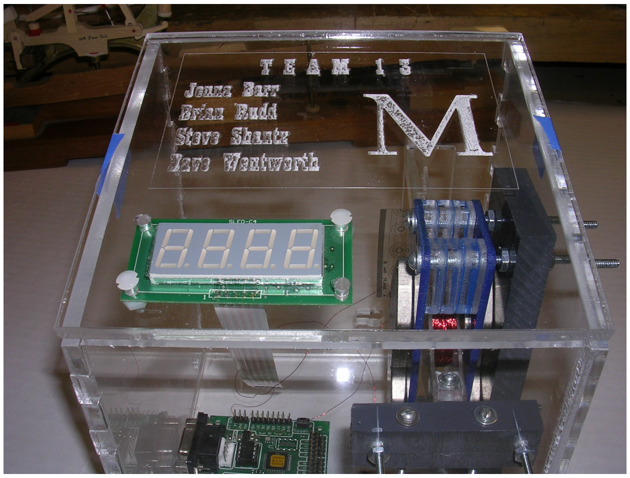

Mechatronic Gauge for Piano Regulation
Final Design

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I. ABSTRACT

The purpose of this project was to reduce the time it takes a piano technician to measure and record data regarding force, balance, and friction in a piano key. We designed and fabricated a mechatronic gauge to assist in the process of keyboard balancing. Our gauge should significantly accelerate the process currently done by hand. It also displays the Up Weight, Down Weight, Balance Weight, and Friction Weight as it measures each key. Engineering specifications for this device were created after considering the customer's requirements and possible market. Also, a timeline was been set for the completion of each following Design Review, culminating with the submission of the final prototype at the Design Expo on April 12, 2007.

II. INTRODUCTION

The goal of regulating a piano is to create a consistent feel and sound when played. For a piano technician to regulate a piano keyboard, he must determine, and adjust, how much force a piano key requires to be depressed. This is typically done with an inconsistent and lengthy process that takes approximately fifteen hours to calibrate all 88 keys.

Professor Robert Grijalva**,** Director and Assistant Professor of Piano Technology at the University of Michigan, suggested we create a mechatronic gauge to reduce the time it takes to regulate a keyboard, and perform the operation with more consistency. He suggested that it be able to read various values and had he ideas about its potential use and market.

Our team has implemented Professor Grijalva's suggestion for a mechatronic piano regulation gauge in accordance with his requirements and delivered a final prototype.

III. INFORMATION SEARCH

The initial information was obtained from a meeting with registered piano technician Nelson Shantz, in which he illustrated the basic principles of the "thump and observe" method. A meeting was also held with the project sponsor, Professor Grijalva, to further detail this process as well as explain its shortcomings. The method involves measuring the Down Weight and Up Weight of the action and using these values to calculate the Friction Weight and Balance Weight.

Currently, the Down Weight is found by placing a gram weight on the end of a key, as shown in Fig. 1 (pg. 2), and lightly knocking, or "thumping" the workbench to break the static friction. If the key does not move, more weight is added until the hammer completes a full down stroke; this denotes the Down Weight. If the hammer moves very easily, weight is taken off and the process is repeated with a lighter weight. The Up Weight is found in a similar manner but the key is pressed down and weight is added. The greatest amount of weight that can be placed on the key but still allows the key to return to its original position is the Up Weight.

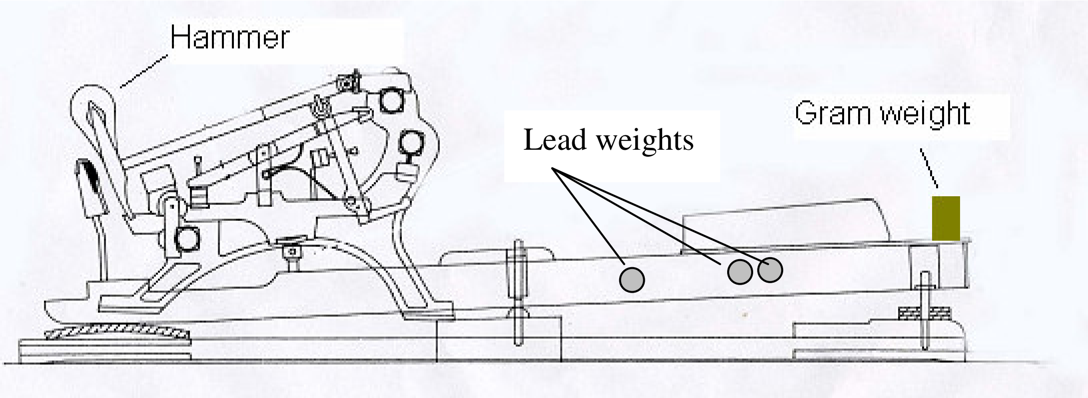


Figure 1: A single piano action with gram weight.

The Friction Weight and Balance Weight can then be calculated, using Eqs. 1 and 2:

$$\frac{DW - UW}{2} = FW \qquad \text{Eq. (1)}$$

$$\frac{DW + UW}{2} = BW \qquad \text{Eq. (2)}$$

Where DW = Down Weight
UW = Up Weight
BW = Balance Weight
FW = Friction Weight

Another measurement used in balancing pianos is the let-off distance. Let-off distance is determined by pressing the key until the hammer slips. It is adjusted by adding or removing paper punches of known thicknesses underneath the key. The let-off distance of a key is another aspect of the feel of a piano and cannot be easily measured with the current device, but may be possible if further testing is completed.

The proposed idea involved developing a portable electronic gauge that measures the Down Weight and Up Weight and calculates the Friction Weight and Balance Weight automatically. To confirm the opportunity for this improvement, we searched for other methods used in balancing keyboards. One method found was the David Stanwood approach in which the parts of the action are weighed individually to find irregularities in the piano action. However, this method is still time consuming, so the proposed idea of a new device is a helpful solution. Also, a search of the US patent office yielded no results of an existing device similar to the one suggested.

IV. CUSTOMER REQUIREMENTS

Professor Grijalva had several suggestions for the design of an electronic gauge. The device needs to:

- Determine the Down Weight, Up Weight, Balance Weight, and Friction Weight
- Eliminate human "thump" to improve consistency
- Have a compact design that easily fits on a workbench
- Have a memory function to store the measured values for each note
- Possibly connect with a computer to store/analyze data

V. ENGINEERING SPECIFICATIONS

The design team took into account the information search and our discussion with Professor Grijalva to determine the functions of the gauge and associate priority levels with each function, as shown in Table 1.

High Priority	**Medium Priority**	**Low Priority**
Determine and digitally readout desired values	Measure all 88 keys in one process	Set target balance weight and measure the difference
Light weight, compact	Export values to spreadsheet	Measure let-off distance
Reduce time to balance		Adjustable angle for screen
Consistency for piano regulation process		

Table 1. Functions and associated priority level.

The most important functions of the gauge are for it to find the four desired values in less time than using the "thump and observe" method, and for the entire device to be an approximately 4 x 3 x 6 inch box and battery powered, which will allow the gauge to fit between the edge of a workbench and a piano action.

Features that were determined to have medium level priorities were a computer interface, and internal software programs. Utilizing a spreadsheet to store and analyze the measured values would a allow the user to examine a graph of Balance Weights and Friction Weights, making it easier to visualize which keys would need to be adjusted. While this would be convenient, it is not the most important aspect of the functionality of the gauge, therefore it is medium priority in the initial design. The software programs would allow the keys to be measured "all at once" or measured and balanced "one at a time."

Functions that have low priority at this point in the design process are a feature that measures let-off distance, and an adjustable screen. Being able to accurately measure and record let-off distance for an entire keyboard could reduce the time required to adjust entire piano action. However, since this function was not stated as a customer requirement, it is labeled low priority.

Making the screen adjustable would also be helpful ergonomic feature for use while sitting or standing, however, this was not a customer requirement.

VI. CONCEPT GENERATION

Through brainstorming and initial rapid prototyping, the design team came up with several designs for a gauge that will fulfill the functions required by the customer.

1. Concept A: Force Gauge The initial design concept was to attach a force gauge to a lever arm that would perform an entire keystroke. The force required to execute an entire keystroke would be recorded and analyzed to determine the Down and Up Weights.

2. Concept B: Water Pump The second concept that was briefly explored was to place a small water tank on the key and then to determine Down Weight by measuring the amount of water that was pumped into the tank until the key moved. To determine Up Weight, the water would then be pumped out until the key returned to its original position.

3. Concept C: Weight Balance The third concept was to implement a balance that allows a constant weight to move along the lever arm in contact with the key. The distance between the weight and the pivot could then be used to calculate the force required to perform a keystroke. There were power-driven and user-driven variants of this model.

4. Concept D: Constant Force The fourth concept was to impart a constant force upon the key. An accelerometer on the end of the lever arm would record the acceleration. Then, the mass required to depress the key could be calculated. The Up Weight could be found by releasing the force on the key and measuring the upward acceleration.

5. System Control and Output One device that was investigated for performing the system control was the cRIO. The other device available to us to perform the control was the OOPic. Both systems can receive digital and analog inputs as well as send outputs and communicate with an LED screen.

VII. CONCEPT EVALUATION AND SELECTION

As a result of brainstorming there were four design concepts explored. These designs were quantitatively compared using a Pugh chart, which can be seen in table 2 (pg 7). By using customer requirements, each design was examined for cost effectiveness, practicality, reaction time, size, power requirements, and ease of use. The cost of the device is very important, since there is a budget of $400 for the initial prototype and a low cost would be more marketable for the final manufactured design. The weight balance and application of constant force were determined to be cost effective, while the force gauge and water pump were not. It was desired for the design to be practical, allowing it to be simple to use and uncomplicated to construct. The water pump was the only design that did not have this attribute. The reaction time of the lever arm needed to be fast enough to allow it accurately measure the Down and Up Weights once the static friction in the action has been broken, and the force gauge was the only design that had this feature. Another customer requirement was for the device to be compact, and the weight balance and constant force designs accomplished this goal. The final aspect that was considered was that the device was easy to use, and all of the designs met this objective, except for the application of constant force design.

VIII.

Design Concept	Measure Forces with gauge(s)	Fluid application of Force	Change weight with balance	Apply Constant Force
Cost	-	-	+	+
Practicality	+	0	+	+
Fast Reaction Time	+	0	-	0
Size	0	-	+	+
Power Requirements	0	-	+	0
Ease of Use	+	+	+	0
Total Score	**2**	**-2**	**4**	**3**

Table 2. Pugh Chart showing process for selecting designs

As can be seen, the only design that had a negative score was the water pump, therefore it was discarded immediately. Of the three remaining designs, the force gauge idea was discarded due to the constraints of the budget and it had the lowest score of the remaining designs. This left only the weight balance and the application of constant force as the only two design concepts.

Concept 1: Force Gauge Dismissed This concept was deemed cost-prohibitive and therefore eliminated. Buying an existing force gauge and manufacturing one from parts were both determined to be not cost-efficient, making the design less marketable.

Concept 2: Water Pump Dismissed This concept was eliminated, because it was found that the pump might not be able to react quick enough to adjust after breaking static friction in the key. Plus, and the pump would be too cumbersome to fit within the constraints set forth by the customer. Also, having water near a piano action would be undesirable for a piano technician.

Concept 3: Weight Balance Selected The Weight Balance was determined to have two variations that could be implemented to satisfy different requirements. The user-driven version would eliminate the necessity for gram weights and is a simple design, but does not internally calculate the required values or display them on a screen. Since significantly reducing the time it takes to balance a piano and calculating and displaying several values were all high priority functional requirements, the user-driven version of this concept was dismissed.

The power-driven variation was selected because it meets all of the high-priority requirements. This design, shown in Fig.2 A (p. 8), uses a motor to adjust the distance the weight is placed. It also has an LED screen that will display the required values. The challenge was getting it to adjust in a timely fashion once the static friction is broken. A possible solution was to create a control system algorithm that could adjust the weight quickly and accurately. Another solution was to add in constant vibration to break the static friction in a way similar to the “thump” used by piano technicians. Further testing was done to determine if a “thump” is necessary

Figure 2 B, below is the modified version that encloses the entire moving mechanism within the housing which is necessary for safety and robust use.

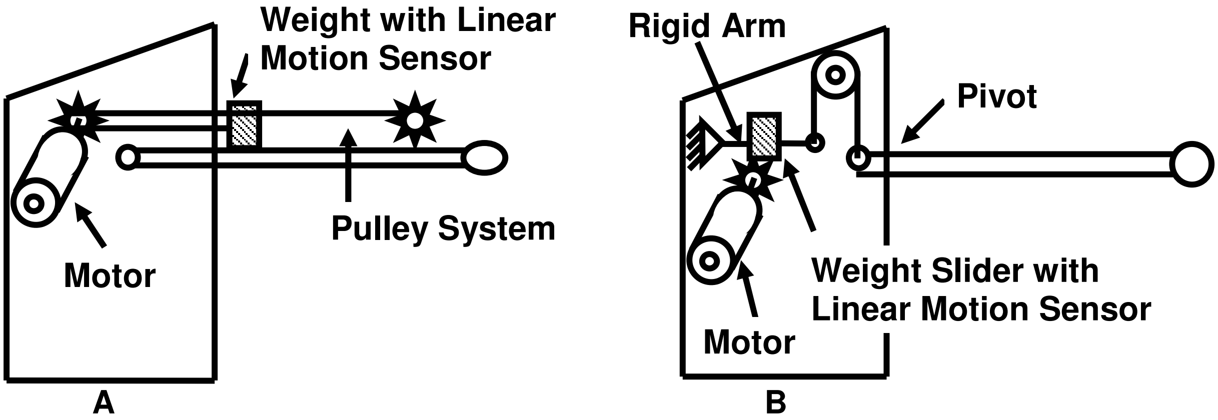


Figure 2. A. External Power-Driven Weight Balance.
B. Internal Power-Driven Weight Balance

Concept 4: Constant Force Selected This concept, shown in Fig. 3, was selected, because it is a promising cost-effective solution that meets all of the high priority requirements. This design is both cost-efficient and contains a few parts that use little power. The concern with this design was whether measuring the acceleration of the upstroke of a free-moving key would give an accurate Up Weight. More testing was planned for once an accelerometer was obtained to determine whether or not this concept was feasible.

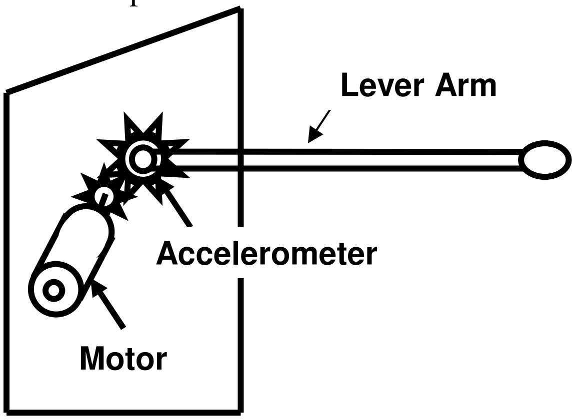


Figure 3. Constant Force with Accelerometer.

Table 3 (pg 9), describes some of the reasoning Team 13 used to dismiss some concepts and chose others for further analysis. See Figure 4 (p 9) for the concept generation, analysis and selection in flowchart form for summary.

Feasible	Too expensive	Impractical	Too Simpl
Constant Force with Accelerometer	Force Gauge	Water pump	User-Driven W Balance
Power-Driven Weight Balance with Automatic Controller	Water Pump	User-Driven Weight Balance	
		Power-Driven Weight Balance with “Thump”	

Table 3. Concepts categorized by feasibility.

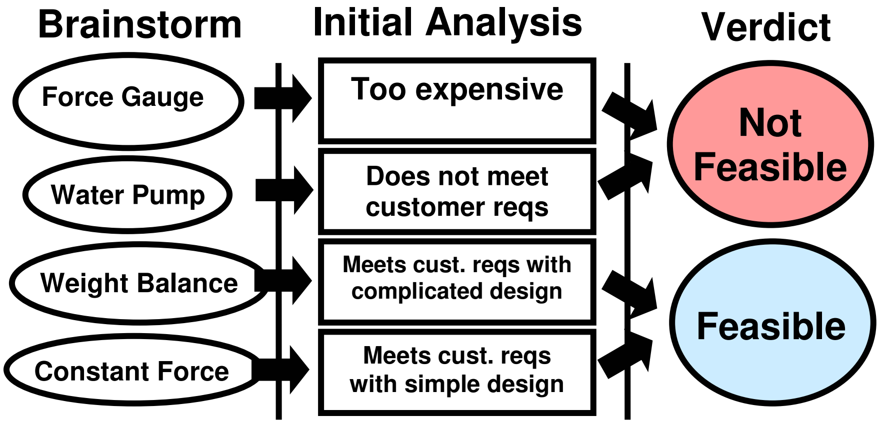


Figure 4. Brainstorm and Concept Selection Summary.

OOpic Seclected While both systems for control and output met all of the design requirements, only the OOpic fit within the budget set forth by the customer.

VIII. SELECTED CONCEPTS

The design team chose to keep two designs as possibilities. They were the Power-Driven Weight Balance and the Constant Force with Accelerometer. Both of these designs have need for an OOPic, a motor that can impart a force of at least 1 N, a digital display, a battery power-supply, and a housing which will be assembled from plexiglass. Figures 2B and 3 (pg 8) show the 2-D renderings of these selected concepts.

After further investigation and conversations with Professor Gillespie, we determined that neither of these concepts would work in their entirety. This is due to the fact that both of them operate with the assumption that the force that is measured is based on the inertial forces which generate the equation F=ma. However, the forces that are measured are frictional forces. Therefore, we decided to create a device in which we were able to determine the force applied by characterizing our motor and determining the force applied by the spring steel used as the pivot point for the motor in our new design concept.

IX. ENGINEERING ANALYSIS

This section details the logical and mathematical reasoning used to select the components for the piano regulation gauge.

A. Geometry of Piano Key The geometric restrictions the piano regulation gauge must follow are dictated by the shape of a piano action as it sits on a work surface. Measurements were made of the piano key, so that the gauge can measure both natural and sharp keys. The gauge will have two parallel adjustment bars to ensure the correct position for each type of key. Below is an illustration of a standard key and the ranges of shapes the piano regulation gauge must accommodate for when the key is upright or fully depressed.

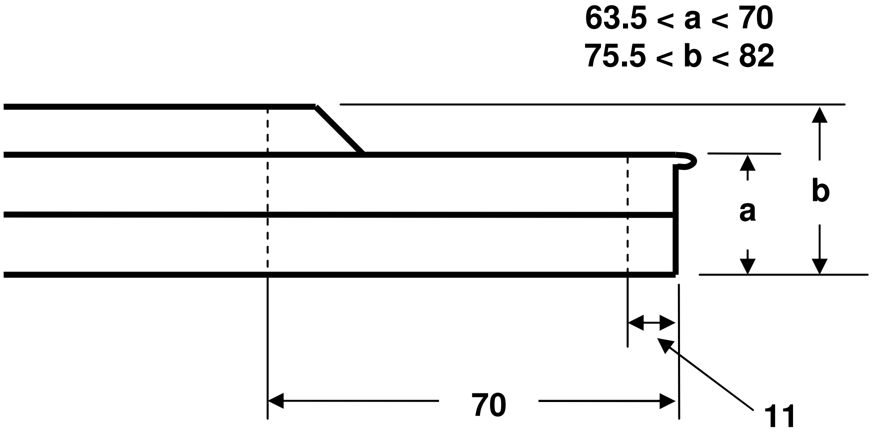


Figure 5. Upright Key Position and Approximate Lengths (all lengths in mm)

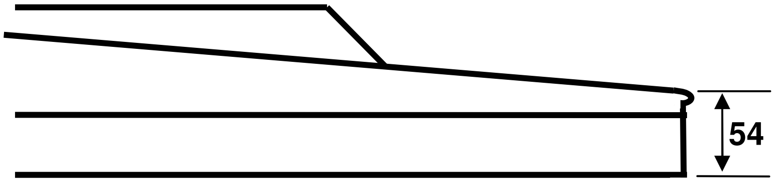


Figure 6. Depressed Key Position (all lengths in mm)

B. Motor Selection From the geometry analysis of the piano key, we determined the necessary torque for the motor. Based on the dimensions of the piano keyboard, we know that the lever arm of our device will need to be 7.0 cm long, from the contact point to the front edge of the housing, and approximately 20 cm long from the contact point to the back of the housing. Since, the device needed to be as compact as possible due to workspace limitations, the arm could be no longer than 20 cm. The motor needs to apply a force of up to 0.8 N at the end of the lever arm. A keyboard Down Weight rarely exceeds 60 grams and Friction Weight rarely exceeds 20 grams, so a total of 80 grams is sufficient to overcome the static friction in the action. Accordingly, the force needs to be 0.8 N as can be seen in Eq. 3 (pg 11). With a Lever arm of 20 cm and 0.8 N of force needed, our motor needed to have a stall torque of 160 mN·m, as can be seen in Eq. 4.

$$80g \cdot 9.81\frac{m}{s^2} = 0.8N \qquad \textit{Eq(3)}$$

$$0.8N \cdot 20cm = 160mN \cdot m \qquad \textit{Eq(4)}$$

One consideration was that the force from the lever arm onto the piano key is not always fully transferred. Since it is a rotating arm, whenever the arm is not parallel with the key, the force being transferred is a component of the supplied force, illustrated in the Figure 7 below. Figure 7A shows a perfectly normal force being applied to the key whereas Figure 7B shows a component of the force being applied due to an angle theta.

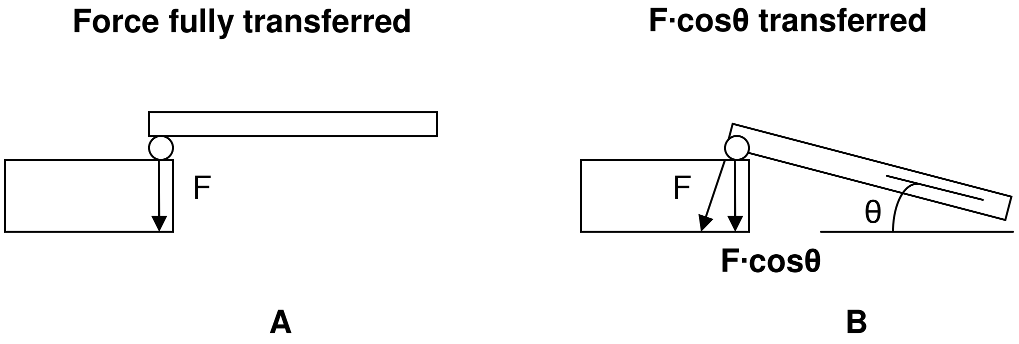


Figure 7. Motor Lever Arm and Force Demonstration

However, even with the shortest arm, which could be 7 cm, the angle θ would never exceed 15 degrees, based on the total amount of key travel from the piano dimensions. Therefore, the component force would never be less than 96.5% of the supplied force. Based on this, the variation in angle did not affect our motor selection, but we considered it when measuring the response of the keyboard and when determining the Up and Down Weights.

Another requirement was a motor that is back-drivable, since it will need to rotate in both directions with high precision. The piano key must be able to push back onto the lever arm to return it to its original position. This motor must be inexpensive to purchase or produce to keep open the option of commercialization. Also, it must be as small as possible to minimize the size of the housing

1. Custom Motor Selected We have decided to make our own motor from plexiglass. It is composed of a coil of wire inside a magnetic field created by two magnets mounted to the housing that produce a force, F, on the key, see Eq. 5 (pg 12) for the force produced. Building our own motor has also allowed us to customize the size and shape to properly fit in the housing, and vary the supplied torque by adding or subtracting coils. Additionally, an optical encoder has been mounted to the housing to determine where the lever arm is positioned and its production was relatively inexpensive.

$$F = (li \times B)2n \qquad Eq(5)$$

l = length of coil
i = current through coils
B = magnetic flux
n = number of coils

The lever arm for depressing the piano key has been directly incorporated into the motor. This eliminates the energy loss that would occur due to a connection to the motor, such as gears. We have also added a leaf spring made of spring steel, which replaced the bearing in the motor. The use of bearings causes damping and friction which vary with velocity, making it very difficult to characterize, whereas, the compliant spring varies with position, making it much easier to characterize, by finding a spring constant. Once we found the spring constant for the steel we were able to account for the force induced by the spring when we calculated the Down and Up Weights, since we were able to find exactly how much torque was being applied to the piano key by the lever arm. The lever arm, with its spring steel pivot can be seen in figure 8, below.

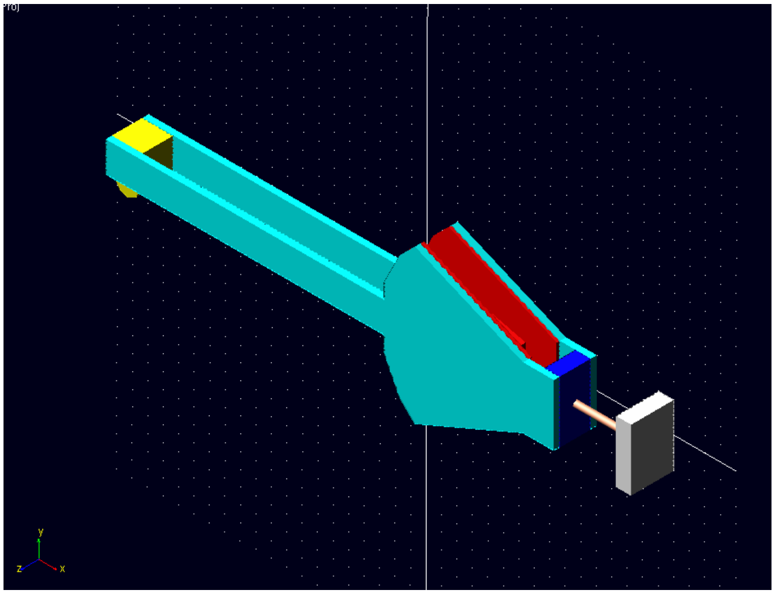


Figure 8. Isometric View of Custom Motor

2. Force Analysis Figure 9 (pg 13) describes the forces acting on the motor arm and their locations. When placing them all at the tip of the arm, as seen in the Free Body Diagram (FBD) on the right, the analysis of these forces can be simplified and summed at one location. Following this concept, we characterized the Fm (motor force) and Fs (spring force) forces as if they were acting at the tip of the motor arm in order to make the calculation of Fa (applied force), which is Fa = Fm – Fs, as simple as possible.

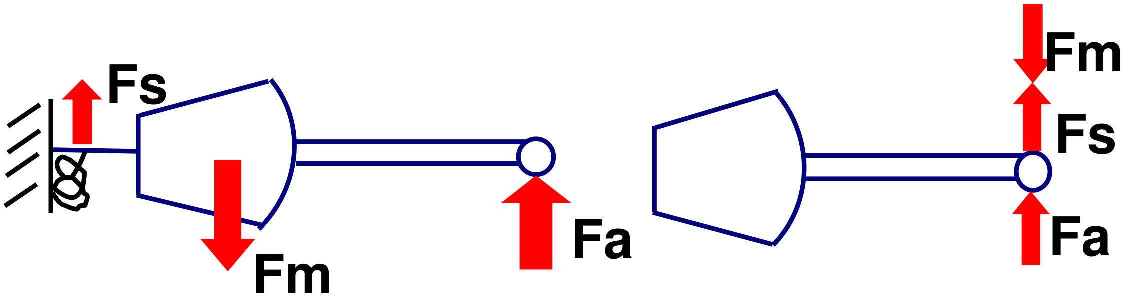


Figure 9. Free Body Diagram of Forces acting on Motor Arm

Using this idea, the equation for our final result becomes:

$$Fa = Fm - Fs \qquad \text{Eq (6)}$$

where Fa is the applied force by a piano key, Fm is the motor force and Fs is the spring force. It is now important to understand Fm and Fs and what contributes to these forces. Fs is a spring force and is a function of the deflection of the arm, x, based on a spring constant, k.

$$Fs = f(x) \cdot k \qquad \text{Eq(7)}$$

Fm is the force from the motor and it is a function of current and constants, as seen in Eq 5 (pg 12). This equation was simplified by combining all of the constants into one, C. Also, since the position of the coils changes as the arm moves, the magnetic field coefficient changes, so the constant, C, becomes a function of position as well. In addition, it is legitimate to use the voltage applied to the motor in place of current. This can be justified since the angular velocity of the motor is very small and therefore so is the loss of voltage due to the electromagnetic force, V_{emf}. Since there is very little V_{emf}, the motor circuit simplifies to V=*i*R, and the resistance can just be accounted for in the constant of the equation below.

$$Fm = f(V) \cdot C(x) \qquad \text{Eq(8)}$$

Combining these functions, we find that we must determine the spring constant of the compliant mechanism, as well as define the function C(x) to be able to accurately describe the force Fa. Therefore the equation for the force applied is now as is seen below in Eq(9).

$$Fa = f(x) \cdot k - f(V) \cdot C(x) \qquad \text{Eq(9)}$$

a. Determining k To find a relationship between Fs at the end of the motor arm and deflection, gram weights ranging between 5-50 grams were placed at the tip, and deflection was measured. Counts were the units of deflection used. Counts are the output of the digital encoder and there are 720 counts per inch. A line of best fit was found, and the slope is the spring constant, k, in units of g/count.

b. Determining C(x) To calculate the motor constant, first a voltage was applied to the motor and the deflection was measured. The voltage was varied digitally by applying a varying duty cycle to the supplied voltage. This duty cycle varied between 1-127 PWM. Since there is no applied force in this test, the only force acting is the motor force, which produces a given deflection. The motor force will then equal the spring force produced by that same deflection. With this relationship, the motor constant can be obtained from the equation below.

$$C(x) = \frac{f(x) \cdot k}{f(V)} \qquad \text{Eq(10)}$$

This produces the motor constant in terms of deflection. A best fit line was applied as seen in Fig. 16 (p.23) and a quadratic relationship between deflection and motor constant was found.

c. Full Force Equation With the spring constant and the motor constant function, the full force equation can be created. This equation will be implemented in the processor code to output the applied force from the input voltage and measured deflection. Since the processor cannot handle complicated algebra, a table of values will replace the function used for the motor constant.

$$Fa = f(V) \cdot (-7e - 07 \cdot x^2 \ + 0.0013 \cdot x^2 - .0061) - f(x) \cdot 0.0816 \qquad \text{Eq(11)}$$

C. Static Friction Control Our original concept for eliminating static friction was to mount an eccentric mass motor onto the lever arm to provide a small vibration to the end of the key. Our initial test of this concept included using a cell phone vibration function as the eccentric mass motor. All of the initial testing showed that the cell phone eccentric mass motor applied to the end of the key does not break the static friction. A test that did break static friction was applying the cell phone vibration directly to the piano action rail.

The solution is to place a clothespin clip, equipped with an eccentric mass motor, to the piano action rail, thus removing the static friction. It runs during the entire piano balancing process. The testing of this concept was completed once an eccentric mass motor was acquired, and it confirmed our hypothesis that the vibration from eccentric mass motor is sufficient to break the static friction in the piano action.

D. Power The components that will need a power supply are the OOPic, motor, the LED screen, and the EC motor. The OOPic has its own system and is already configured to run off of its own 9-volt battery. After testing, using the current set-up, with an OOPic, we have determined that the circuit only needs 200 mA.

1. Battery Power A 9-V battery is listed as having a capacity of 500 mAh (Ampere – hours). We are currently using about 200 mAh to run our motor. Thus, two 9-V batteries should be able to power our gauge for five hours. The LED screen uses a very small amount of power in comparison with the motor and so it can be assumed that it can run off of the same power source as the motor without significantly reducing the lifetime of the battery

2. DC Power DC Power can be used as an alternative, since it is readily available and consistent. This should be used as if the battery life becomes short enough that one full set of readings for all 88 keys cannot be accomplished during the life of two 9-V batteries.

E. Feedback Control (552 Support) The ME 552 support group has assisted us in creating a means of controlling the current supplied to the motor. This is done centrally by an OOPic. The OOPic communicates with an optical encoder to determine how much current is needed to deflect the piano key fully. The length of the motor lever arm, the voltage used by the H-bridge amplifier, and the amount of force lost due to the spring steel bearing are taken into account when determining the actual amount of current needed apply the correct amount of force used to depress the piano key.

The OOPic sends a reading of the Up Weight, Down Weight, Balance Weight and Friction Weight to an LED screen that the user will be able to read, after performing the needed calculations.

Below is a visual depiction of the flow of information within the piano regulation gauge. The 552 team has based their algorithm of control on this diagram.

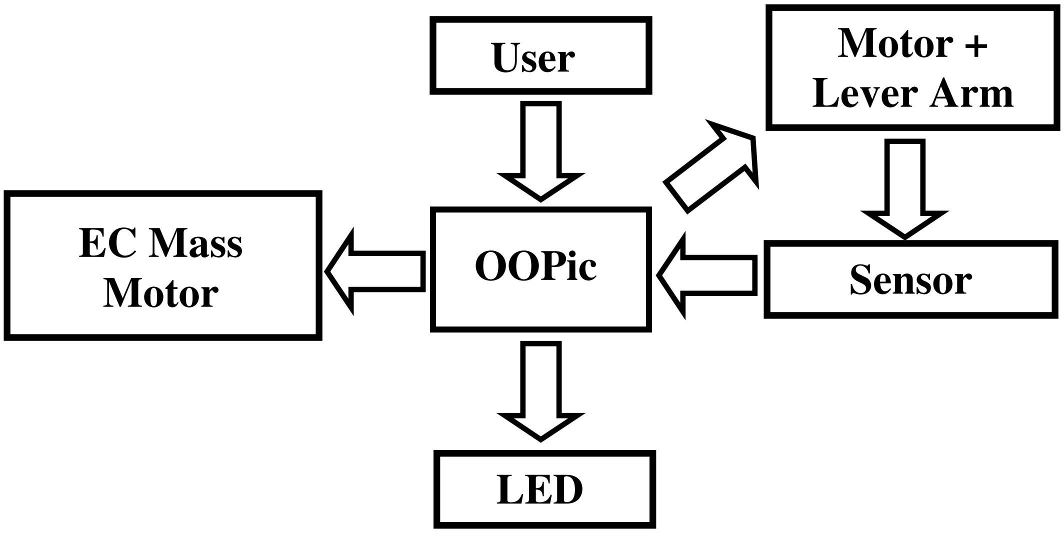


Figure 10. The logic flow within the piano regulation gauge.

F. Design for Manufacturing The Failure Modes and Effects Analysis can be seen in Table 4 (p.16) and has been used as a guide for the process that was undertaken to sufficiently analyze the design of the device before it was built. After doing the analysis it became quite clear that testing of parts was a necessity, and was performed immediately after the completion of this chart. By testing parts individually problems were reduced before the device is constructed, thus reducing the number of aspects of the design that needed to be checked while troubleshooting the device. It was also quite clear that the motor selection for the device was critical to getting the device to work, since it was essential to getting the proper amount of force to measure the needed values with the desired accuracy, thus the customized motor design.

Part	Function	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) of Failure	O	Current Proccess Controls	D	RPN	Recommended Action(s)
Motor	Drive Arm	Over-heating	Motor stops	10	Motor undersized	3	Characterize motor	1	30	Characterize motor
		unresponsive to control	Force not consistently applied	8	Improper connection to OOPIC	6	Test with OOPIC	2	96	Run tests
Lever Arm	Apply force on key	Lose contact with key	Force applied incorrectly	7	Arm placed incorrectly	1	Place consistently	2	56	Instruct consumer
		Fracture	Arm dysfunctional	10	Improper motor	4			100	Select correct motor
OOPIC	Control torque of motor	Slow reaction time	Takes longer	6	Slow Processing speed	2	Buy correct OOPIC	1	12	Research OOPICs
		Short circuit	motor overexerted	7	Bad connection	4	Test	3	84	Run Tests
			Failure of OOPIC	10	Bad OOPIC	2	Test	1	20	Run Tests
LED Screen	Read out values	Loss of power	Values not known	6	Bad connection	2	Test	3	24	Run Tests
		Wrong value displayed	Values become misleading	9	Wrong Code	3	Debug Code	2	54	
Power Source	Supply current to motor	Overload	Power source breaks/fails	8	Undersized power source	1	Find capacity of source	1	8	Locate information on power source
Vibration Source	Eliminate static friction	Becomes disconnected from piano	Friction not broken	4	Too much vibration	8	Stabilize vibrator	5	160	Test different locations
					Connected wrong	4	Place consistently	2	32	Instruct consumer
Housing	Holds together device	Melting	Device no longer connected	4	Too much heat from motor	7	Don't run too frequently	5	140	Test to find when motor overheats
		Fracture	Mechanical integrity of device compromised	3	Too much force exerted at connections	4	Building housing robustly	4	48	Analyze force exerted on housing by device

Table 4. FMEA for Parts of Design

S=Severity of Failure, O=Occurrence Rating, D=Detection Rating
RPN (Risk Priority Number)=S x O x D

X. MANUFACTURING PLAN

A. Design for Manufacture and Assembly Guidelines In order to efficiently manufacture the device a plan was first developed using guidelines for Design for Manufacture and Assembly (DFMA). The most important guidelines are discussed below.

1. Few parts: The assembly process was easiest with as few as possible parts to put together to form the device. This also created fewer manufacturing processes to undertake.

2. Easily drawn/cut on laser cutter: The overall shape of the device was drawn in CAD without too much trouble and was one that was easily cut on the laser cutter. The majority of the parts in our design were made using a laser cutter, allowing for fast, simple, and repeatable manufacturing.

3. Round edges: The device needed to have edges that were rounded for ease of cutting and minimization of stress risers. A round edge at the contact point of the lever arm allows for contact with the key in an efficient manner so that the force is consistently applied.

4. Pieces easily joined: The pieces of the device needed to be designed so that they fit together and were assembled in a relatively low number of steps. The sides of the housing have notched edges that match up, ensuring that walls are properly aligned. In our prototype model, this also allowed us to temporarily assemble the housing, but still be able to remove sides to access the inner parts. The angle of the screw holes and number of screws, as well as the orientation of the holes was considered for this aspect of the design, allowing us to properly mount the motor and spring steel, and be able to remove and replace each of these parts.

5. Housing for size of design: The size of the housing is big enough to not only fit the entire device in it, but also allows for there to be ventilation for the motor so that it doesn't overheat. The housing is also large enough to accommodate the power supply (two 9-V batteries) and the control circuit. At the same time, we made the housing small enough to be compact and portable.

6. Standardization of motor: Now that the motor is characterized, a process needs to be developed in which it can be manufactured in mass quantities so that the forces applied and measured are consistent.

B. Design for Environment Guidelines The design's affect on the environment was also considered with the following guidelines for Design for the Environment (DFE):

1. Easy to disassemble: The device is fairly easy to disassemble, allowing the user to be able to disconnect parts that are recyclable and/or reusable before disposing of the device.

2. Uses minimal power: The device uses a relatively low amount of power (supplied by only two 9-V batteries) to run all of its parts.

3. Parts can be reused: Portions of the device, LED screen, the OOPic, and potentially the batteries can be reused for other purposes once the gauge's purpose has been fulfilled.

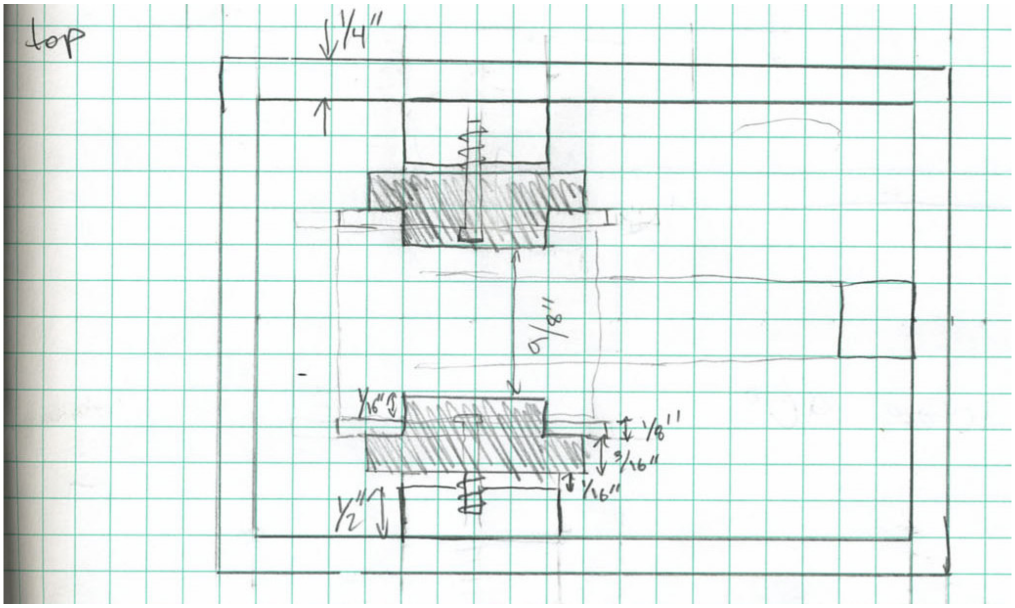


Figure 11. Drawings of Housing

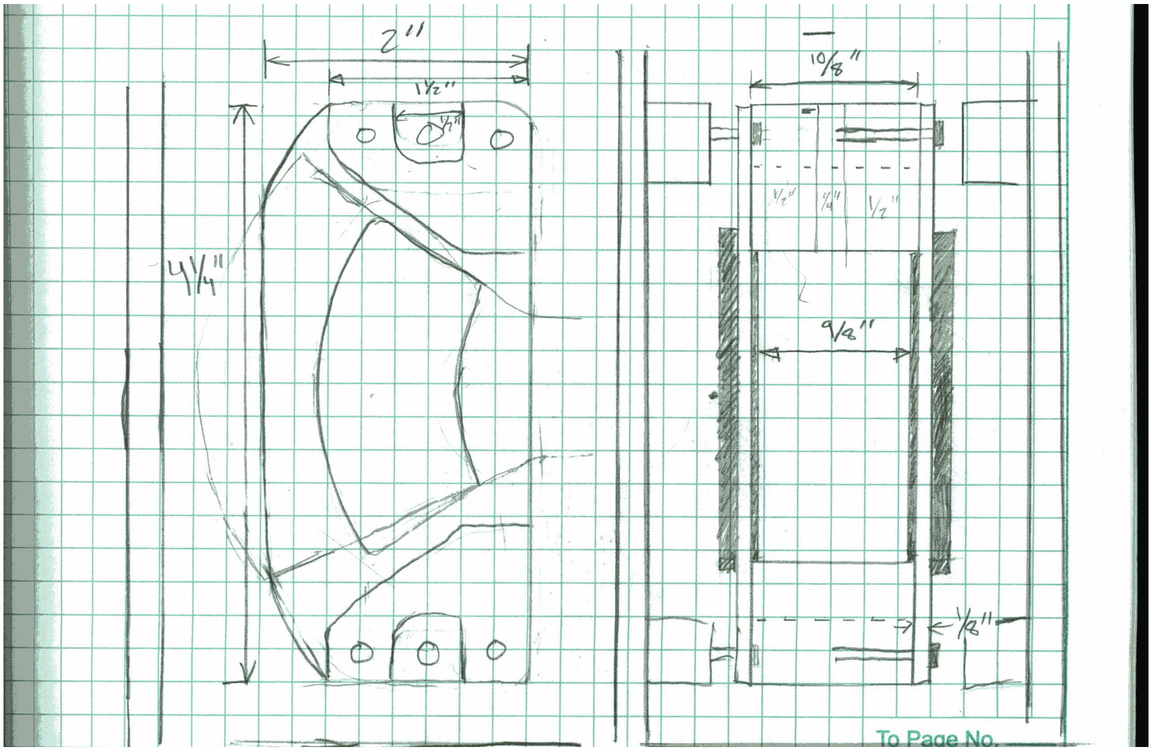


Figure 12. Drawings of Magnet Bracket

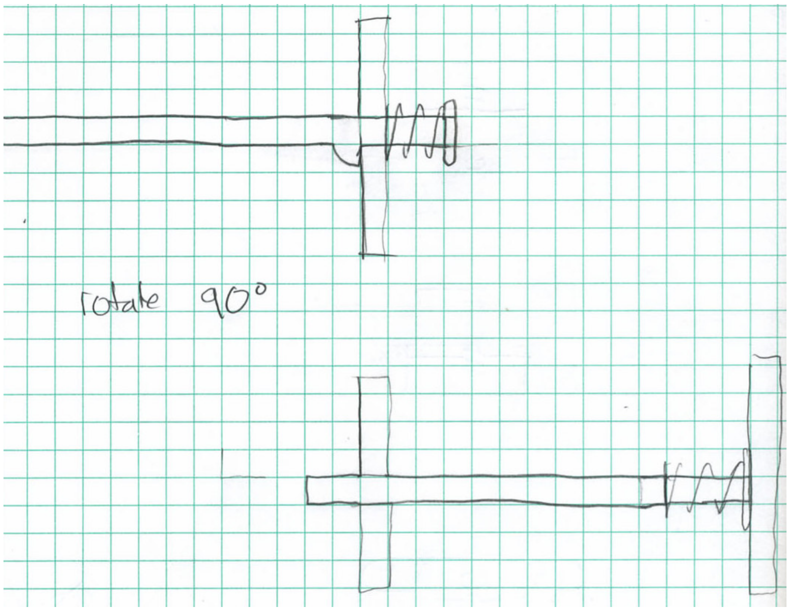


Figure 13. Drawings of Sharp/Natural Adjustment Pin (SNAP)

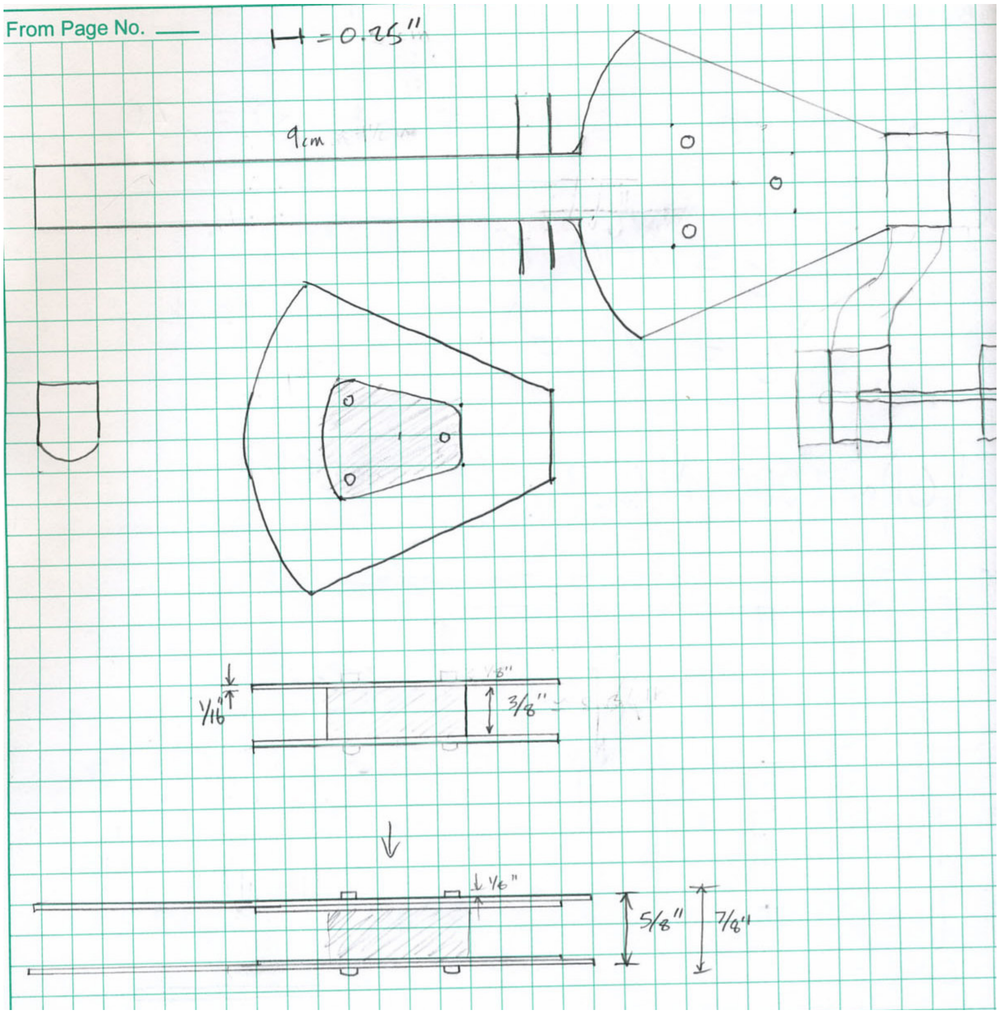


Figure 14. Drawings of Motor Arm

XII. MANUFACTURING AND ASSEMBLY PROCESS

The above drawings (figures 11 -14, pp.18 and 19) were be the basis for the dimensioned CAD drawings used by the laser cutter. Once the drawings were finalized, they were made in Bobcad, and sent to the laser cutter. The components were then cut out of plexiglass. The components were then assembled using glue and screws. The following is a detailed explanation of the manufacturing process:

1. Lever Arm The lever arm was made out of 1/8" acrylic on the laser cutter with parts drawn out in Bobcad. The original version had a removable spindle to wrap the electrical coils around. Both the spindle and the lever arm were held together using plastic bolts and nuts. After the final number of coils was determined to be 1280, the spindle pieces and hardware were removed and the lever arm was glued together, in order to allow for a smaller spacing between the magnets and thus a greater magnetic flux. In the final lever arm design, it was extended one and a half inches in order for the device to accommodate sharp keys as well as naturals.

2. Housing The housing was also drawn up in Bobcad and made on the laser cutter, using 1/4" acrylic. The sides were bonded using acrylic glue. The initial prototype housing was simply two adjacent walls. The magnets were mounted on the side wall on the spring steel pivot was mounted on the back wall. This allowed easy access to all parts of the mechanism for testing and changes. The final housing design is a cube shape except that the top surface is angled up to make the display easier for the reader to use. The housing assembles in two pieces. The right side, back, and bottom were glued together with acrylic glue, as were the left side, front, and top. The intersections of these two parts are notched to fit together. This provides for ease of manufacturing as well as easy maintenance.

3. Spring Steel Once the spring steel with the correct stiffness was chosen, we incorporated it into our lever arm. The spring steel is a thin ribbon, which was cut out using a shear and has a hole in one end. The end with the hole bolts between two acrylic blocks that attach to the back of the lever arm and the other end is clamped in place between two PVC blocks. The PVC blocks were made on the mill and then cut to have a 5 degree angle. The blocks were then bolted to the back side of the housing. The blocks on the housing were tried in several different vertical locations as well as flipped around to try different starting heights and angles for the lever arm.

4. Magnet Housing The original magnet brackets were made out of 3/32" acrylic, which was cut on the laser cutter after being drawn out in Bobcad. Acrylic spacers, also made using the laser cutter, were put in between the top and bottom of the magnet brackets to create a spacing of 9/8". When the spacing between the magnets was changed to 11/16" the magnet brackets showed considerable deflection from the increased attraction. The magnets were remade using 1/8" acrylic and fillets were added to the inner corners of the magnet cut-outs in order to decrease stress risers. The magnetic brackets are bolted on to the right side housing with a PVC spacer, which was made on the mill. These parts are all fastened using four nuts and bolts.

5. Encoder mount The encoder mount was one of the last pieces manufactured as it was important for the encoder to be in a very precise location in order for it to accurately read the position of the lever arm. The encoder mount was made out of PVC on the mill and then later milled down to the exact height necessary for the positioning of the encoder. The encoder mount was secured to the housing with epoxy and then the encoder was mounted also using epoxy.

Mounting of Encoder The optical encoder was mounted to the front of the housing so that the encoder strip ran through the slot in the encoder, allowing the LED beam to be broken by the counts on the strip. The strip was attached to the lever arm so that it would move the same distance as the arm while the force was being applied to the piano key. The measurements are made by the encoder reading the number of counts passing by the LED beam. This number of counts is then related to the number of counts per inch and the radius of the curve of the encoder. The strip was mounted so that the curvature matched the circle around the center of the pivot point of the motor.

6. Sharp - Natural Adjustment Pins (SNAP) The Sharp - Natural Adjustment Pins were made out of 1/8" acrylic and cut out on the laser cutter. Each pin consists of two pieces, the pin that slides in and out of the housing front, with a lock for each position, and a circular piece that is glued on to the rear end of the first piece using acrylic glue. This circular piece keeps the pin in the correct level position, as well as allowing it to rotate with ease.

7. Completion of Control Circuit The control circuit was constructed by the ME 552 support team and was made to connect each of the necessary components of the gauge's design. See Fig.15 below for the block diagram of the Control circuit. This control circuit was implemented to make the gauge do the necessary actions for the measurement of the force applied to the piano key.

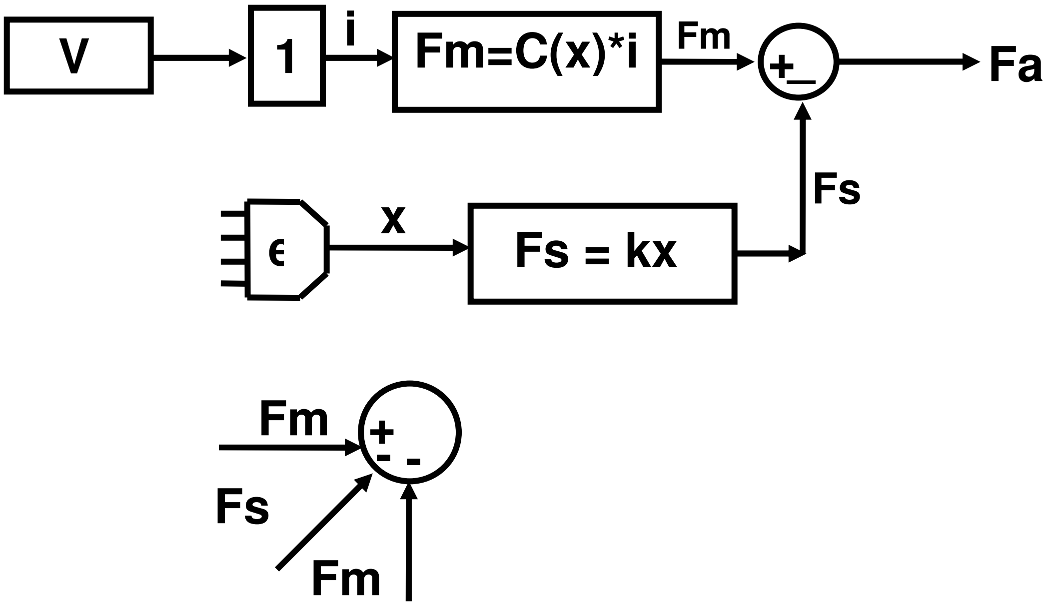


Figure 15. Block Diagram of Control Circuit

XII. FINAL PROTOTYPE

The final prototype is a 6 x 6¼ x 5¾ inch box with an angled faceplate. It contains an OOPic, an H-bridge, five 9V batteries, an LED, a position sensor and a motor.

The OOPic contains three subroutines that are called Search Key, Down Weight, and Up Weight. Once the gauge is started, the first subroutine begins when the voltage is increased. The deflection is monitored until it stops increasing. At this point the arm has made contact with the piano key.

The second subroutine, Down Weight, then begins and the eccentric mass motor is engaged to release static friction in the piano action. The voltage is then increased until the piano key just begins to depress. The voltage and deflection at this point are recorded and Down Weight is calculated by the OOPic.

The third subroutine, Up Weight, then begins and the eccentric mass motor continues to run. The voltage is decreased until the piano key just begins to come up. At this point the voltage and deflection are recorded so the Up Weight can be calculated by the OOPic. Once the Down and Up Weights are recorded, the Balance Weight and Friction Weight are calculated and displayed on the LED screen, along with the Up Weight and Down Weight.

XIII. TESTING RESULTS

A. Spring Constant Determined After setting up the encoder to accurately measure the deflection of the motor arm, characterization of the spring could be performed. Gram weights were placed on the end of the lever arm, so that a known force was applied to the arm. Deflection readings were then taken from the LabView equipment attached to the encoder. Three trials were preformed and the values were combined into a graph of weight applied v. the deflection imposed. This graph can be seen in Fig. 16 (p. 23) below. A line of best fit was applied to this data, and its slope was 0.0816 g/count, and used as the spring constant. There was a standard deviation of only 0.002 between the 3 different spring constants associated with each individual trial. This means the error in the spring constant is approximately 0.004 or only approximately 5% error in the spring constant value, making it a good value.

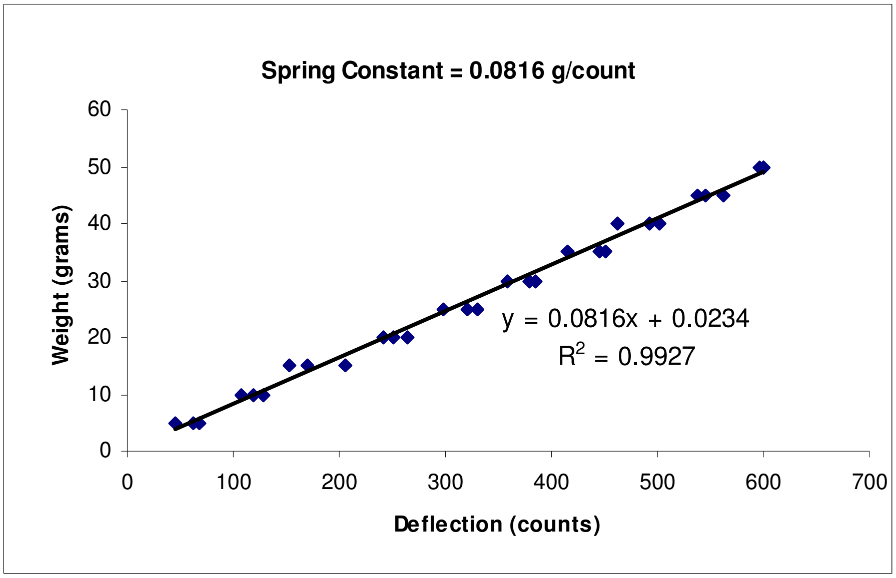


Figure 16. Spring Constant Determined from Comparing Weight to Deflection

B. Motor Characterized The encoder was also utilized to determine the motor constant for the customized motor. To do so, the motor was attached to the control circuit and the voltage was input to the circuit, and measured. The deflection of the motor was then sensed by the encoder and transmitted to LabView, where it was then recorded. Each deflection was therefore recorded with a corresponding voltage. The measured voltages and corresponding deflections were then used in Eq. 10 and the motor constant was determined for each reading. The quadratic best fit function was determined and the relationship between the motor constant and deflection was found, as seen in the fig. 17.

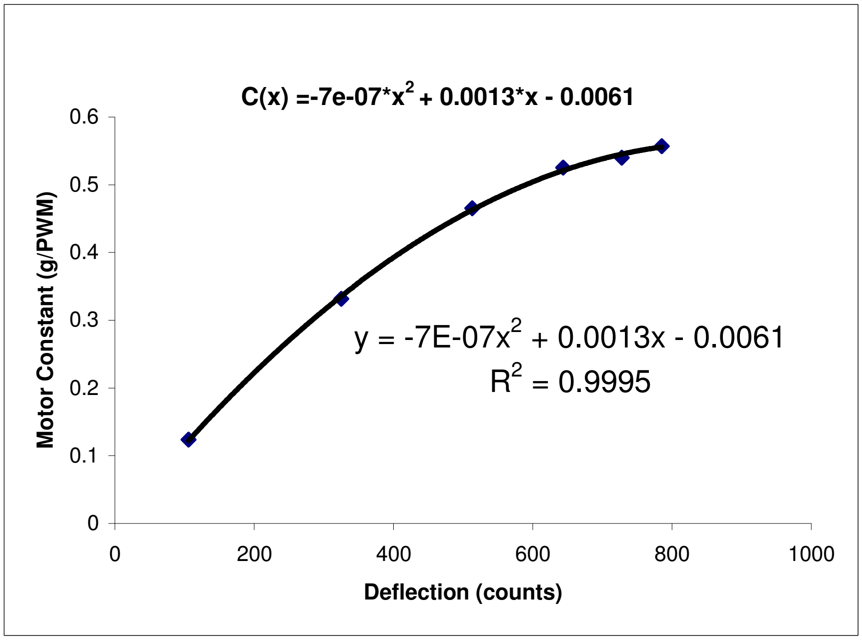


Figure 17. Motor constant as a function of deflection

C. Full Force Equation With the spring and motor constants determined, the full force equation that will be applied can be formulated, seen in Eq(12). This equation will be implemented in the processor code as described in section IX.

$$Fa = f(V) \cdot (-7e - 07 \cdot x^2 \ + 0.0013 \cdot x^2 - .0061) - f(x) \cdot 0.0816 \qquad \text{Eq(12)}$$

D. Communication with Circuit Through working with the ME 552 team, the control circuit was constructed so that deflections of the motor arm could be read by the encoder and transmitted to the OOPic for use in calculations of the force applied to the piano key. To do so, extensive code writing and compiling was performed. There was a separate code for the LED screen that was then integrated into the OOPic code, and tests were run to see if the two were able to communicate. On several occasions the code was unable to download from the computer to the OOPic, but this was not a problem that prevented use of the code. Connections between different aspects of the gauge, such as the encoder were also the source of problems in making the OOPic communicate with the devices it was controlling. On a few occasions all aspects of the gauge were functioning and the results provided were similar to what was expected in that the Down Weight was approximately 43.5 g, as calculated using the generated force equation, and when it was measured using gram weights it was between 43g and 45g.

XIV. SUGGESTIONS FOR FUTURE IMPROVEMENTS

Following the construction of the gauge, and after an extensive period of testing and troubleshooting the following is a short set of suggestions as to what needs to be accomplished in order for it to function properly and ideally

A. Implement Wall Power Due to the nature of the script that is used to run the OOPic, and most other control circuits, battery power cannot be accurately implemented for long-term use of the device. This is the case, because the circuit reads the percentage of voltage that is being supplied to the circuit, and only reads the percentage of the initial voltage. It however does not detect that the voltage diminishes as the battery loses its strength. Therefore the amount of voltage that is actually being supplied is lower, and at times much lower, than the OOPic is reading, and this has an adverse effect on the calculation of the force applied, since the voltage supplied is an important value in the force equation. In addition to this problem, the gauge needs at least two 9-V batteries to operate, and with the amount of current that is needed, as is previously discussed in the Power supply section, the batteries will only last for approximately two or three hours. This may not even allow for the balancing of one piano, therefore, this is not desired.

B. Use of different control circuit The source of a majority of the problems associated with the functionality of the device stem from the OOPic. The process to compile the information from the code writing software to the OOPic becomes time consuming and cumbersome due to the OOPic not excepting the new script at some points and due to how out of date the software is that is needed to write code for the OOPic. In addition to this, there were many instances in which the OOPic would read values consistently and then without alteration to the code, not do so. Therefore, with these problems, and many hours spent writing and rewriting code, it was suggested by the ME 552 support group that a different control circuit would be a very good idea.

C. Resolder connections Towards the end of the testing period a lot of the connections of the connections were starting to fail. In particular the connection between the encoder and the OOPic was severed and difficult to reconnect. The soldering between a lot of the aspects of the circuit were also quite uncertain due to the inadequate soldering equipment available in the X50 lab. Therefore, if the circuits were resoldered, their reliability would be much higher and could be removed as possible source of error or failure in the circuitry of the gauge.

D. Consistency of Measurements Once the force equations are determined, they need to be implemented in the control circuit so that the force that is actually being applied to the piano key can be accurately measured. Several iterations of tests need to be preformed in order to ensure that the force measured is indeed accurate. A piano action with an adjustable wippen can be utilized to ensure that the force equation works for each action that requires different levels of force applied to cause the hammer to move at a consistent velocity. This will be similar to a test of an entire set of 88 keys.

E. Modifications for Mass Production The current gauge is one that can be reproduced as a prototype, and functions well as a prototype, but a few modifications need to be made in order for it to be appropriate for mass production. One aspect is the arrangement of the circuit, since currently there are a lot of wires and the appearance is quite jumbled. The length and orientation of the wires can be modified so that they do not get get tangled and take up too much space. The location of the OOPic, batteries, and H-bridge should also be modified so that they take up less space and so that they are safe from accidental disconnection which would cause failure. Another aspect is the housing. While the current housing holds all of the necessary components of the device, it can be reduced in size once the circuit is finalized and soldered in a consistent manner. The buttons to operate the gauge can also be located in one panel to the right of the LED screen and their operations should each be labeled.

XV. CONCLUSIONS

To create a consistent sound and feel while playing a piano, the Balance Weight and Friction Weight must be regulated. The current regulation process is lengthy and inconsistent. Automating this process can eliminate these two problems. Therefore, Professor Grijalva has requested a mechatronic piano gauge that measures the Down Weight and Up Weight, calculates the Balance Weight and Friction Weight, and digitally displays these four values. This device has been completed and was presented in the University of Michigan Design Expo on April 12, 2007. Future improvements have been suggested to make this device fully operational and possibly marketable.

REFERENCES

Grijalva, Bob. Professor and piano technician, School of Music, University of Michigan.

Shantz, Nelson. Registered piano technician

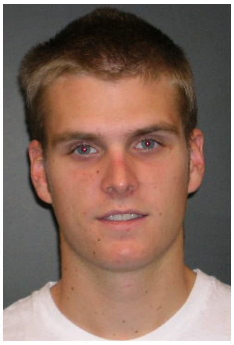
Stanwood Piano innovations. (http://www.stanwoodpiano.com)

U.S. Patent Office (http://www.uspto.gov)

TEAM BIOS

Jenna Barr, Treasurer: I am a senior engineering student from Acton, Massachusetts. I am currently planning to graduate in December 2007. After graduation I would like to work in the research and design of biomechanical devices. I am interested in mechanical engineering because I like discovering how things work and finding new ways to improve them. In addition to academics I am a member of both the Ski Team and the Baja Team at Michigan.

Brian Rudd, Recorder: I am a fourth year senior from Holt, MI. I plan to finish my undergraduate degree in Mechanical Engineering in the fall semester of 2007. After I graduate, I hope to work for a design firm or the research and development section of a company. I am interested in Mechanical Engineering, because I am interested in the design process and how different devices function mechanically, as well as how structures are design to withstand different kinds of stresses and strains. In addition to my engineering coursework, I have an interest in history, in particular war history, and I also played trombone for four years in the Michigan Marching Band.



Steve Shantz, Sponsor Contact: I am from Ann Arbor, Michigan and I'm a senior mechanical engineering student who will graduate in the spring of 2007. I enjoy many aspects of mechanical engineering, such as design, finite element modeling, statics, dynamics, heater transfer, and more. Upon graduation, I plan on working in a small firm that performs many of these listed facets so I can continue to enjoy a varied engineering curriculum. I have significant background in the field of this project. My father is a piano technician and I have worked many summer hours in his shop on various piano rebuilding projects. I am also a pianist myself. I am very familiar with the piano action and am looking forward to working on this project.

David Wentworth, Team Leader: I am a senior in Mechanical Engineering from Sterling Heights, MI. I will be graduating in April 2007. I will eventually be pursuing a Master's Degree in Mechanical Engineering, but until then, be working in the automotive industry for a car company or a supplier. I enjoy IM sports and also have played for four years in the Michigan Marching Band. I am interested in learning much about how this gauge will determine the force required to depress a piano key and look forward to designing the mechanical aspect of it.