Final Report
Project #12:

Mechanized Characterization of Musical Keyboard Touch Response

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Picture Provided by [2]

Table of Contents

Abstract

Current digital keyboards, even weighted keyboards, have a different touch response (feel) than acoustic pianos, which affects a pianist's ability to learn and perform. Keyboardists rely on the touch and haptic response from the keys as feedback. We have designed and fabricated a device that measures the touch response of a grand piano key, by taking force, position, velocity, and acceleration measurements. Our device, while measuring response, will impose force/motion inputs on a key that mimic key strikes by a human. In the future, this data could be used to create a digital keyboard with a touch response that more closely approximates that of the acoustic grand piano. Our device will be a research tool to help bridge the gap between digital and acoustic keyboards.

Introduction

Nearly all professional piano players prefer the feel of an acoustic grand piano to the feel of a synthesizer keyboard. While this is known widely among pianists, no one has objectively tried to quantify the difference in the feel between standard and synthesizer keyboards [3]. Digidesign, a company specializing in music mixing and most recently keyboard design, would like us to build a device that can systematically measure the difference in feel among various types of pianos and keyboards. The purpose of this device would be to obtain quantitative data about the feel of grand and upright pianos that could then be used to reproduce a more accurate feel on synthesizer keyboards.

Information Search

Professor Brent Gillespie has conducted much of the research on the topic of haptic interface devices and was able to provide us with a number of useful articles and websites to gather background information. Prof. Gillespie also supplied us with several papers he had written on the subject including his thesis. These articles gave us a better understanding of the studies that had already been conducted along with how our device would be used.

We also conducted our own information search from which we learn some of our engineering specifications and other essential background information. In a document by Anders Askenfelt and Erik Jansson, measured ranges of velocity and position of the piano key where found while it was being played. (Figure 1 pg. 3) This data was important so we could determine the precision and range required by the instruments. These results were reproduced and verified in a thesis by Werner Goebl.

We joined another team in their interview with Professor Grijalva, a teacher in the music school, and discovered how pianos work and are maintained. He took us to his lab where he demonstrated the piano action and how keys are balanced by placing weights near the end of the key. This also led to defining a standard on where the finger strikes the key: approximately 13 mm from the end of the key. He also discussed the importance of the whole keystroke, which involves the pressing of the key and also the motion of the key returning to the original position. Overall the whole interaction gave us a great base on which we might want our project to head and also just great background information [5].

Linearity and Non-Linearity

We conducted an Internet search to better define linearity and non-linearity so that we could improve our understanding of the affects of the piano stoke being non-linear.

A function is only linear when it is both additive (superposition properties hold) and homogenous. In order for a function to be additive the output of a function with *input one* added to the output of a function with *input two* must be equal to the output of the function *input one plus input two*. Algebraically, $f(x_1)+f(x_2)=f(x_1+x_2)$. A function is homogenous if the same output occurs for an input multiplied by a constant, whether it is multiplied before or after the function is carried out. Or algebraically $f(k\cdot x)=k\cdot f(x)$ [6],[7].

Nonlinear systems are simply those that do not follow the rules described above for linearity. They are very difficult to treat analytically because their outputs do not vary proportionally with their inputs (i.e. they cannot be scaled) making their behavior unpredictable [8].

Linearity is important because if a system is linear it can be analyzed by linear algebra and outputs can be easily determined. Non-linear functions are much more difficult if not impossible to analyze mathematically and often require experimental testing which allows for modeling from empirical data.

Mechanical Impedance

Mechanical impedance (Z) is the relationship between the force applied to an object (F), and the resulting velocity (V), given by the following expression:

$$Z(\omega) = \frac{F(\omega)}{v(\omega)}$$

The value for the impedance of an object is dependant on various parameters of the interaction between the force and the object including stiffness (k), damping (b) and mass (m). The mechanical impedance is a function based on the frequency of the applied force, with the lowest impedance value occurring at the resonance frequency of the object.[11] This value of impedance changes for the human finger depending on the type of strike applied to the piano.

Customer Requirements

Digidesign has asked us to design a device that will mimic the human input to a piano and measure the feel of the key accurately. The device would have to be able to be used on all types of pianos and synthesizers, and be able to test both the white and black keys of the piano. The device must be easy to setup, operate, and be easy to use for recording the data. The device should also be robust for many measurements while not damaging any of the pianos or synthesizers in the process of testing.

Engineering Specifications

We have determined that the best way to systematically test the touch response of piano keys would be to use computer controlled input of a linear electrical motor. The motor must be mounted on a stable mount as to minimize the noise in measurement from environmental or motor induced vibrations so measurements are more accurate. The computer interface will deliver an input signal to an amplifier that will drive the motor for a desired key stroke, and then the computer will record various data including key position, velocity, acceleration, and force response. The ranges and general precision requirements of the sensors are as follows and listed in Table 1. As Figure 1 shows the position sensor will have to measure a range of 0 – 10 mm and the velocity sensor will have to measure over a range of 0 – 7.5 m/s [1], [4]. The acceleration will have to measure over a range of 0 – 300 m/s^2 [4]. The range of forces the human finger in common piano strikes range from 2-50 N.

Figure 1: Velocity and position graphs for both staccato and legato keystrokes [1]

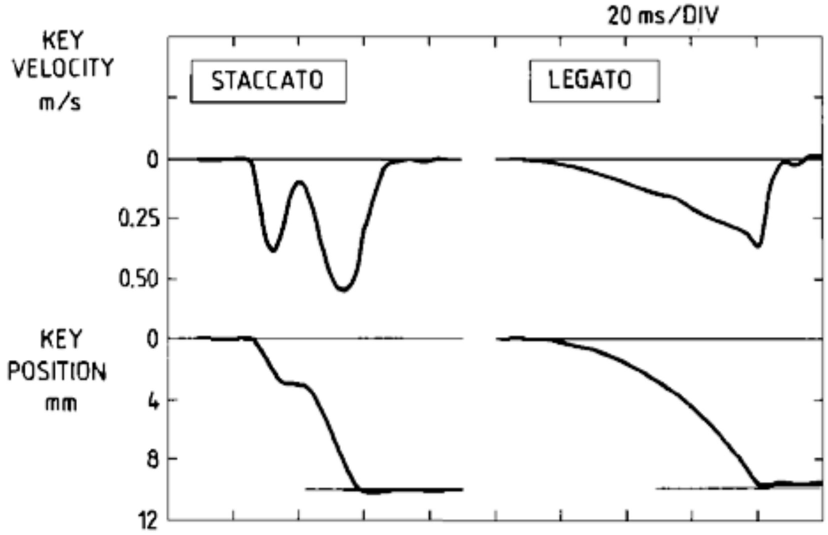


Table 1: Sensors required to accurately test piano touch response.

Device	Measuring Range	General Precision Need
Position Sensor	0-10 mm	Very high
Velocity Sensor	0-75 cm/s	High
Accelerometer	0-300m/s^2	High
Force Transducer/Strain Gauge	0-50N	High

To synthesize the behavior of the human finger, the mechanical impedance of fingers will have to be researched. This impedance can be reproduced with our input signal by using real-time feedback control loops; implementing virtual springs and dampers.

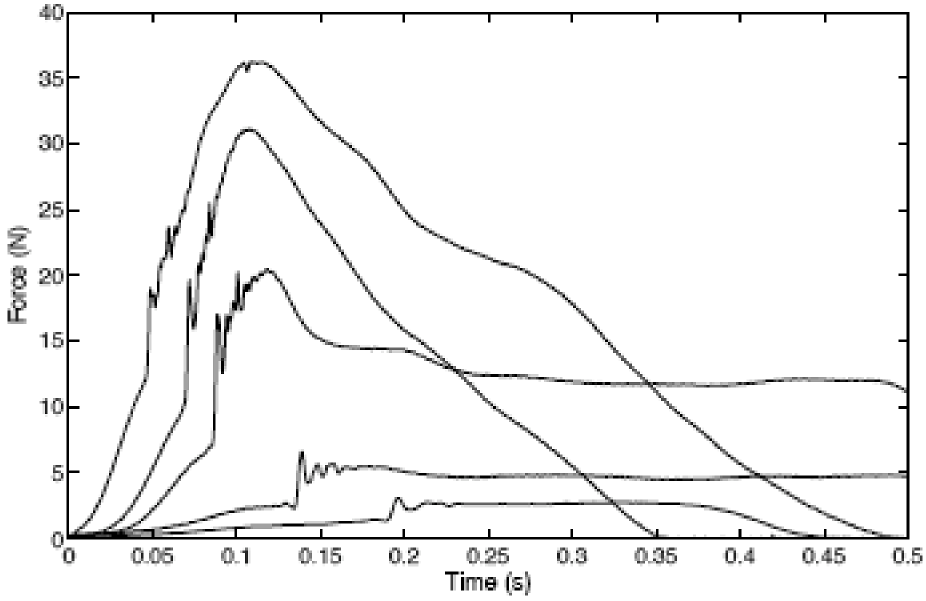
Non-Linearity of a Piano Key Stroke

To consider the piano as a non-linear system, we simplified the system to mimic a simple linear mechanical system with mass, damper and spring, to look at the motion of the key, which in the end we assume to be related to the force at the key. The governing equation is then:

$$m\ddot{x} + B\dot{x} + kx = F_{in}(t)$$

This equation is simple enough to solve making two assumptions, first that the force input is a simple function. This assumption cannot be made because the player provides the input force. Human actions are hardly uniform or repeatable. The following figure (Figure 2), from Hirschkorn's thesis, shows the force for five different key strikes. With an input force that is so variable, it would be impossible for the resulting motion of the key with respect to time to be linear.

Figure 2: Measured Force Profiles by an Amateur Pianist



Secondly when traditionally solving the differential equation it is assumed that the constants (*m, B, k*) are in fact constant. For the piano, these parameters are inherent in the construction, they are however not constant during the keystroke. Without testing, we predict that these parameters are functions of both time and position. Consider the mass of the key at the beginning of the stroke; it is considerably larger than the mass of the key at the middle of the stroke when the hammer has been released. The damping and stiffness are affected by the contacts of the moving parts, which are changing throughout the keystroke. The variable input and the changing system parameters, result in a system that is highly nonlinear, which motivates the collection of experimental data, from which a model can be based.

Parts and their Planned Interaction

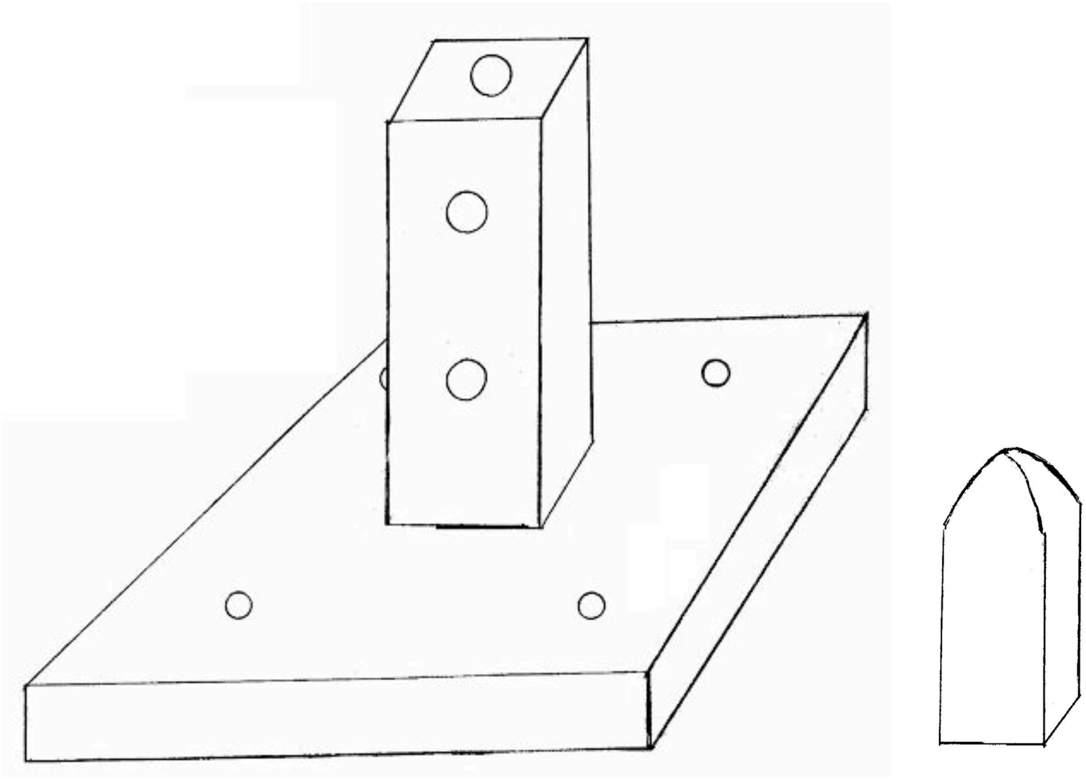
Motor – Piano Intermediary

After receiving our linear motor, force transducer, position sensor, accelerometer, and necessary amplifiers to run our devices, we looked up the specification sheets on all of the products. We decided we would need to mount all the devices on the linear motor by attaching a small lightweight plate to the end of the actuator on the motor. This would give us more surface area to attach the accelerometer and force transducer. Also we decided to use a lightweight material, so that the inertia change on the motor would hopefully be small. The small motor momentum is desired because we do not wish the motor's mass to be the main application of force on the keys, but rather just the motion.

The difference might be compared to smashing an elbow on a key versus a double forte strike by a pinky finger.

We decided we would need a device that would attach to our motor and that we could attach mount our various sensors too. The device would also need to create an acceptable surface to strike a piano key. It is desired that the fixture be lightweight to reduce the amount of force needed from the motor. With that in mind we have decided that the best material to use is aluminum because of its light weight, low cost, and ease of manufacturability. We decided the design shown below in Figure 3 would be the best design allowing us to attach our sensors while minimizing our total mass.

Figure 3: Design for motor fixture (left) and striking tip (right).

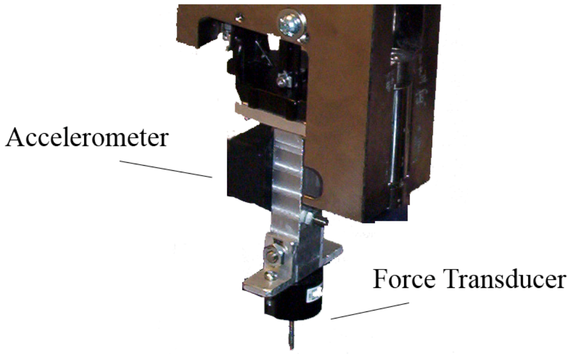


The design shown in Figure 3 was then fabricated in the machine shop, and the sensors attached to it. With all of the sensors attached to the motor now, the sensors can be calibrated and the programming of the software to control the motor in the testing can be finalized and key testing can begin.

We also attached a backup linear encoder on the motor in case of failure in the first position sensor. The backup was positioned on the armature of the motor and used Plexiglas to attach it. This second encoder is more carefully aligned, however its signal seems very similar to that of the first. If used, the position signal must be adjusted by a gain of -1 because it is reading in the opposite direction than the first encoder.

The striking tip shown in Figure 3 was eventually replaced because the original force transducer broke. A compression force transducer was ordered and attached to the motor fixture using 'L' brackets to the end of the motor fixture. The tip of the force sensor was too short to depress a key without interfering with the other keys because of the width of the force sensor, and thus the button sensor for the compression sensor had to be extended. Because the button wasn't threaded, and the original striking tip was too bulky, it had to be replaced with a smaller extension. A small piece of metal was attached to the button using epoxy, allowing us to read the depression of one key, while minimizing extra mass on the system. The set-up is shown in the photo below (the back-up encoder is not shown).

Figure 4: Locations of sensors on mounting tip

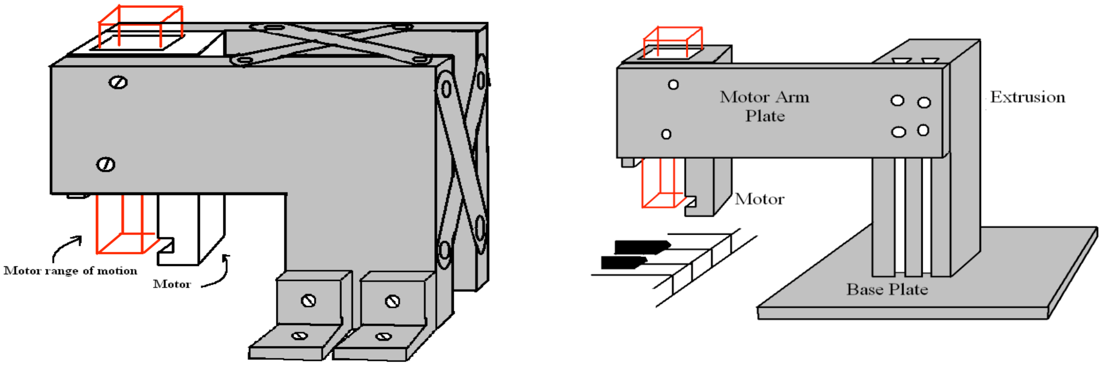


Ground – Motor Mount

Initially we thought it would be desirable to make a motor mount that was capable of both horizontal and vertical adjustments. Designs were considered using various slotted adjustable parts, as well as one design that featured a rotating crane-like arm. A concern arose as to whether the adjustability of the motor mount would compromise the stability of the motor during testing. We noted that if the mount were prone to vibration, the various readings from the keystroke could be compromised. Since precision is of great importance to us, we decided to go with a design that has limited mobility, while still allowing the desired range of movement

We narrowed the structure down to a motor mount similar to the one shown in Figure 5(a) below. This design is desirable for its stability gained from the lack of adjustable mechanisms for vertical and horizontal displacement, as well as cross-bracing to prevent torsion between supports. This device was further revised to the one shown in Figure 5(b). The mount in Figure 5(b) is desired because it offers an easy way to adjust the vertical operation of the motor. While this does introduce the potential for potential slop in the device, we feel that the 4 bolts securing the mount arm plate to the extrusion will be secure enough to allow very little motion of the motor with respect to ground and maintain the same accurate measurements of a solid mount. The mount can be adjusted vertically to conform to pianos of differing heights, and the entire mount can be repositioned to hit both the white and black keys of the keyboard.

Figure 5: (a) Proposed design sketch for mounting the motor to a stationary ground. (b) Finalized motor mount design with vertical adjustment.



(a) (b)

Motor Mount Manufacturing

The design features a piece of extrusion provided by Prof. Gillespie's lab, two sheets of aluminum of ½" thickness, as well as brackets and bolts necessary for assembly. The base plate was attached to the extrusion brackets with nuts and bolts. This was done because threading the base plate and directly screwing into it could cause a lot of strain on the threads. The supplied bolts that were designed for use in the extrusion were used for mounting the extrusion brackets and the arm plate to the extrusion.

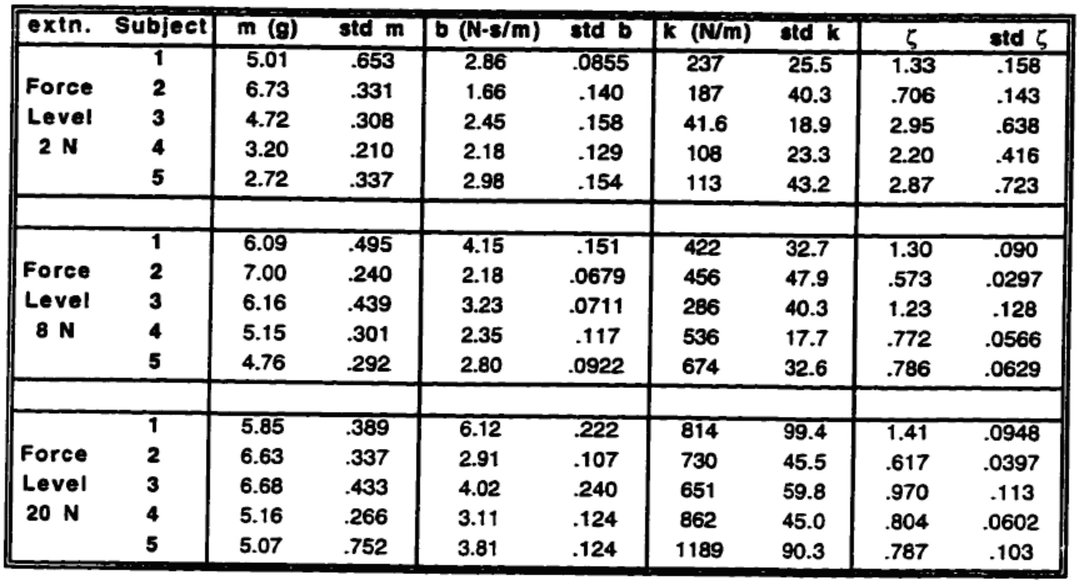
Securing the motor to the mount proved to be a more difficult process than expected. We discovered that in addition to the tap size being of an undetermined (possibly metric) dimension, the top hole contained a threading tap that had broken off in a previous manufacturing endeavor. This meant that we could only insert bolts from one side of the motor. We were able to find a 3/4" bolt of undetermined thread size that fit into the top threaded hole (which contained the broken tap in the opposite side), however the bottom hole that was drilled all the way through was threaded in a way that it was difficult to insert any bolt. The solution to this was to redrill the hole to make it designed for bolt clearance. The intended clearance was for a 10-24 bolt, however the hardware store at which the bolt (6" in length) that was bought supplied a slightly different size so there is a small difference in diameter. As such, we were unable to immediately obtain a washer and nut to fit on the opposite side.

The motor was secured to the table using four 3/16" x 6" nut/bolt washer combinations. A location was found on the edge of a standard small, adjustable-height banquet table where the bolts would not interfere greatly on the underside, and corresponding clearance holes were drilled through both the mount base and the table. The electronic portion of the project built by the ME 552 team was placed in the remaining space. This did not include space for the associated computer, which was placed on a separate table or cart depending on available resources.

Determination of Input Curves

In order to accomplish our goal of measuring the feel of a piano key, we need to accurately simulate the impedance of a human finger based on the type of strike applied to the keyboard. Part of this is designing the input curves for the device considering the values of the effective mass, damping and spring constants. These values are extracted from the study conducted by Hajian and the values can be seen in Table 2 below. [10]

Table 2: Subjects' mean and standard deviation (std) values of the parameters m,b,k, and ξ for three of six finger tip force levels in extension from Hajian's thesis.[10]

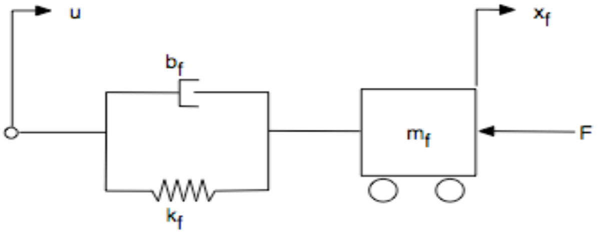


extn.	Subject	m (g)	std m	b (N-s/m)	std b	k (N/m)	std k	ζ	std ζ
Force Level 2 N	1	5.01	.653	2.86	.0855	237	25.5	1.33	.158
	2	6.73	.331	1.66	.140	187	40.3	.706	.143
	3	4.72	.308	2.45	.158	41.6	18.9	2.95	.638
	4	3.20	.210	2.18	.129	108	23.3	2.20	.416
	5	2.72	.337	2.98	.154	113	43.2	2.87	.723
Force Level 8 N	1	6.09	.495	4.15	.151	422	32.7	1.30	.090
	2	7.00	.240	2.18	.0679	456	47.9	.573	.0297
	3	6.16	.439	3.23	.0711	286	40.3	1.23	.128
	4	5.15	.301	2.35	.117	536	17.7	.772	.0566
	5	4.76	.292	2.80	.0922	674	32.6	.786	.0629
Force Level 20 N	1	5.85	.389	6.12	.222	814	99.4	1.41	.0948
	2	6.63	.337	2.91	.107	730	45.5	.617	.0397
	3	6.68	.433	4.02	.240	651	59.8	.970	.113
	4	5.16	.266	3.11	.124	862	45.0	.804	.0602
	5	5.07	.752	3.81	.124	1189	90.3	.787	.103

The damping and spring constants can be simulated virtually using PD controller. The device has its own mass and damping constant and these must be offset so that the finger is simulated. The spring constant and damping factor were determined from the motors frequency curve and by weighing the motors arm. By doing this you can calculate the spring constant and damping factor. Two input curves were developed for testing, however when it was time to test the device a simple pulse input was used, in order to verify the accuracy of the device. The mechanical device was simulated using Simulink. The figure below shows the basic schematic of the mechanical model.

The device model is connected to a model of the key developed by using mass, spring and damping constants estimated from the Hirshkorn papers (m=0.12008 kg, b=3.75 $\frac{Ns}{m}$, k=257 $\frac{N}{m}$). [9] The key model has two discontinuities that simulate the limits of the key motion. This is done by introducing a very stiff virtual spring when the signal reaches the limit of the key stroke (approx. 10 mm), and a lighter spring when the key reaches its original equilibrium position (denoted x=0, key position at rest). This discontinuity causes the non-linearity observed in the position and force measurements, from previous work and piano key model seen in Figure 7. A spring-mass-damper model of the finger can be seen below in Figure 6.

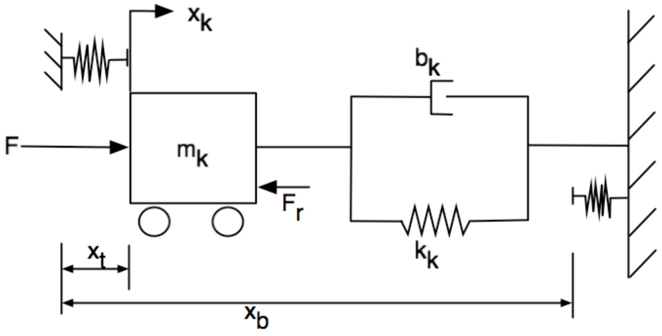
Figure 6: Spring-mass-damper model of the human finger.



$$\begin{aligned} m\ddot{x} + b_f(\dot{x} - \dot{u}) + k_f(x - u) - F &= 0 \\ m\ddot{x} &= k_f u + b_f \dot{u} - k_f x - b_f \dot{x} \end{aligned}$$

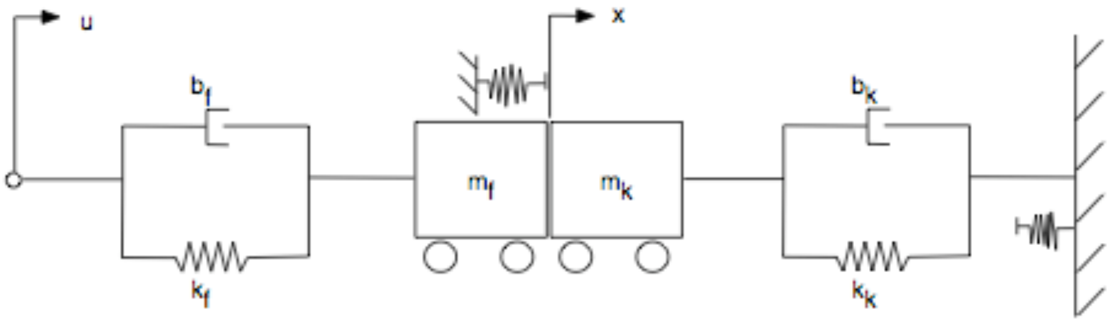
After accurately modeling the system, the input curves can be designed by trial and error, in order to match the position curves in the Hirschkorn paper. After the position results of the simulation are matched to the known curves, the force measurements can be simulated. It is assumed that if the impedance and motion of the device is matched to that of that of the finger, the force measurements taken during experimentation will match those felt by the finger. Mathematical spring-mass-damper systems of the piano key and combination of the key-finger system can be seen in Figure 7 below and Figure 8.

Figure 7: Spring-mass-damper model of the piano key.



$$\left.\begin{aligned} -m_k\ddot{x} - b_k\dot{x} - k_k x + F - F_r &= 0 \\ F = m_k\ddot{x} + b_k\dot{x} + k_k x - F_r & \end{aligned}\right\} x_t < x_k < x_b$$

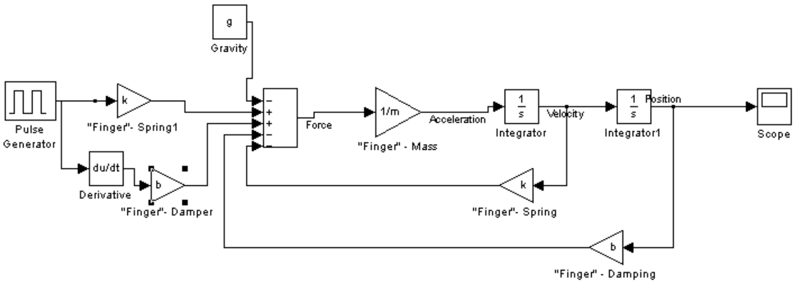
Figure 8: Spring-mass-damper model of the combined piano key and finger system.



$$(m_f - m_k)\ddot{x} = -b_f\dot{x} - k_f x + b_f\dot{u} + k_f u + b_k\dot{x} + k_k x$$

After running simulations involving these models we realized that we had neglected one important force: that of gravity. Because this force is constant it merely offsets the results of our simulation, and can be added in the control model of this system.

Figure 9: Control Model used with Linear Motor.



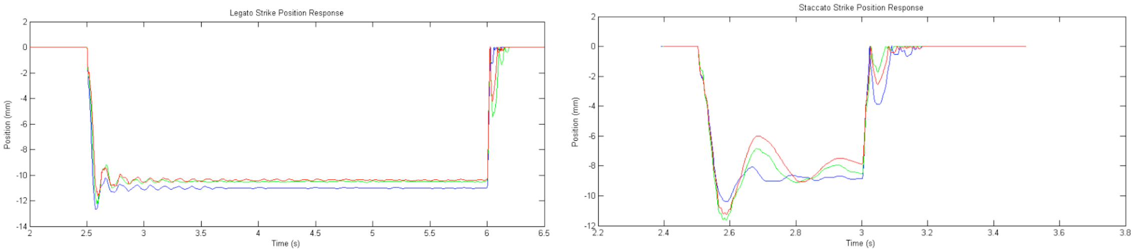
The only aspect of this control model that was not implemented is the mass gain. The mass of the motor needs to be corrected so that it matches the effective mass of the finger.

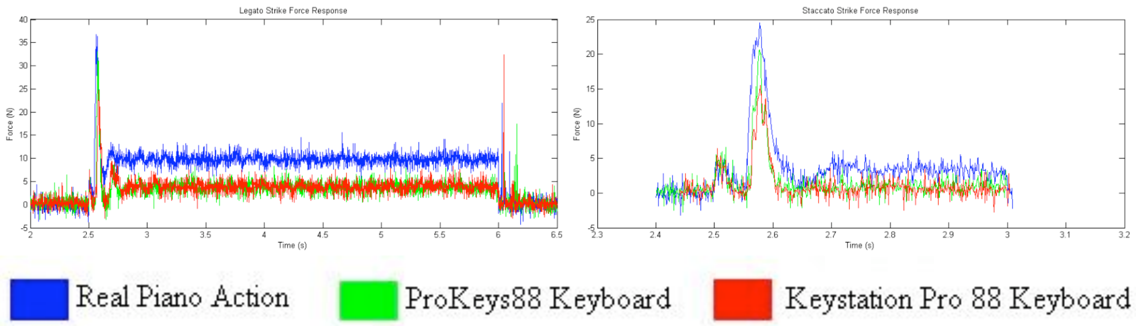
Results

The first obstacle in testing the device that our team faced was calibrating the force transducer. First the reading was zeroed. Next a scale was placed so that it was supporting the full weight of the armature. In this manner we were able to measure the total mass of the armature including sensors. This value corresponded to a certain voltage reading from the force transducer. Once this value was determined a linear scale was fit in order to make sense of the force readings. The spring gain and damping gains were adjusted in order to develop desired forces. We did not end up using the gains described in the Haijin papers because the force produced was not high enough.

To test the functionality of the device, the two M-Audio keyboards were used in addition to a keyboard action model. Two different strikes were created using LabView. The first was a strike peaking at approximately 30 N lasting about 3.5 seconds. The second strike was one peaking at about 20 N lasting for approximately 0.5 seconds. The position and force graphs are shown below for each case and each instrument.

Figure 8: Key position (top) and key force response (bottom) for two different inputs. Legato (left): A high force long duration key strike. Staccato (right): A medium force short duration key strike.





The position graphs still have quite a bit of oscillation in them, which needs to be reduced by adjusting the gains. The blue line represents the piano action model, the green and red datum the keyboards respectively. The force signals were not filtered. The concern was that if the signal was filtered the large spike at the beginning might be missed. The most significant results of these tests are that the position and force profiles for each of the devices are similar. The force response of the two keyboards is quite similar particularly for the longer strike. This demonstrates the ability of the device to reproduce results, delivering a constant strike each time. Once the range of gains for the system is adjusted to a satisfactory range, the device will be an accurate method for obtaining force curves. Of course, extensive further testing must be completed in order to characterize the differences between instruments.

Conclusions and Recommendations

The device works properly. All of the sensors function, and are integrated into the feedback control loop designed in LabView. Although the input curves we designed were not used, the program is set-up to read a text file. The motor is mounted successfully, although a more finely tuned high adjustable table might be advantageous. The output of the tests can be seen on the various graphs created in LabView, as well as stored as a text delimited file in the CRio. This device is very powerful because it is set-up to be able to quickly change the spring and damping gains, as well as the input files in order to test a large range of "piano strikes."

After our testing there are a few more improvements that could be made. Due to a slight movement in the armature, it might be helpful to change the aluminum plate that holds the motor above the piano to a box-shape instead of just a plate. This will aid in keeping the mount rigid. Also another way we can minimize the movement between the piano and the table is attach some type of clamping device to the piano so that the measuring device and piano move as one, if there is any movement. It is also unclear at this time whether or not the force transducer will provide accurate enough readings; whether or not a filter can be implemented which will not discard valuable data, in order for the noise to be reduced.

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Bios

Jessica Alspaugh grew up in Traverse City, Michigan. She decided to study mechanical engineering because she enjoys combining math and science skills with the opportunity to solve problems creatively. In the future she looks forward to a job that requires working with people in the creative design process. In her free time she enjoys playing soccer, cooking, and spending time with friends. She is passionate about music, even though she is not musically talented.

Robert DeLeon hails from the city of Bloomfield Hills, Michigan. In his early years of life, his excitement of automobiles started a flame in his soul and he knew he would somehow become a part of the industry. This in turn fueled the passion to pursue a career in mechanical engineering. When he is not found on North Campus in class or doing homework, you could find him socializing with his brothers in his fraternity or singing in his a capella group. He also enjoys drawing and playing the guitar when he gets the chance.

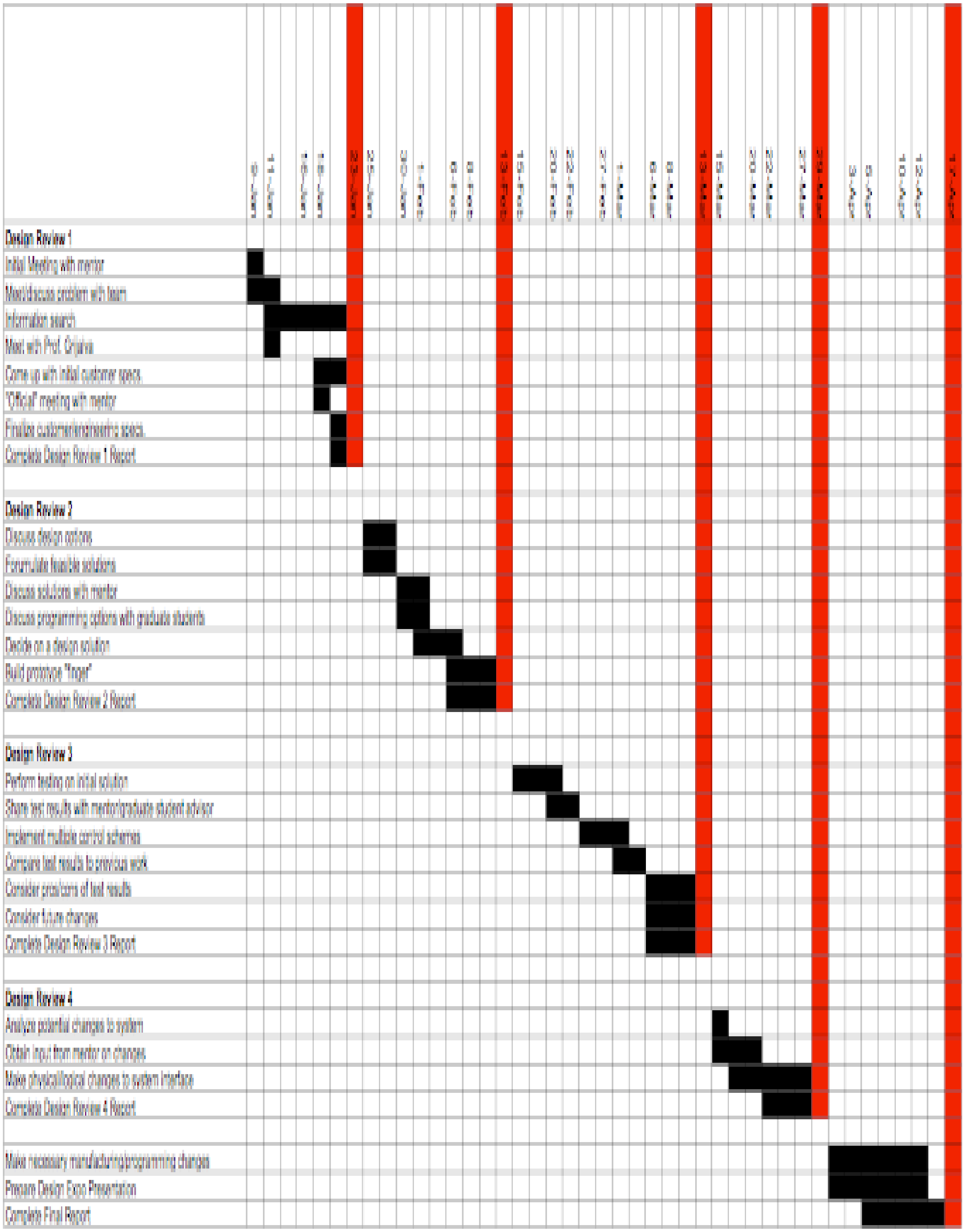
Katherine (Kate) Feeney was born in Columbus, GA and spent about half her childhood living in Atlanta. Her family then moved to Portage (Kalamazoo), Michigan where she lived until coming to the University of Michigan. She decided to study mechanical engineering because she has always enjoyed taking items apart, playing with them and figuring out how they work. The process of designing and creating products is exactly what Kate wants to be doing. After finishing up with classes in June, Kate plans on taking a couple months off and traveling (destinations undecided at this point). She will then, ideally, be starting a job as a design engineer at a consumer goods company. Although Kate spends most of her time on schoolwork, she also enjoys playing all types of IM sports, visiting with friends and has set herself a goal to learn to snowboard this winter.

Corey Griffiths is a Mechanical Engineering Major from South Burlington, VT. Before becoming a mechanical engineer, he experienced classes in the fields of biomedical, computer science, and naval architecture and marine engineering. He has one summer's experience of internship work at Control Technologies, an HVAC controls distribution and installation company. In the future, he aspires to work in the research and design department of a company with high engineering standards. His musical interests lie in his experiences at the University of Michigan include one semester of musical theatre singing and three years of playing tuba with the Michigan Marching Band. He is looking forward to seeing this project come to life over the semester.

Anthony Roman is originally from a small town called Morenci in Michigan. He became interested in mechanical engineering because he enjoys math, problem solving, and building things, and wants a career that will allow him to continue to think and problem solve. Of the classes taken thus far, he has enjoyed math, static behavior of materials, and dynamic behavior of materials. He was drawn to piano feel characterization because of his appreciation of music, both in listening and playing.

After graduating, he would like to get a mechanical engineering job in a field of personal interest including, but not limited to, music or automotive engineering, and use the money earned from working to travel. A job that allowed him to travel both within the country and without would be greatly enjoyed.

Appendix – Gantt Chart



Simulink Schematic