Paper ID #15574

MAKER: Interdisciplinary Senior Design Project to Print Mozart's Fortepiano

Dr. Yalcin Ertekin, Drexel University (Tech.)

Dr. Ertekin received his BS degree in mechanical engineering from Istanbul Technical University. He received MS degree in Production Management from Istanbul University. After working for Chrysler Truck Manufacturing Company in Turkey as a project engineer, he received dual MS degrees in engineering management and mechanical engineering from Missouri University of Science and Technology (MS&T), formerly the University of Missouri-Rolla. He worked for Toyota Motor Corporation as a quality assurance engineer for two years and lived in Toyota City, Japan. He received his Ph.D. in mechanical engineering from MS&T in 1999 while he worked as a quality engineer for Lumbee Enterprises in St. Louis, Missouri. His first teaching position was at the architectural and manufacturing Sciences department of Western Kentucky University. He was a faculty at Trine University teaching mainly graduate courses as well as undergraduate courses in engineering technology and mechanical engineering departments. He is currently teaching in Engineering Technology Program at Drexel University. His area of expertise is in CAD/CAM, Computer Numerical Control (CNC) machining, rapid prototyping and quality control. His research interest includes sensor based condition monitoring of CNC machining, machine tool accuracy characterization and enhancement, non-invasive surgical tool design, reverse engineering and bio materials.

Dr. Warren Rosen, Drexel University (Eng. & Eng. Tech.)

Dr. Warren Rosen received his Ph.D. in physics from Temple University. He has served as Assistant Professor of Physics at Colby and Vassar Colleges where he carried out research in solar physics, medical physics, and instrumentation. Following this experience he was a research scientist at the Naval Air Warfare Center in Warminster, PA where he established a laboratory for research in high-performance computer networks and architectures for mission avionics and signal processing systems, and served as the Navy's representative on several national and international standards committees. In 1997 joined the staff of Drexel University, first as a research professor in the Electrical And Computer Engineering Department and later as a clinical assistant professor in the Department of Engineering Technology. Also in 1997, Dr. Rosen founded Rydal Research and Development, Inc., which has carried out research in networking devices and protocols for the Air Force Office of Scientific Research and the Office of Naval Research. Dr. Rosen is the author or co-author of over 80 publications and conference proceedings and the holder of six U.S. patents in computer networking and signal processing.

Mr. M. Eric Carr, Drexel University (Eng. & Eng. Tech.)

Mr. Eric Carr is an Instructor with Drexel University's Department of Engineering Technology. A graduate of Old Dominion University's Computer Engineering Technology program and Drexel's College of Engineering, Eric enjoys finding innovative ways to use microcontrollers and other technologies to enhance Drexel's Engineering Technology course offerings. Eric is currently pursuing a Ph.D in Computer Engineering at Drexel, and is an author of several technical papers in the field of Engineering Technology Education.

Mr. Michael Cassidy

I am a continuing education student in the Drexel University Electrical Engineering Technology program.

Maker: Interdisciplinary Senior Design Project to Print Mozart's Fortepiano

The desired current set of skills required of modern engineers and technologists has been steadily expanding. In addition to familiarity with manual machining and prototyping techniques, mastering CAD/CAM, Computer Numerical Control (CNC), automation methods, and embedded control are increasingly becoming essential tools in the design, prototyping and manufacturing of complex systems. In this paper, we describe an inter-disciplinary senior design project aimed at using modern techniques such as 3D printing and electronic signal processing to build a hybrid replica of Mozart's piano with accurate feel and sound quality but at an affordable cost of ~$2,000. Accurate reproductions of Mozart's piano are available but these can cost in excess of $60,000 new, due to the large number of parts that must be hand carved from wood, as well as the string/soundboard system. The high cost limits the availability to academic musicologists or anyone simply interested in hearing the music the way it sounded to Mozart, Beethoven, and Haydn. The keybox and soundboard are accurate reproductions of the original, but to reproduce the proper feel for the keyboard the expensive, labor-intensive parts of the key action are made using 3D printing, namely Fused Filament Fabrication technology, as well as hand crafting out of wood. In place of the strings, an electronic key velocity sensing and sound reproduction system was designed and developed.

The significance of the methodology to be applied in this capstone course project is to combine theory and practice to prepare the students to become better problem solvers and obtain practical solutions to real life/simulated problems using a project based approach. Students in the Mechanical, Electrical, and Industrial fields along with many others can learn many new skills from multi-disciplinary projects such as the design and development of a musical instrument. Such projects show students how to use different types of technology, and demonstrate how advanced technology can be used in an innovative application. Over the past few years many senior design projects in the Engineering Technology program are beginning to reflect the availability of makerspace technologies to develop useful products rapidly and at low cost. The MakerSpace programs and related technologies such as 3D printing and prototype making encourage curiosity for learning and creating new things and sharing of work and processes with others in the community of students, teachers, staff, and local residents[1]. Overall, many different fields of engineering, academia and artists can benefit from this application, enabling the development of skill and knowledge in many different engineering aspects and processes.

Introduction

Learning should be a journey through inquiry and discovery. Incorporating project-based education in engineering technology education has been for decades more and more stressed out and the reasons are obvious. Project-based teaching fosters student centered learning, allowing to cater to alternative student learning styles and to accommodate heterogeneous student communities. The Drexel University's Engineering Technology program capstone experience is completed by each student in a series of three courses during 9 month academic year – Senior Design Project I, II, and III. Capstone experiences are assessed to determine their contribution to students' ability to meet the ABET Program Educational Objectives and Student Outcomes (ABET-ETAC a-k). Assessment data is provided under Student Outcomes section at the end of the paper.

In this paper, we describe development of a student capstone design project prototype that is an electro-mechanical (hybrid) version of an 18th century fortepiano. The goal is that such an instrument could be produced at a much lower cost than a modern reproduction, making it more accessible to musicians and researchers interested in the instrument. The key enabling technologies used are the 3d printer, the microcontroller development system, and the rapid prototyping printed circuit board milling system. Using theses technologies, the student design team has reduced the number of handmade parts. They were also be able to remove the strings and frame, and replaced these with electronics that perform the same function, such as monitoring the keys and recreating the auditory tones. These changes allowed the instrument to be produced more quickly, cheaply, and consistently.

Design and Prototyping of Electronic Fortepiano

The key mechanism in a fortepiano is quite complex (see Figure 1). The key action can be broken down into several steps[2]. As the key is initially pressed there is a small amount of free play before the beak leather engages the pawl. As the key is further depressed, the hammer arm is accelerated by the force exerted by the beak on the pawl. As the hammer is accelerating, the damper is engaged and raised off the string. The next step is where the hammer is just below the string and the beak leather disengages from the pawl, and momentum flings the hammer into the string. The beak catches the front face of the pawl and the hammer is held against the check until the key is released. The haptic feedback as the key is pressed is nonlinear and changes throughout the key press. A simple spring or weight would not provide the proper feel of an actual key. The same feel could be maintained by building replica key actions in the same way modern reproductions are made, but this would be too costly. The challenge was developing a system that would exhibit the same complex behavior, but at an affordable cost.

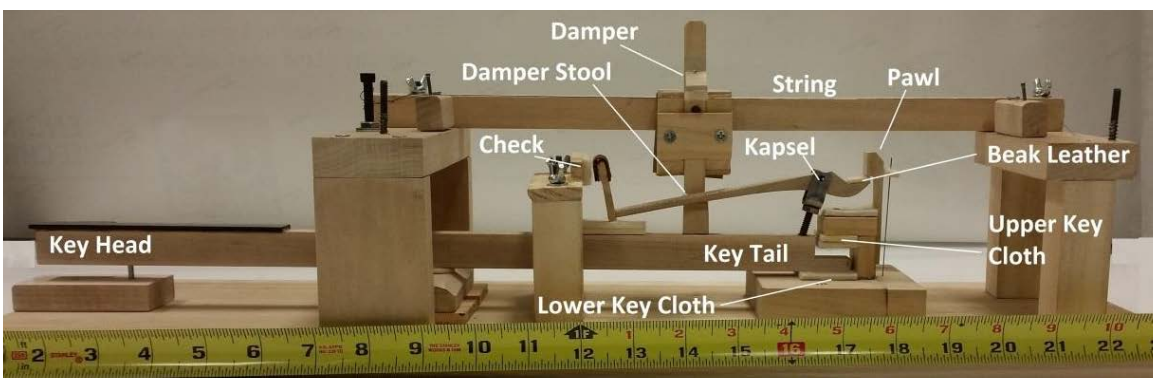

Figure 1 Fortepiano Key Mechanism

Physical Keyboard Design & Prototyping:

A key goal of this project was to produce an instrument that provides the correct haptic feedback to the pianist. The touch weight necessary to move the keys, the travel of the keys, and the motion of the hammers, etc. must all make the proper contribution to the way the fortepiano keyboard action feels to the musician. The plan proposed initially was to build a single-key model as a starting point and then begin removing mechanical components in an effort to reduce costs and complexity. The design team replaced more complicated components like hammers and escapement pawls with simpler devices involving springs and latch mechanisms, made with a 3D printer.

By the winter quarter the students constructed a 5-key prototype that gave us a platform to test a few types of alternative mechanisms. Larger parts such as key bodies were made from wood, as they were too big to be 3D printed by Dimension FDM 3D printer. Pictured below are two variations of key return prototype models:

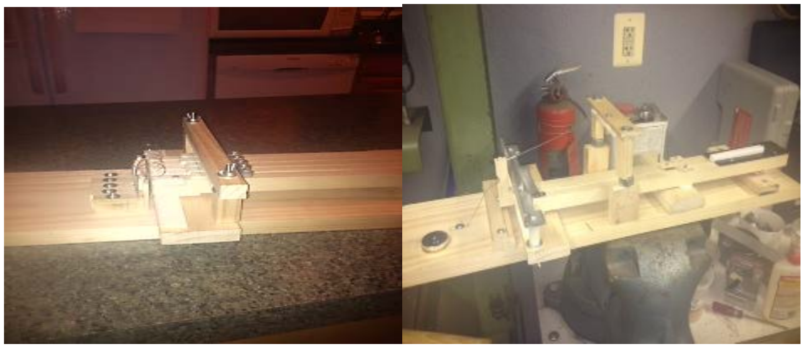

Figure 2 Coil Spring Key Return (left); Dual Leaf Style Spring Key Return (right)

The students were able to replicate the touch weight required to move the keys, but we soon realized that without the moving mass of the hammer travelling and escaping at string contact the design was seriously flawed. None of the hammerless tests that we conducted produced a piano-like feel; in fact they felt more like an organ.

The design team decided that 3D printing would allow the fabrication of the hammers and escapement parts economically, so the components were designed in SolidWorks. Previously, the students contacted the Germanisch National Museum in Nuremberg, Germany and obtained plans for a 1795 Anton Walter fortepiano, which included complete component specifications. There will be no strings in the prototype device so our hammers strike a soft media such as felt or foam. This limits the hammer travel as a string would, yet allows for the moving mass to produce the required haptic feedback to the player. Figure 3 shows a picture of parts designed in SolidWorks CAD modeler and made on the Stratasys uPrint 3D printer in the mechatronics lab[3].

Figure 3 SolidWorks rendering of CAD models (top left); 3D printed ABS components (top right); Steel and ABS Plastic/Aluminum Kapsel (bottom left); The Stratasys® uPrint 3D Rapid Prototyping machine used for 3D printing key components (bottom right).

A 5-key prototype completed with hammers and escapement mechanism, and set the key touch weights (weight in grams necessary to move the key to sound a pianissimo note) from 35 to 50 grams[4]. The prototype was tested by the local expert, Dr. Matt Bengtson, a world-renowned concert fortepianist to ask for his input[5]. Figure 4 indicates a picture of this key prototype.

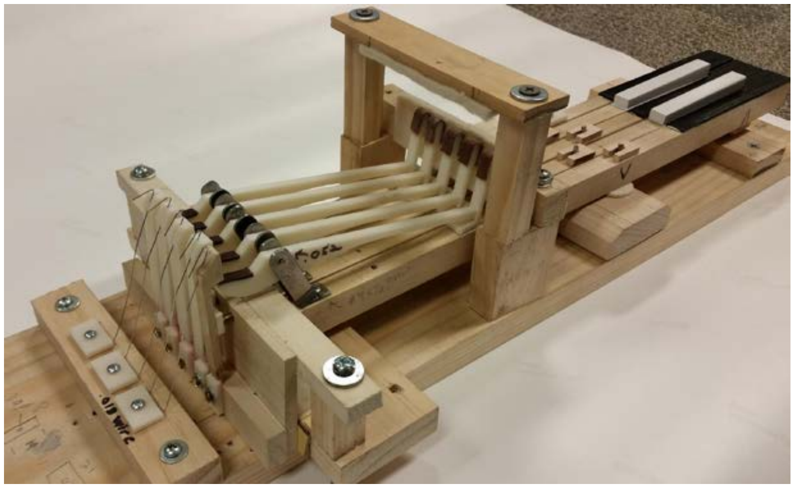

Figure 4 Key Prototype with 3D Printed Hammers and escapement system (Top);

Dr. Bengtson suggested to lighten the hammer end slightly. He liked the way that the way spring wires were attached which tensioned the escapement pawls. As shown in the picture, these are mounted with plastic hold down 3 D printed plates attached with screws. This is a more robust method than simply pressing the wire ends into the wooden block, which is the method used by Anton Walter. The kapsel (the component from which the hammer pivots) was fabricated from 16 gauge steel in the prototype. The weight of this component was reduced by almost 5 grams by 3-D printing the base and using aluminum sides. These differences are shown in Figure 3.

For a successful prototype, a high level of repeatability and precision in manufacturing is necessary. For example, the keys were made of hand-selected poplar and cut using a band saw with a secure guide fence. All keys were cut without moving the guide fence to ensure width consistency. The pivot holes in the keys were drilled using a fixture mounted to a drill press (Figure 5). After the majority of the key blanks were installed, we again utilized the 3D printer to make horseshoe shaped plastic plates, which were glued to the key bodies at the pivots to limit excessive movement in the keys. At this point, the basic structure of the keybox was complete and the frame and legs were fabricated. The Figure 5 below shows the piano at this point in its construction.

Figure 5. Cutting of the Keys (left); Key Pivot Hole Drilling Jig (middle)); Keybox with all Key Blanks, Horseshoes, and Frame(right)

Imitation black ebony veneer was used for the key tops of the natural notes. The sharps are made from wood and painted white – just the opposite of a modern piano but historically correct. Some parts also required machine work: The hammers had to be be drilled for a .052 inch diameter pivot pin, the escapement pawls must be grooved to allow a polypropylene hinge to be glued in, and the kapsels must have their aluminum sides glued on and drilled for the pivot pin. By now, many of the parts were prepared and were ready to begin assembly. Also, a plastic tab added to the hammerhead that allows it to return to a felt-covered rail instead of dropping back onto the key after the string strike. This and the completed piano internals are shown below Figure 6.

Figure 6 Completed keyboard internals (left); Hammer head resting on felt (right)

Velocity Measurement and Processing:

Measuring the keys' velocities and processing them properly is vital to having the notes sound right as well as avoid audio latency. As the project progressed throughout the design process, various alternative methods for measuring key velocity were considered such as mechanical switches, accelerometers, magnetic sensors, and optical sensors. Although each method has its pros and cons, we chose to go with an optical method for measuring velocity.

The motivation behind this decision is that the sensor is not mechanically coupled to the key, which could cause wear and, more importantly, have a negative impact on the physical feel of the key stroke. Also, there are no electronics that have to be mounted to the key, so removal of keys for modification or replacement is simple, and all of the electrical components are centrally located under the keyboard.

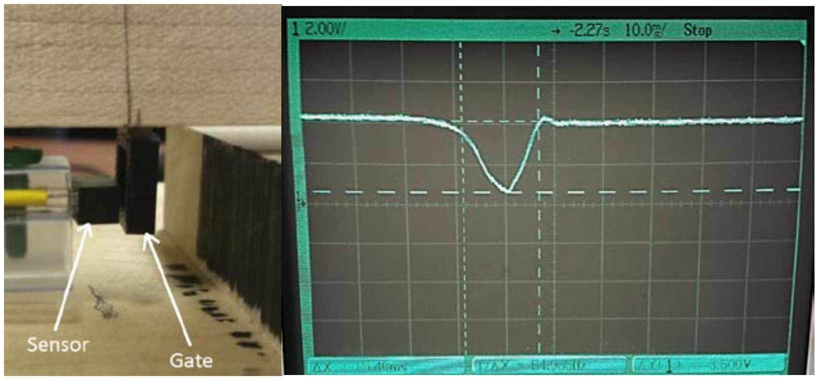

Figure 7 Sensor and gate (left), Sensor Output Signal (right)

The way in which we implemented our system was to use a single optical sensor per key that is aimed at a plastic gate mounted to the key. As the key is pressed, the gate passes in front of the sensor causing a voltage drop. By the bottom of the key press, the gate fully passes the sensor, and the signal returns to source voltage. The figures above (Figure 7) show the sensor system mounted to our test key and the corresponding output signal.

Electronics Design and Assembly:

Designing and building circuit boards for the electronics system were done in house. Due to the large number of components for the whole keyboard it wouldn't be possible to breadboard the entire design. Designing circuit board makes it much easier to mount, as well as being more robust. Figure 8 below shows the circuit board design.

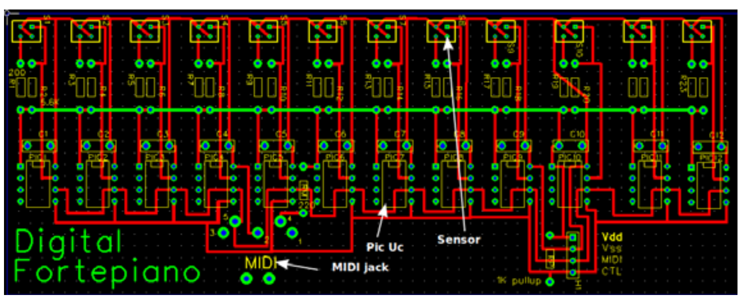

Figure 8 Circuit Board Design for 12 Key Sensors

One early idea that the design group had was to use an Arduino (Arduino Mega2560), and use one I/O pin per key. This is the current trend in maker activities to rely on Arduino technology and introduces related problems with doing that in this project. The advantages of this approach would, of course, be the ready availability of MIDI[6] (Musical Instrument Digital Interface) libraries, add-on shields, and community expertise. However, due to the sampling-speed limitations, it was quickly determined that an Arduino -- even an Arduino Mega programmed in efficient, bit-banged C was simply not up to the task in terms of timing. The timings required for velocity sensing required a dedicated microcontroller running in a tight loop, looking for an input pulse on a single pin. A PIC 12F683, running on its internal 8MHz oscillator, can monitor a GPIO pin in a single-instruction loop, taking eight clock cycles. It can therefore check for the start of the pulse with roughly microsecond accuracy.

The Fortepiano is really sixty-five MIDI instruments operating in cooperation. All of the microcontrollers share a common MIDI line as well as a common "control" line. When a microcontroller detects a keypress and determines the velocity, it assembles the MIDI command that would be associated with that event. It then waits for the (open-drain) CTRL line to be high. When the CTRL line has been high for a random number of clock cycles, the microcontroller then asserts the line low, "locking" the MIDI bus, and proceeds to send its MIDI event. Once done, it releases the CTRL line to float high, "unlocking" the MIDI bus for the other keys to use.

The final step in the keyboard control system was milling and populating the designed circuit boards. Figure 9 shows one of the finished circuit boards. A ProtoMat S42 rapid printed circuit board fabrication system from LPKF Laser & Electronics housed in the Engineering Technology Department was used to make the boards[7] (Figure 9).

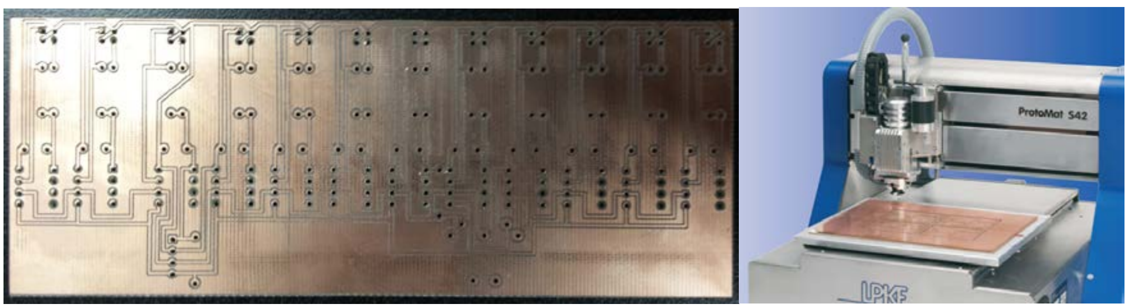

Figure 9 Control System Printed Circuit Board (left); ProtoMat S42 rapid printed circuit board fabrication system (right)

Once milling the circuit boards finished, populating them with components began. One of the challenges for assembly was the sheer number of components per board. There are over 200 connections that have to be soldered per board. The milling process removes material on the copper surface to insulate the traces from each other. These insulation lines are very thin and the pads are small, so even the smallest amount of remaining copper or solder in the joint would short out the board. This meant a lot of time scraping the traces and checking the board for shorts. Figure 10 shows the partially assembled circuit board mounted under the keybox.

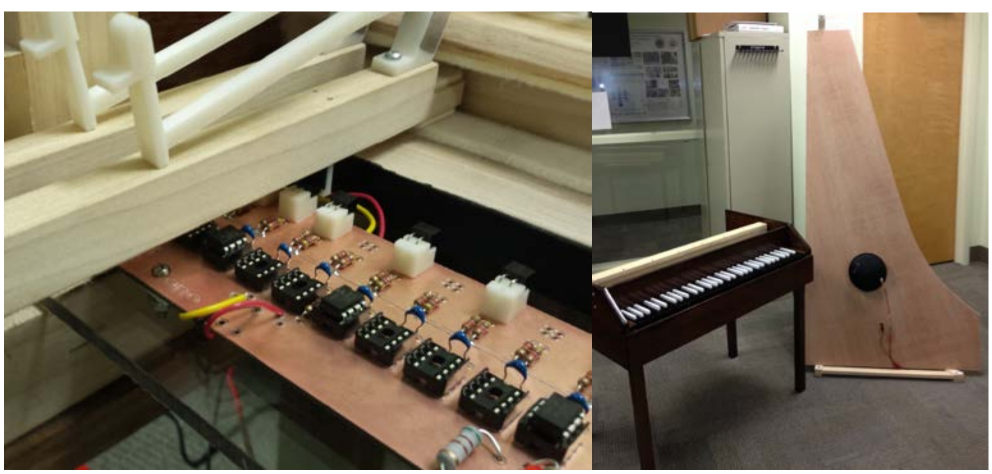

Figure 10 Mounted and Partially Populated Control Board (left); Full-Scale Soundboard and Electronic Fortepiano (right)

Students performed testing on the keys after assembly to check their responsiveness and any possible bus conflict issues. The instrument was able to play all the notes individually, and were able to play chords. This validated both circuit board and logic design.

The prototype cost $2,450 to fabricate, including labor (Figure 10). The cost also included a one-time cost of $280 for jig fabrication and software development.

Student Outcomes:
Oral presentations and written reports during the senior capstone course series are evaluated by department faculty and qualified external engineering professionals according to the Likert-type scale. Each assessor assigns a value for Performance Indicators according to a Likert-type scale. The scale (rubric) indicates the following three levels: Exceeds, Meets, and Minimally Meets (these values may be interpolated resulting in a 5-level scale). These results are used to produce an average assessment of a student team's oral and written presentation. Overall assessment scores are provided in Figure 11for fall, winter and spring quarters indicates that Fortepiano senior design team attained ABET student learning outcomes in each assessed category.

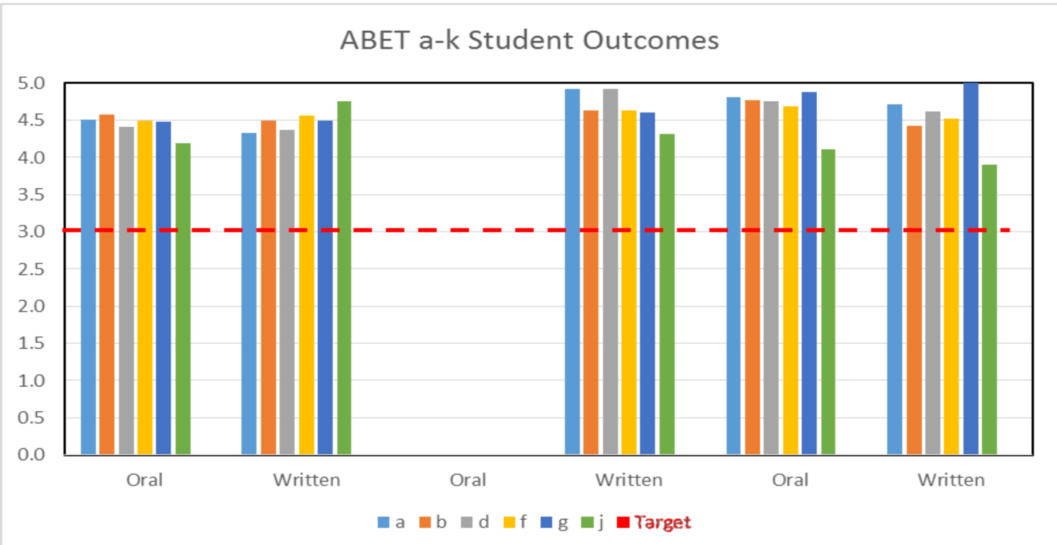

Figure 11. ABET assessment for Fortepiano senior design team during Fall, Winter and Spring 2014-15 AY.

Conclusion:
The fortepiano was the instrument used by some of history's most influential musicians, including Mozart, Haydn, and the young Beethoven. These three defined what we now know as "classical music." Interest in its effect on the music of the period, as well as its effect on performances, makes the instrument desirable again, hundreds of years after its inception. The senior design team worked to produce a final prototype of the design that captures the essence of the instrument. This meant overcoming challenges in replicating the feel of the instrument, measuring and processing the velocity of the keys, designing a control system to handle all the sensors and produce the MIDI output, and create a sound synthesis and output system that produce the correct tones. Through applied courses in Engineering Technology program such as robotics, rapid prototyping, and sustainable manufacturing and the incorporation of Making in many project-based courses, students are exposed to Making and its tools such as laser cutters, CNC machines, and 3D printers. These key making technologies are ultimately used in the

senior design capstone project. By using 3D printing students were able to produce many of the complex mechanical parts quicker and more affordably than handcrafting. The combined work over the past 9 months has yielded a working prototype that captures much of the qualities of the original instrument that Mozart and others composed his music on centuries ago.

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