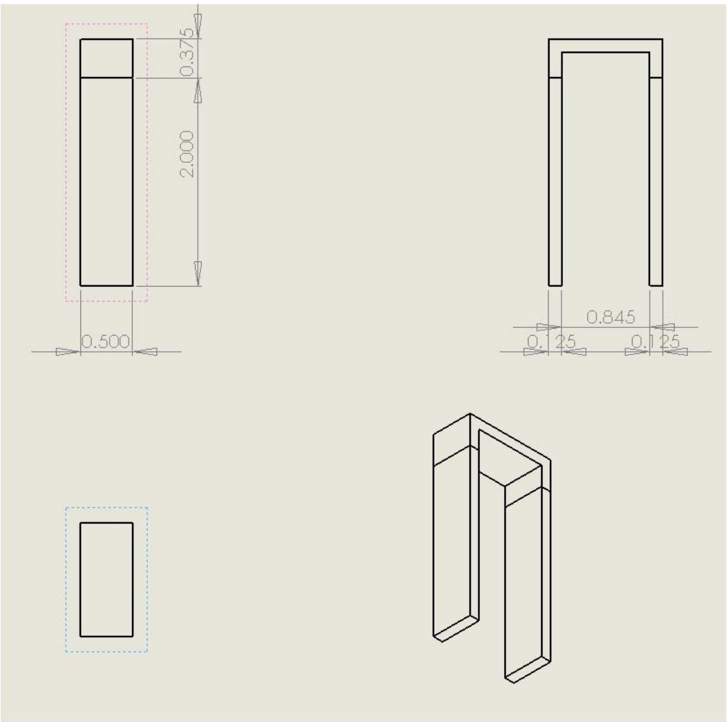


Figure G1: Back iron

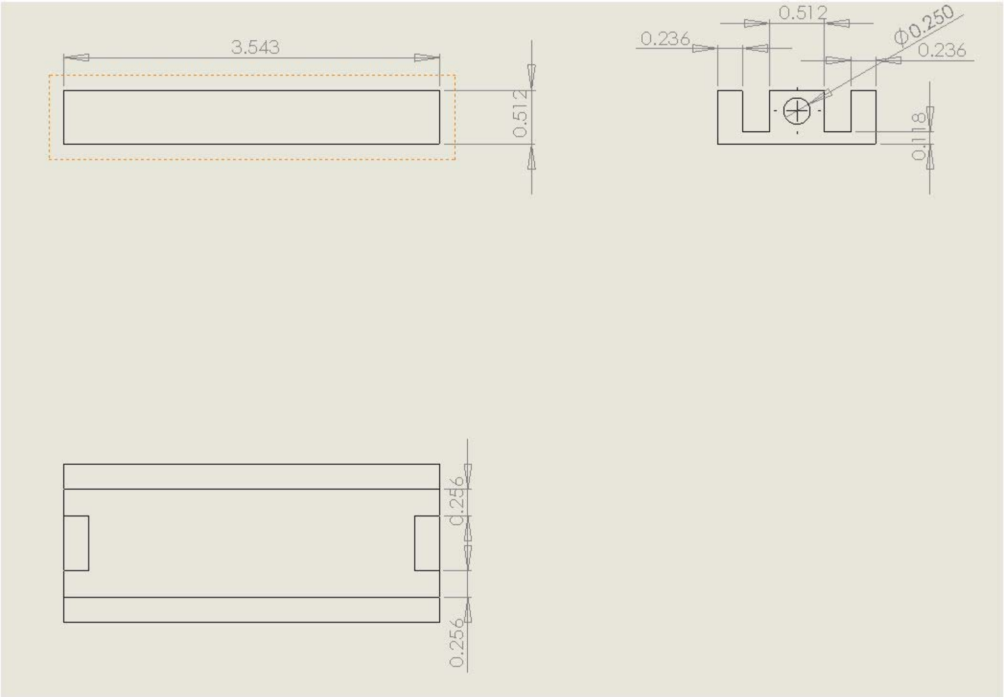


Figure G2: X-axis table base

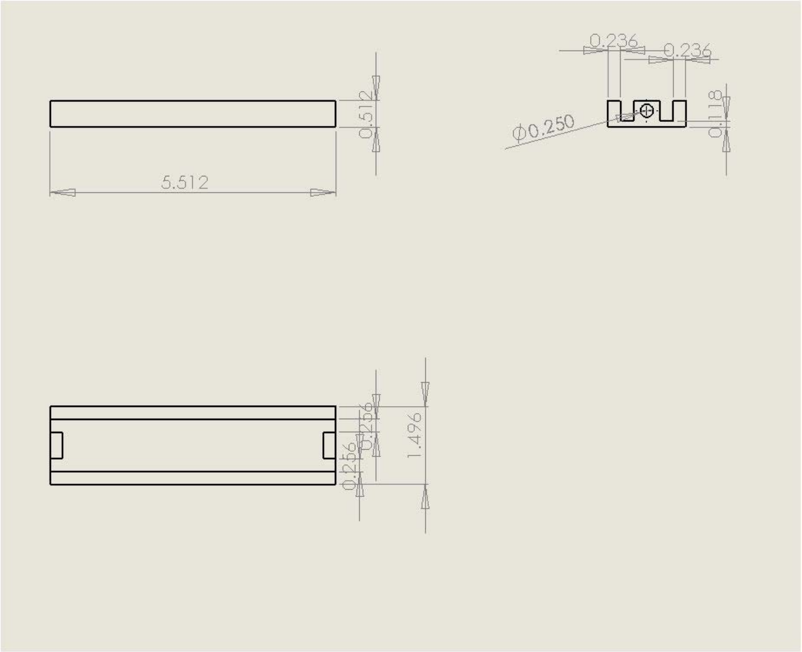


Figure G3: Y-axis table base

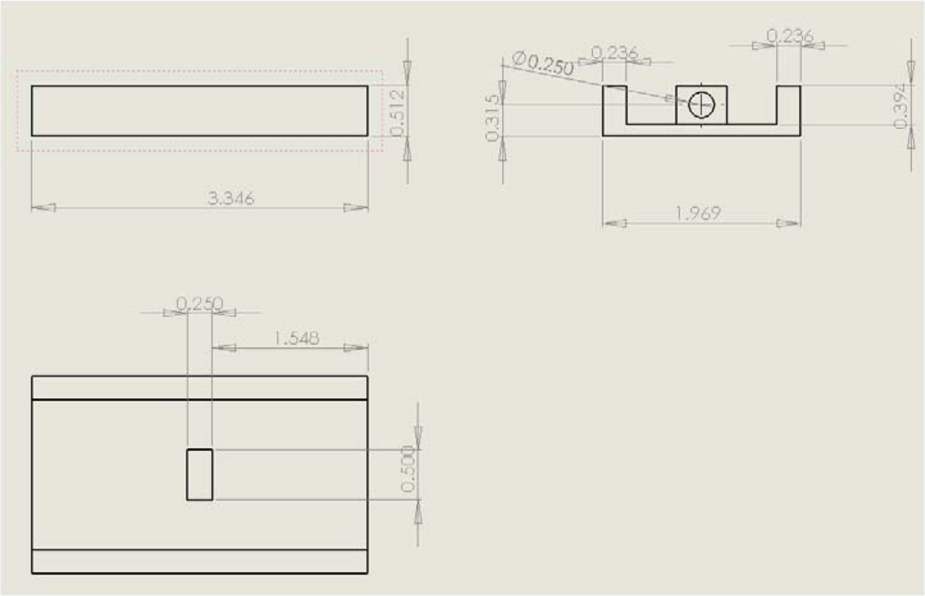


Figure G4: X- and y-axis table top

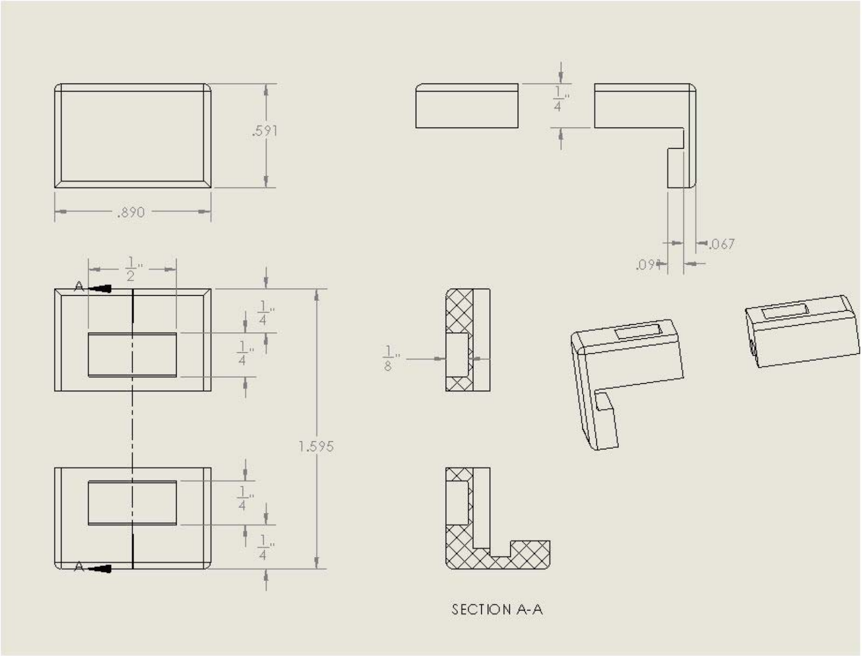


Figure G5: Magnet base plates

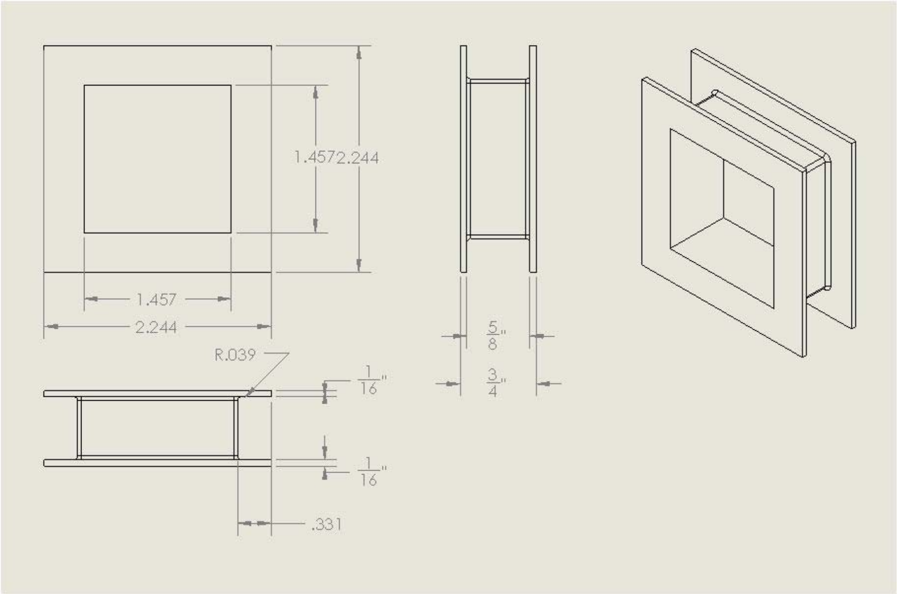


Figure G6: Armature

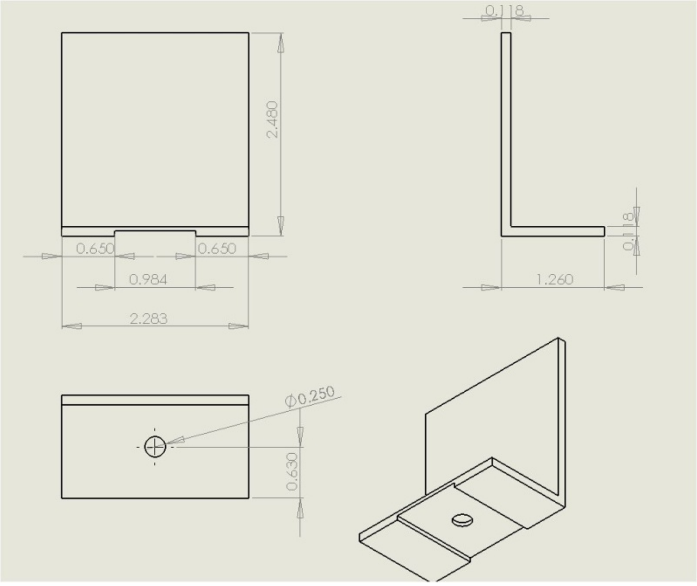


Figure G7: Z-axis table plate

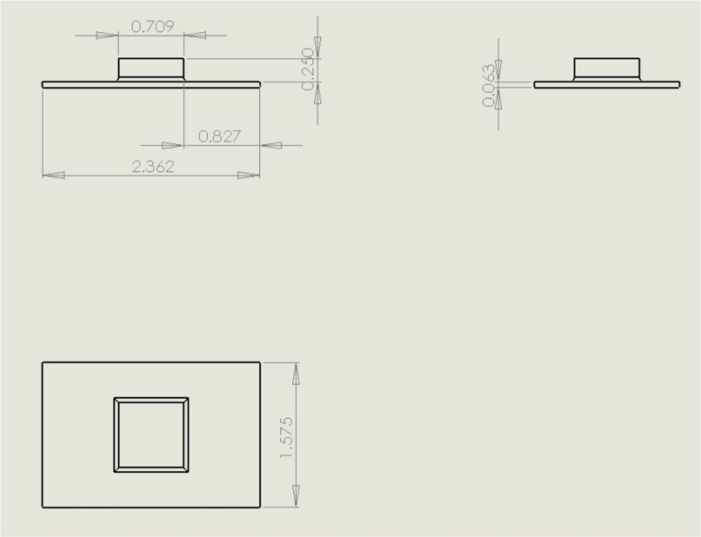


Figure G8: Z-axis yable base

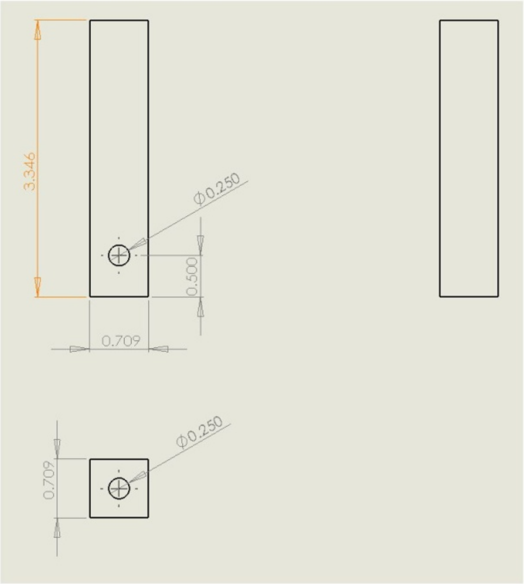


Figure G9: Z-axis table shaft

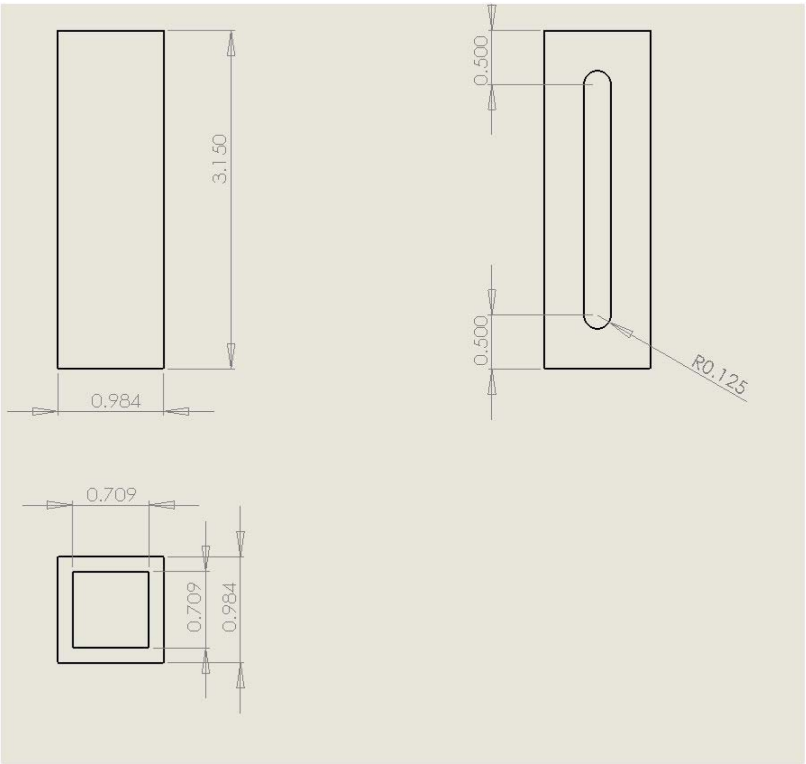


Figure G10: Z-axis table tube

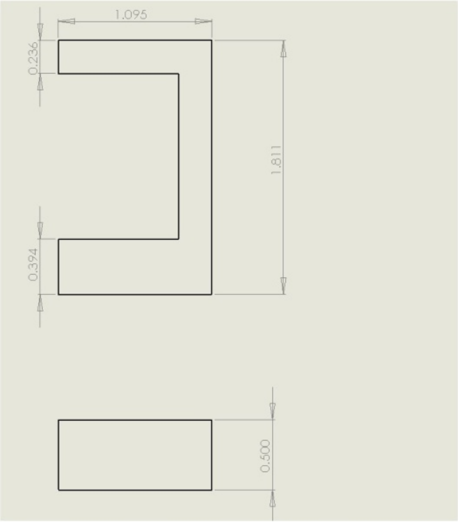


Figure G11: Hall effect magnet bracket

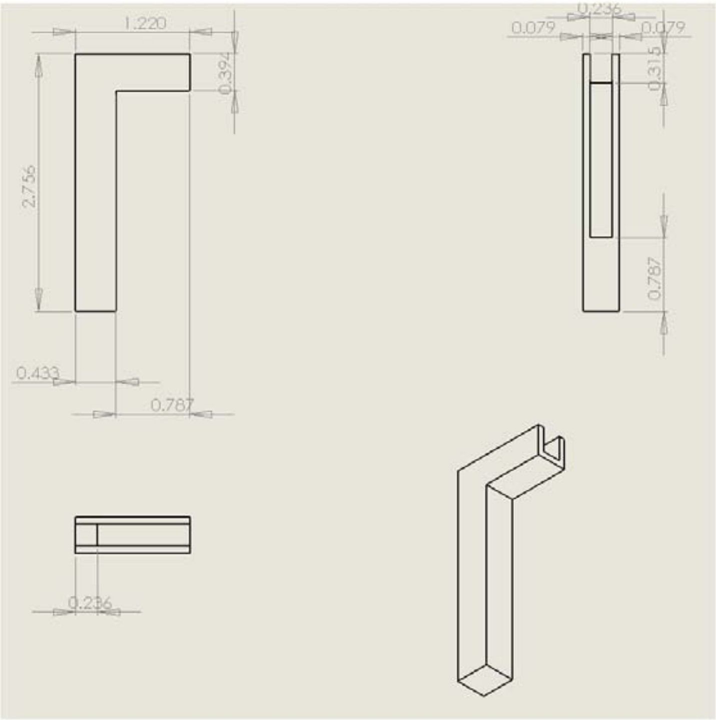


Figure G12: Hall effect sensor bracket

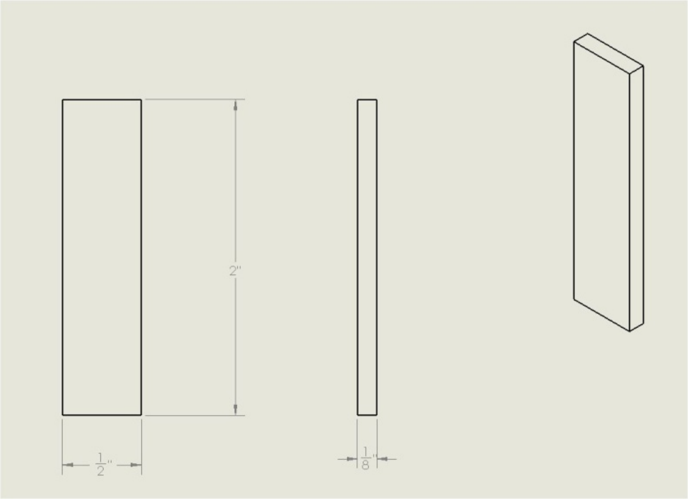


Figure G13: Voice coil magnet

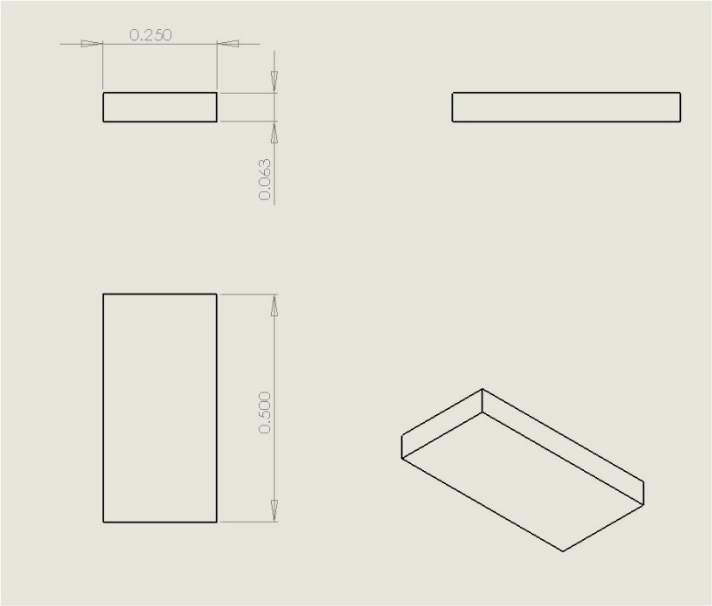


Figure G14: Hall effect magnet

ME 450 Safety Reporting: Winter 2010

Project 17 **Date:** March 22, 2010

Report Version 1

Project Title: Labor Reducing Piano Balancing Mechanism Using Precise Voice Coil Motor with No Friction

Team Member Names:	David Boehmer Phil Eklem Vijay Venkataraman Michael Werries
Team Member Uniquenames:	dboehmer pjeklem vvenka mwerries

Attach your Safety Report to this cover page and instructions found on Pages 2 and 3.
The Safety Report is to be completed by your team and must be approved by your section instructor (or approved substitute) prior to any hands-on experimentation, manufacturing or testing of your prototype.
The safety hazards inherent in your experimental plans, component selection, manufacturing methods, assembly techniques, and testing must be expressed and evaluated before any hands-on work with safety consequences will be allowed to proceed.
The purpose of this safety report is to assure that you have thought through your hands-on work before it begins, and that you have shared your plans with your Section Instructor. You may submit more than one version. This will likely be necessary as your project evolves.

APPROVAL:

Name: ___________________________

Signature: ___________________________

Date: ___________________________

EXECUTIVE SUMMARY

This report covers safety issues involved with process experimenting and fabrication of the design prototype and final design units. After considering each of these aspects in great detail by considering each step that would be required to complete each process, potential hazards have been identified and include high temperature in coil wire, shock in electrical components, and injuries associated with high power machinery.

Process Experimenting

Hazards caused by heat generated within coil wires will be eliminated by experimentation to identify dangerous power output levels and limiting power generated in the final design. Some hazard will still exist during the experimentation to identify dangerous power generation, but will be limited by designing a controlled environment to perform such experiments. Hazards caused by electrical shock have been eliminated by using low voltage components during experimentation and in the final design.

Fabrication

Hazards involved with high powered manufacturing machinery cannot be entirely eliminated since the safety of a machine operator depends upon how careful and conscientious his or her methods are, but they can be greatly reduced by using protective equipment and other precautionary measures. Such protective equipment includes safety glasses and gloves to protect from projectile chips at high speeds and temperatures. Other precautionary measures include wearing clothing without frayed and loose pieces that could get caught in the machinery, wearing close-toed shoes, not wearing jewelry, and double checking that all machines are used under appropriate settings.

Therefore, it has been determined that with careful procedures and safety equipment that all required activities are of low to moderate risk.

EXPERIMENTATION PLANS PRIOR TO DESIGN COMPLETION

Coil wire resistance, input current for a given voltage, and qualitative heat generation measurements. All of these measurements are necessary to predict and confirm performance aspects of the final design. This data is also very important to consider so that the final design does not allow generated heat to destroy components of the device or injure the operator in any way.

The ultimate goal of this design is to produce a controlled variable force using a voice coil motor. The force produced by a voice coil motor is governed by the following equation:

$$F = (ILxB)N$$

where F is the output force, I is the input current, L is the length of coil though the magnetic field, B is the magnitude of the magnetic field, and N is the number of turns in the coil. This design will use a variable current, caused by a variable voltage, to produce a variable force output. Ohm's law governs the variable current by the following relationship:

$$I = V/R$$

where V is the input voltage, R is the constant resistance in the wire, and I is the resultant current. While these two relationships are enough to predict the output force for any change in parameters, we are extremely concerned with the power generated by the circuit as much heat can be generated in the coil. Power generation is governed by the following relationship:

$$P = IV = IR^2$$

where P is the power generated and I and V are current and voltage respectively. Since a relationship between power generated and wire temperature is difficult to predict under the given circumstances, a qualitative method of testing this relationship is used instead. This qualitative method consists of creating several different coils of different wire sizes and turn numbers and determining the power threshold for which the coil reaches a concerning temperature. Temperature determination will be done by touching the coils at various voltage settings in a very carefully controlled manner.

Before optimizing the parameters in the above equations to select coil parameters for the final design, several coils of different wire sizes and turn numbers will be created by winding wire around a rectangular piece of wood and holding their shape with electrical tape. Each coil will be connected to a variable voltage power supply and current will be run through each. By starting at the lowest voltage setting and gradually increasing it until the first team member indicates that the temperature is concerning, the voltage and resistance will be recorded for each coil at this point and the power generated will be calculated using the governing equation and recorded. With a power threshold to limit heat generation in the coil, the rest of the coil parameters can be optimized and a final coil design can be generated.

FMEA ANALYSIS OF ALL MATERIALS

FMEA analysis was performed on the components that are assumed to be most likely to fail during manufacturing and testing: magnets, back iron, armature, coil, circuit components, and Hall Effect sensors (see Appendix A). Failure in the magnets, back iron, and Hall Effect sensors are included primarily to account for the decrease in measurement accuracy and reliability that will result if not assembled correctly. Proper selection of armature material ensures that it will be an unlikely failure. Failure of the coil and other circuitry components are presumed to be more severe as they can cause destruction of the device and injury by generating heat. Proper inspection will keep these failures as infrequent as possible. Proper handling and inspection prior to installation and testing will greatly reduce the likelihood of failure of all components included in the prototype and final design.

CAD DRAWINGS

Dimensioned engineering drawings included in this section describe the parts of the prototype and final design that will require machining in coordination with our safety analysis.

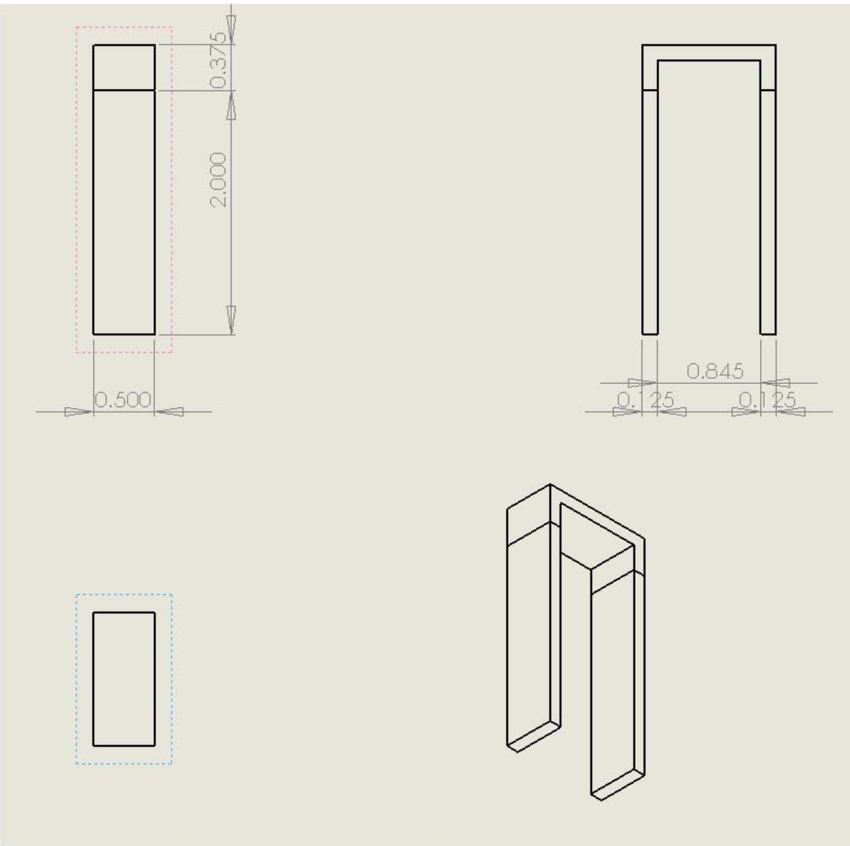


Figure SR1: Back iron

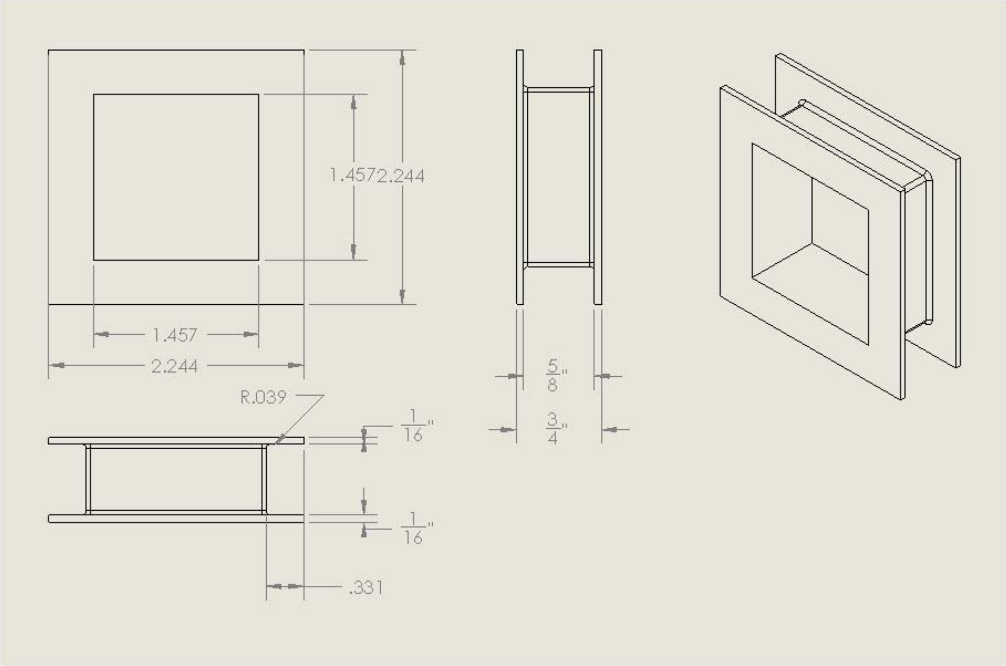


Figure SR2: Armature

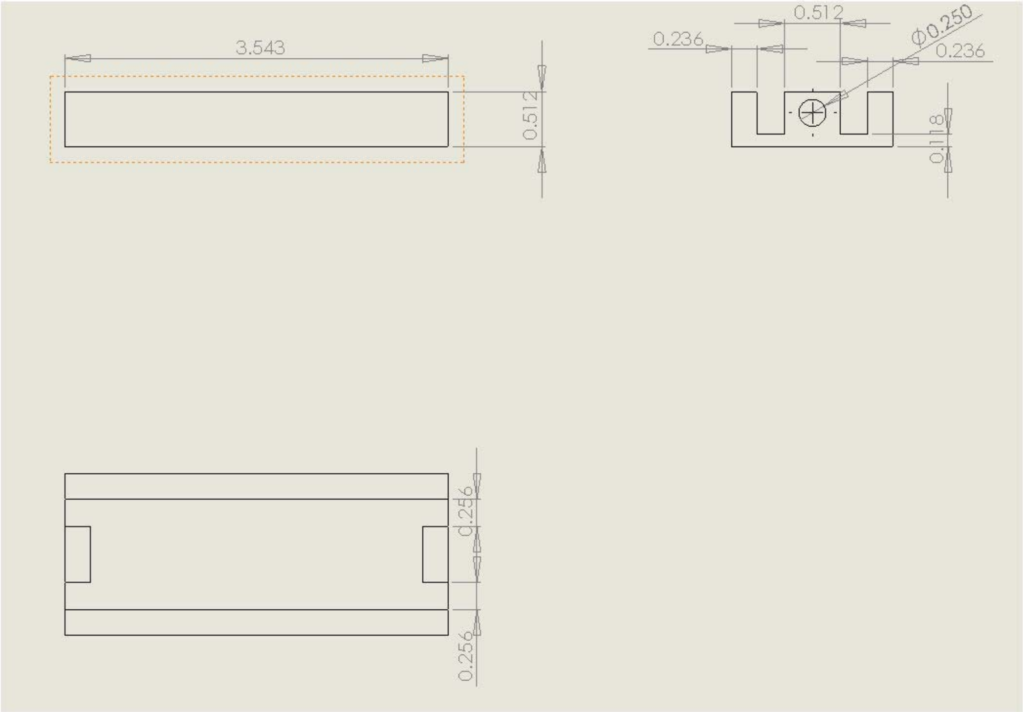


Figure SR3: X-axis base table

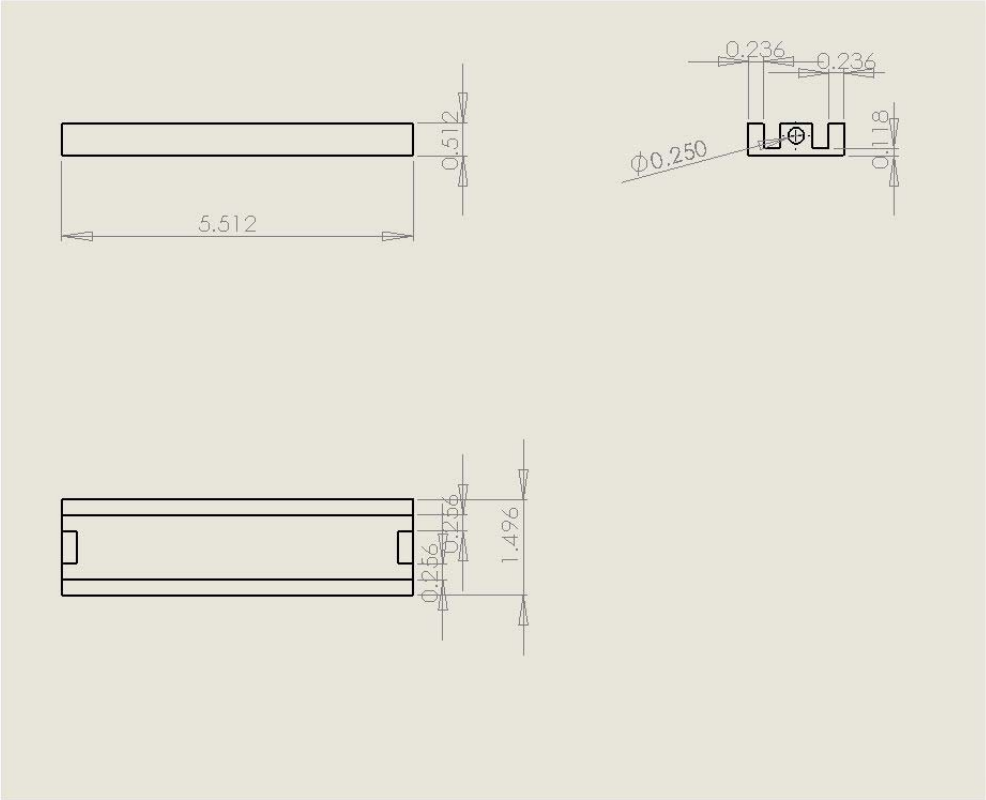


Figure SR4: Y-axis base table

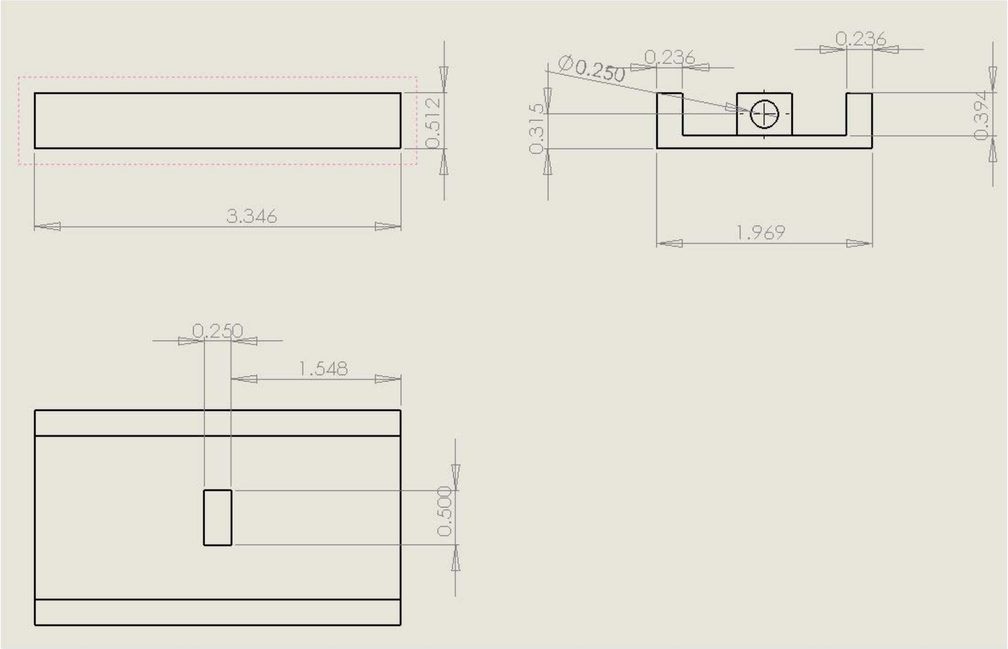


Figure SR5: X-axis and y-axis top plate (2 total)

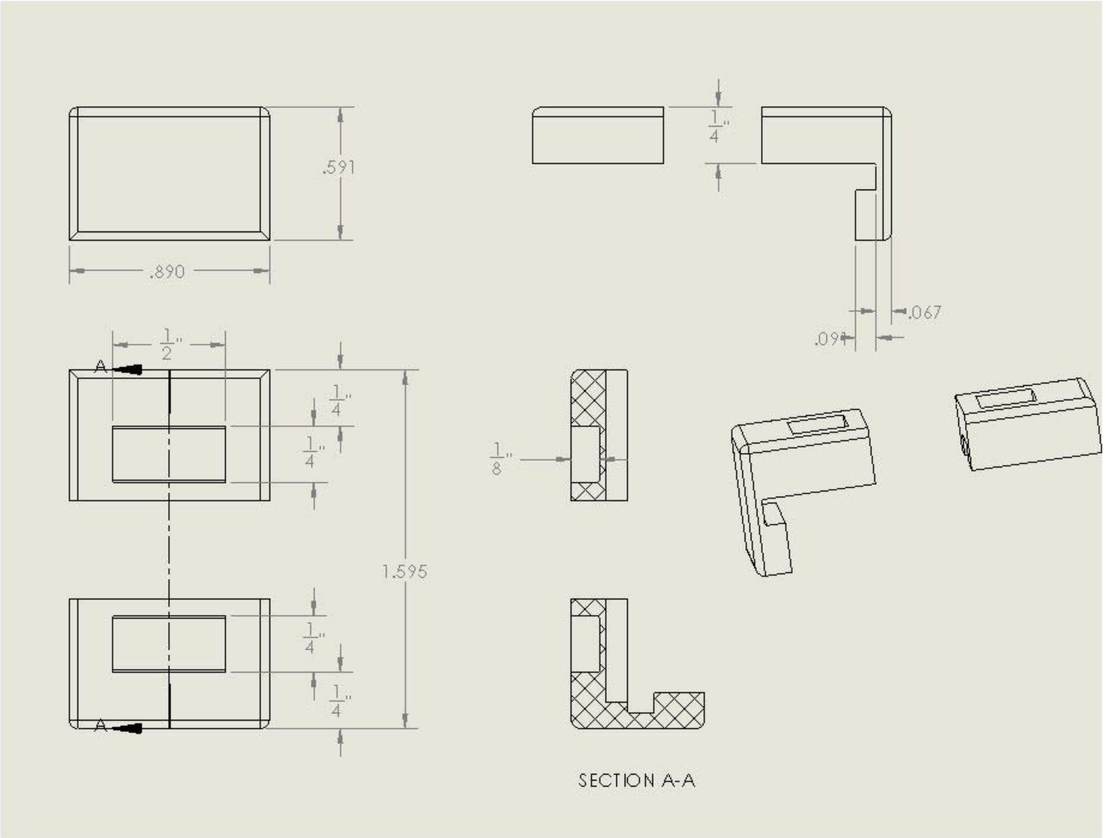


Figure SR6: Black/white key back iron base

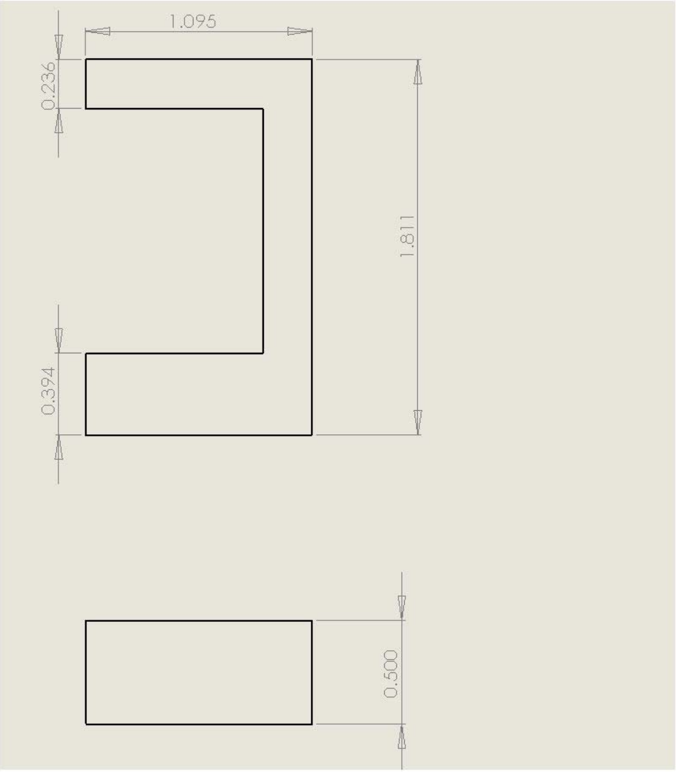


Figure SR7: Hall Effect Bracket

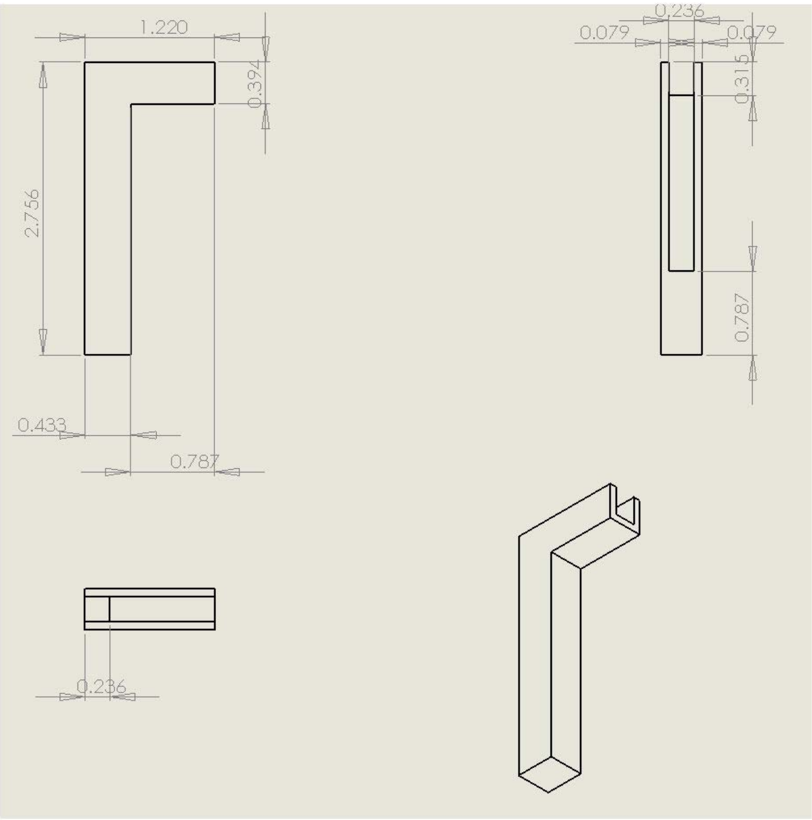


Figure SR8: Hall effect bracket

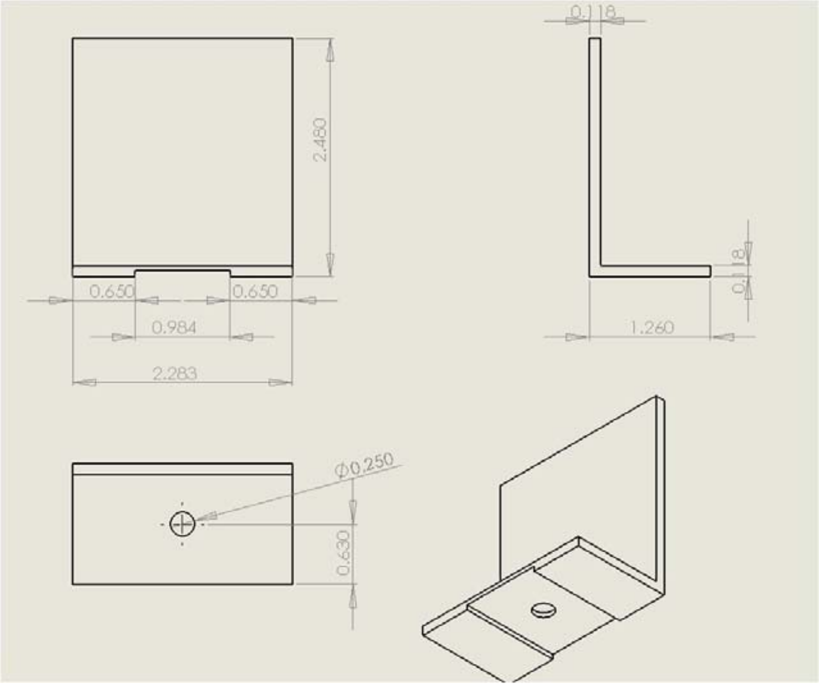


Figure SR9: Coil bracket

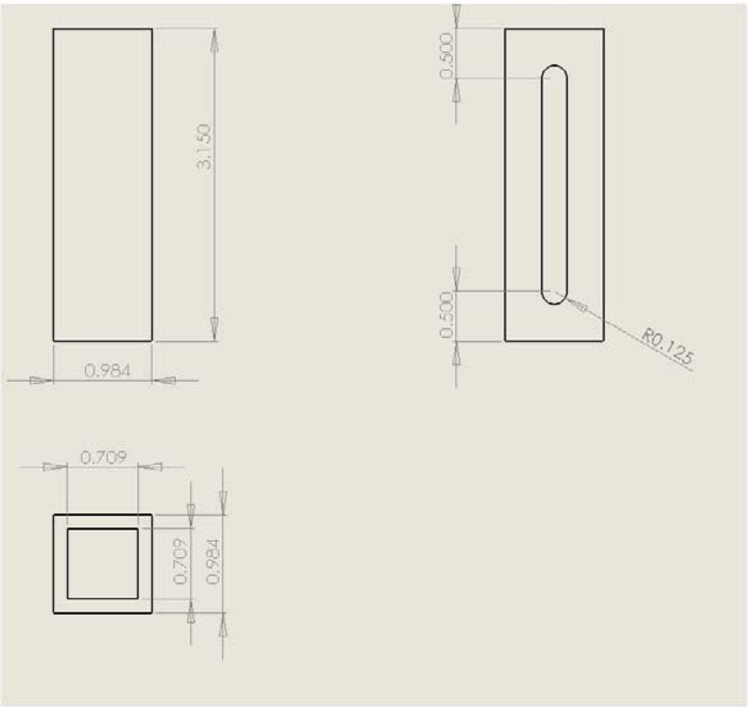


Figure SR10: Z-axis tube

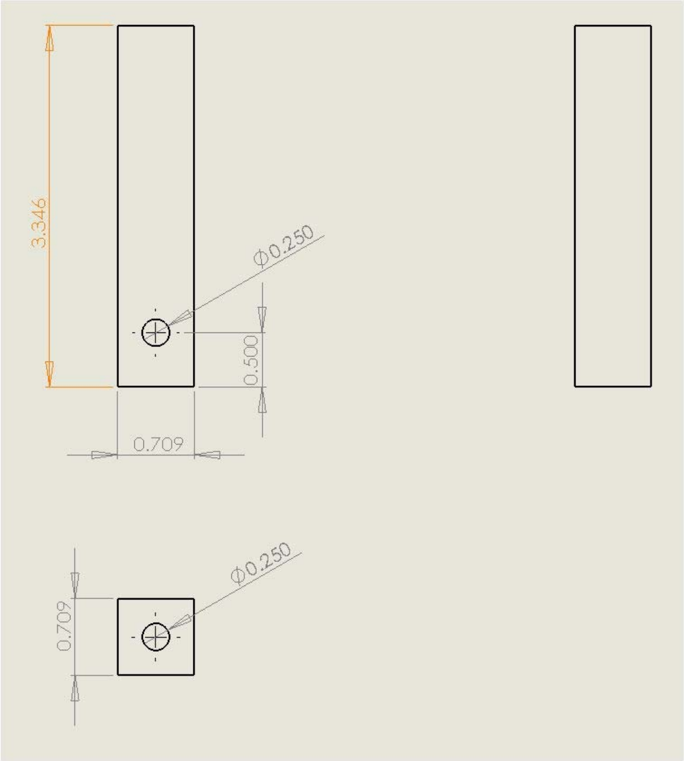


Figure SR11: Z-axis shaft

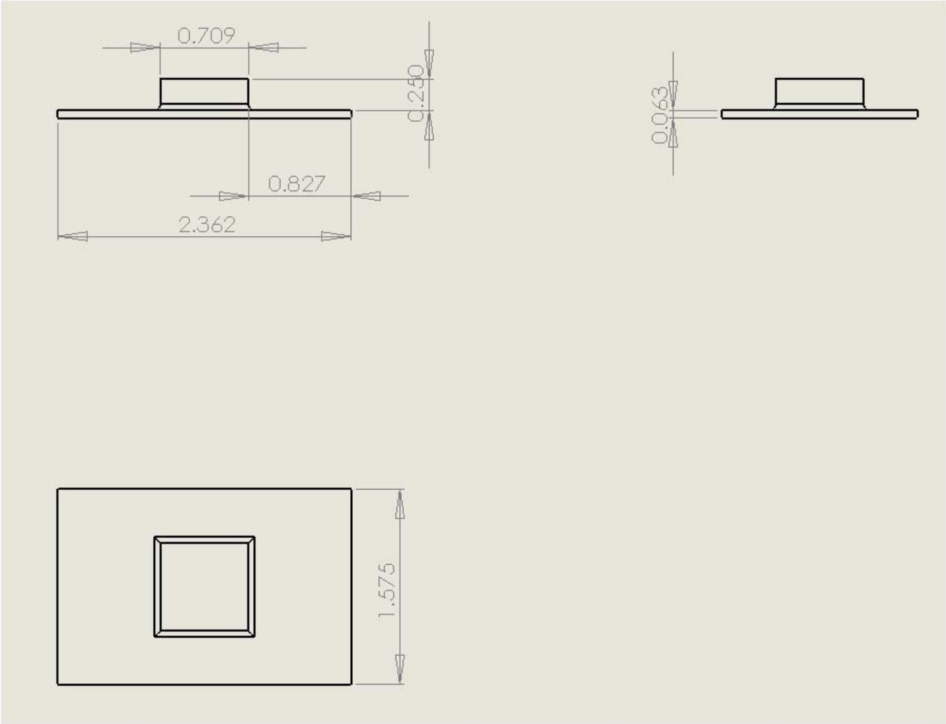


Figure SR12: Z-axis base

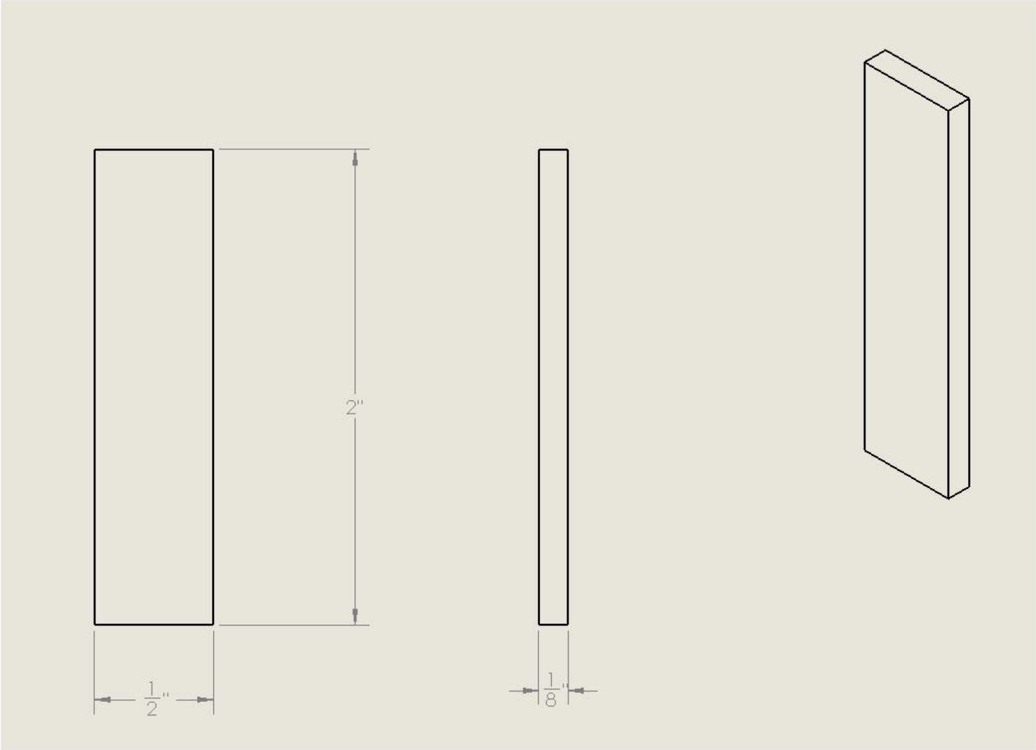


Figure SR13: Back iron magnet (2 total)

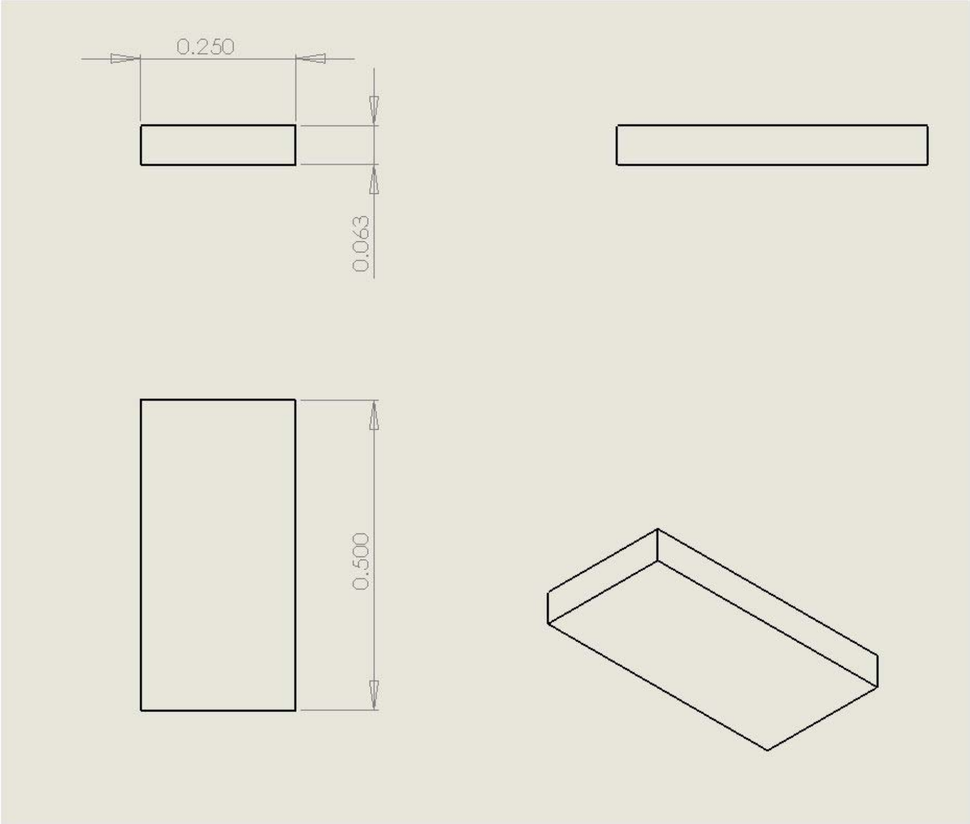


Figure SR14: Hall effect magnet (2 total)

DESIGNSAFE RESULTS FOR MANUFACTURED COMPONENTS

Designsafe was used to determine the risks and hazards involved in the two most potentially dangerous parts of the product: the coil and the magnet apparatus. The Designsafe report is in Appendices B and C. The risks associated with the coil are insulation failure, water contact, overvoltage/overcurrent, smoke, and severe heat. The hazard with the highest risk is severe heat as the current passing through the wire cause it to heat up, and there is a chance for it to hot enough to cause to injury to the user if contact is made with the wire. Insulation failure would occur if the wire became exposed to the user, resulting in electrocution, but this risk is low as we will make sure there more than enough of a barrier between the coil and the user to prevent this risk from occurring. The coil being exposed to water could also result in electrocution or worse, but this is a very low risk because water or other liquids should not present on the work bench since pianos are very sensitive to them. Overvoltage/overcurrent refers to applying too much voltage or current through the coil, resulting in rapid heating of the wire and smoke, but this risk is low because a control system will be implemented to ensure the current and voltage are within safe limits. Smoke is a moderate risk because of its potential impact of respiratory irritation. In addition to the controls, warning labels will be placed on the device to make the user aware of these risks, however unlikely they may be.

The risks associated with the magnet apparatus are crushing, cutting, exposure to a pinch point, magnetic attraction/movement, machine stability, and movement to/from storage. All these risks were moderate, except for the machine stability which was high. The machine instability arises from the fact that the device will placed close to the edge of the workbench, making it susceptible to falling off the edge and landing on the user, potentially resulting in injury. Also, the presence of external magnetic fields may prevent the device from being perfectly constrained. To prevent this risk, we are recommending the user to wear appropriate footwear when using the device. The crushing, cutting, and exposure to a pinch point are all risks that can cause injury to the user due the magnetic plates converging together with user's hand or other extremity between them. The magnets being used are very strong and very much attracted to each other. These risks will be avoided by advising the user to keep extremities out of the magnetic field when the device is in operation and ensuring the adhesive holding the magnets to the armature is more than strong enough to overcome the magnetic attraction between the plates. The final risk is movement to/from storage, which can result in injury if the magnets are exposed to another magnetic field while being stored, resulting external objects being drawn to the device and colliding with the user. This risk will be avoided by advising the user to store the device in a place where objects that may attract to it not be present. As with the coil, there will be warning labels placed on the device to ensure the user is aware of the risks.

MANUFACTURING

All machining referred to in this section takes place in the Student Machine Shop.

Fabrication begins with machining the back iron for the magnet apparatus. The specified amount of teel bar stock in the inventory is first taken from a larger piece by using a band saw running at 85 ft/min. The large piece of stock is placed on the saw table and is pressed into the moving saw blade with a piece of wood so that the operator's hands are not required to come near the blade. The required piece of carbon steel is then taken to the mill where each side is leveled by a 0.625 inch four-flute end mill running at 397 rev/min. The steel piece is then repositioned so that a 0.25 inch four-flute end mill running at 993 rev/min can be used to remove material from the magnet gap area. Once the gap is finished, the remaining material around the outside of the work piece is removed with the 0.625 in four-flute end mill at 397 rev/min until the desired outside dimensions are met.

The coil armature is machined by first cutting the desired size from the aluminum sheet specified in the inventory list using a band saw running at 375 ft/min. The work piece is pressed against the moving saw blade with a piece of wood so that the operator's hands are not required to come near the blade. The work piece is then taken to the mill where each side is made level by a 0.625 inch two-flute end mill running at 1200 rev/min. A rectangular hole is removed from the inside of the work piece using the same machine setup. A 0.1875 in ball-end mill running at 1200 rev/min is used next to remove a 0.1875 inch deep trench around the perimeter of the work piece. Finally, a 0.25 inch drill bit running at 1200 rev/min is used to machine holes into the surface of the armature so that 90° angle brackets can be fastened to the armature. Armature support arms will also be cut using the bad saw and holes drilled at both ends so that they can be attached to the angle brackets.

The other ends of the support arms will be attached to the rigid structure or body for both the prototype and final design. The prototype will use a rigid structure made of 90° angle stock with a wood base. A hack saw or band saw will be used to cut the metal frame pieces to correct lengths and a circular saw will be used to cut the wood pieces of the base. The rigid body of the final design will be an adjustable post extending from a box that contains all necessary electronic components. The final design may also include a four-bar linkage system in place of an adjustable post, but further analysis of this function must be completed before a final decision is made. Body pieces of the final design will be made of transparent acrylic sheets or of wood boards.

The white/black key base plate sits are machined on the mill using a 0.25 inch two-flute bit running at 993 revs/min.

Brackets for the Hall Effect sensor will also be machined from epoxy castings. Molds of the bracket will be machined into wax blocks and back filled with epoxy. Once the epoxy is cured, the final shape and dimensions will be achieved through further machining on the mill. Machining will be performed on the mill using a 0.25 inch two-flute bit running at 993 revs/min.
Assembly of the body will begin by drilling holes into the walls for fastening locations to join electronic components to the inside walls. Holes will also be drilled along the perimeters so that the walls can be joined after all electronic components are connected. Each component will be screwed into place followed by each body wall.

ASSEMBLY

Assembly of both the prototype and the final design will take place in the X50 laboratory. With all necessary components pre-machined and prepared for installation, the bodies of both the prototype and final design will be assembled first. In the case of the prototype, the body structure will entirely be constructed before any other components are attached. The final design contains a power supply, amplifier, and LCD display within the body and has each of these components fixed to its inner panels before they are assembled.

Before the armature is attached to the body structure, the coil is wound around the armature a specified number of times and the angle brackets are attached to the armature surface. For Position sensing purposes, the Hall Effect sensor core must be fixed to the center of the armature. The armature is then attached to the body structure in both cases by fastening the armature support arms to both the armature and body structure.

Magnets can then be placed on the back iron in appropriate configuration so that the plate faces are of opposing poles. Hall Effect magnets can then be placed on the Hall Effect sensor brackets.

The magnets and back iron can then be placed in the proper base plate for the appropriate key being tested. At this point, all of the mechanical pieces requiring assembly are accounted for. The electronic components must now be connected to appropriate power sources and data acquisition centers. The prototype will only require that the coil wires be connected to external an external circuit composed of a power supply and computer, whereas the final design must have an integrated circuit of power supply, signal amplifier, processor, and display.

Since all mechanical components of the prototype and final design are composed of strong materials and are securely fastened with nuts, bolts, and adhesives, failure prior to or during use is not anticipated. The electrical components of the final design will be completely secured and protected by the body structure so that failure of these components will be very unlikely, assuming they were assembled properly. While the electrical components of the prototype are not protected by a body structure, its components will be used in the same location that they are assembled and will not be relocated for the duration of prototype testing.

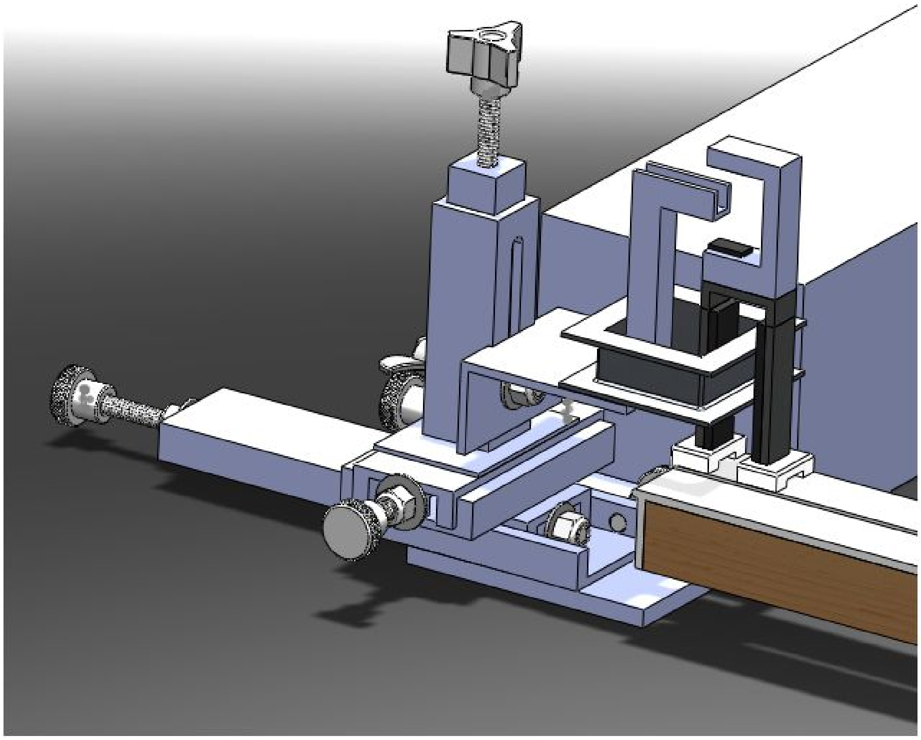


Figure SR15: Final assembly

DESIGN TESTING AND VALIDATION

Testing and validation of the design took place in Professor Gillespie’s lab. Testing was performed on a fully functional piano key model. Proper function of components and verification dimensional correctness was tested during prototype testing. Parameters and specifications such as heat generation, force output, and special compliance was confirmed using the prototype.

The device does produce enough force on the key (81.1g) but programming still needs to be done to control its motion. When the device is deemed sensitive enough for data collection, it will be tested and calibrated to achieve the desired resolution, accuracy, and precision of measurement.
When fully functioning, the device will then be taken to the Director of Piano Technology, Professor Robert Grijalva, so that the device can have a final validation by the customer.

ADDITIONAL APPENDICES

Appendix SRA: FMEA Analysis

Team #: 17	**Report Version:** Design Review 3	**Date:** March 22, 2010
Project Title: Labor Reducing Piano Regulating Mechanism Using Precise Voice Coil Motor with No Friction		
Team Members: David Boehmer, Phil Eklem, Vijay Venkataraman, Michael Werries		

Part and Function	Potential Failure Mode	Potential Effects of Failure	Severity (S)	Potential Causes of Failure	Occurrence (O)	Current Design Controls/ Tests	Detection (D)	Recommended Actions	RPN (=SxOxD)
Magnets: provide uniform magnetic field	Cracking/ shattering	Rapid/ unpredictable self-realignment	4	Dropping/ allowing to collide	3	Epoxy magnets to back iron/check with light pressure	1	Install one magnet at a time/use sufficient adhesive/test with light pressure	12
Back Iron: provide magnet structure/increase magnetic flux	Bending	Non-uniform magnetic field	2	Poor machining/ dropping	1	Start machining with extra material/use specific order of operations	1	Inspect final dimensions for misalignment	2
Coil: Provide induced magnetic field	Overheating /short circuit	Melting/burning/injury/ motor failure	8	Overload of voltage/ poor handling/ exposed wire	3	Operate with current limitation and control/avoiding sharp tools	1	Confirm proper circuitry before use/inspect wire while installing/look for smoke and sparks	24
Armature: provide structure to coil/ dissipate heat	Overheating	Melting/burn/ injury	2	Overload of voltage	2	Operate with current limitation and control/use material that dissipates heat	2	Confirm proper circuitry before use/slowly check temp before handling/look, smell for smoke	8
Power Supply: supply voltage	Overheating /short circuit	Melting/ burning/ device failure	7	Overload input voltage/ poor handling/ circuit flaw	2	Confirm proper circuitry/prevent damage by covering unit	2	Check system wiring/look,smell for smoke/listen for humming	28

Amplifier: amplify signal	Overheating /short circuit	Melting/ burning/ device failure	6	Overload input voltage/ circuit flaw	2	Confirm proper circuitry/prevent damage by covering unit	2	Check system wiring/look,smell for smoke/listen for humming	24
Processor: calculate force values	Overheating /short circuit	Melting/ burning/ device failure	6	Overload input voltage/ circuit flaw	2	Confirm proper circuitry/prevent damage by covering unit	2	Check system wiring/look,smell for smoke/listen for humming	24
Hall Effect Sensors: detect position of key	Alignment flaw/field saturation	Poor results/ inactivity	2	Poor assembly/ stronger magnetic field in proximity	6	Perform preliminary test before data collection/allow for adjustability	3	Include alignment indicator light	36
LCD Display: visual readout of weight values	Cracking/ malfunction	Inactivity	2	Poor handling/ circuit flaw	2	Confirm proper circuit connections	1	Ensure circuit connects are correct/ use protective cover	4

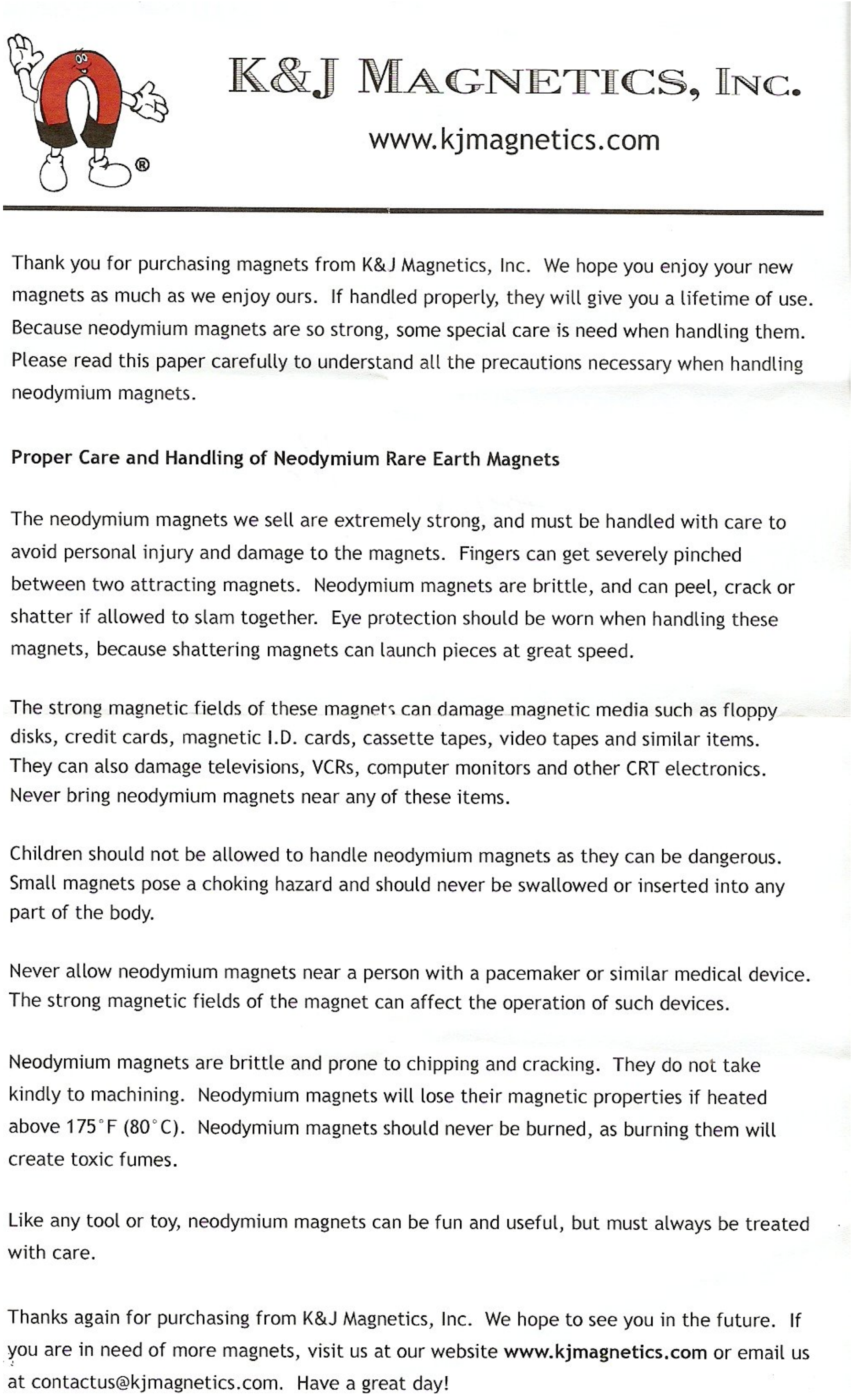
APPENDIX SRB: Designsafe Results for Magnet and Back Iron

Users/Tasks	Hazards/ Failure Mode	Initial Assessment Severity, Exposure, Probability	Initial Risk Level	Risk Reduction Method	Final Assessment Severity, Exposure, Probability	Final Risk Level
All Users/ All Tasks	Mechanical Crushing: The epoxy bond holding the magnets to the U-shaped back iron could fail. As a result, the highly attractive magnets could converge and crush/injure extremities if between/near plates.	Slight, Occasional, Unlikely	Moderate	Warning Labels	Slight, Remote, Unlikely	Low
All Users/ All Tasks	Mechanical Cutting/Severing: The epoxy bond holding the magnets to the U-shaped back iron could fail. As a result, the highly attractive magnets could converge and cut extremities if between/near plates.	Slight, Occasional, Unlikely	Moderate	Warning Labels	Slight, Remote, Unlikely	Low
All Users/ All Tasks	Mechanical Pinch Point: The epoxy bond holding the magnets to the U-shaped back iron could fail. As a result, the highly attractive magnets could converge and pinch extremities if between/near plates.	Serious, Occasional, Unlikely	Moderate	Warning Labels	Slight, Remote, Unlikely	Low
All Users/ All Tasks	Mechanical Magnetic Attraction/Movement: The previous three hazards arise since the magnetic plates/back iron are a separate, small component of the device. Sensitive objects to the magnetic field such as medical devices and electronics could also be disrupted by this component.	Slight, Remote, Possible	Moderate	Warning Labels	Slight, Remote, Unlikely	Low
All Users/ All Tasks	Mechanical Machine Instability: Since the device will be placed near the edge of the workbench, it may topple and injure any user. Additionally, external magnetic attraction may prevent this component from being constrained appropriately.	Slight, Frequent, Possible	High	Footwear	Minimal, Frequent, Unlikely	Moderate
All Users/ All Tasks	Mechanical Movement To/From Storage: This component should be isolated from objects sensiitive to magnets as it will continuously produce a magnetic field.	Slight, Occasional, possible	Moderate	Special Procedures	Minimal, Occasional, Unlikely	Low

APPENDIX SRC: Designsafe Results for Coil

Users/Tasks	Hazards/ Failure Mode	Initial Assessment Severity, Exposure, Probability	Initial Risk Level	Risk Reduction Method	Final Assessment Severity, Exposure, Probability	Final Risk Level
All Users/ All Tasks	Electrical/Electronic Insulation Failure: If the insulation is compromised, and the user comes into contact with the copper, electrocution can occur.	Slight, Remote, Unlikely	Low	Fixed Enclosures/ Barriers	Slight, None, Negligible	Low
All Users/ All Tasks	Electrical/Electronic Water/Wet Locations: Electrocution/Cardiac Arrest/Diarrhea could result if water is brought into contact with coil.	Slight, Remote, Negligible	Low	Instruction Manuals	Slight, Remote, Negligible	Low
All Users/ All Tasks	Electrical/Electronic Overvoltage/Overcurrent: The overvoltage/overcurrent through the wire would result in severe heat and the smoking of the wire. Thus, making the wire unsafe to touch.	Slight, Remote, Unlikely	Low	Instruction Manuals	Slight, Remote, Unlikely	Low
All Users/ All Tasks	Fire and Explosions/ Smoke in Work Areas: The overheating of the coil wire may result in production of smoke. Inhalation of smoke may irritate respiratory tract.	Serious, Remote, Unilkely	Moderate	Instruction Manuals	Serious, Remote, Unlikely	Moderate
All Users/ All Tasks	Heat/Temperature Severe Heat: The current running through the wire cause it to heat up. If this current is too much or applied for too long, the wire will be unsafe to touch. If touched by the user, burning may occur.	Serious, Occasional, Possible	High	Warning Labels	Serious, Occasional, Unlikely	Moderate

APPENDIX SRD: Magnet Safety Information Provided By *K&J Magnetics, Inc.*



K&J MAGNETICS, INC.

www.kjmagnetics.com

Thank you for purchasing magnets from K&J Magnetics, Inc. We hope you enjoy your new magnets as much as we enjoy ours. If handled properly, they will give you a lifetime of use. Because neodymium magnets are so strong, some special care is need when handling them. Please read this paper carefully to understand all the precautions necessary when handling neodymium magnets.

Proper Care and Handling of Neodymium Rare Earth Magnets

The neodymium magnets we sell are extremely strong, and must be handled with care to avoid personal injury and damage to the magnets. Fingers can get severely pinched between two attracting magnets. Neodymium magnets are brittle, and can peel, crack or shatter if allowed to slam together. Eye protection should be worn when handling these magnets, because shattering magnets can launch pieces at great speed.

The strong magnetic fields of these magnets can damage magnetic media such as floppy disks, credit cards, magnetic I.D. cards, cassette tapes, video tapes and similar items. They can also damage televisions, VCRs, computer monitors and other CRT electronics. Never bring neodymium magnets near any of these items.

Children should not be allowed to handle neodymium magnets as they can be dangerous. Small magnets pose a choking hazard and should never be swallowed or inserted into any part of the body.

Never allow neodymium magnets near a person with a pacemaker or similar medical device. The strong magnetic fields of the magnet can affect the operation of such devices.

Neodymium magnets are brittle and prone to chipping and cracking. They do not take kindly to machining. Neodymium magnets will lose their magnetic properties if heated above 175°F (80°C). Neodymium magnets should never be burned, as burning them will create toxic fumes.

Like any tool or toy, neodymium magnets can be fun and useful, but must always be treated with care.

Thanks again for purchasing from K&J Magnetics, Inc. We hope to see you in the future. If you are in need of more magnets, visit us at our website **www.kjmagnetics.com** or email us at contactus@kjmagnetics.com. Have a great day!