Printing Mozart's Piano

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Abstract

This paper describes a senior design project aimed at developing a hybrid electromechanical keyboard and sound system that accurately replicates the unique sound and keyboard feel of an 18th century fortepiano. The target cost of the system is $2,000, substantially less that the $60,000 cost of many currently available hand-fabricated replicas. The cost saving is achieved using 3D printing techniques for the most labor-intensive hand-carved components together with advanced sensing and sound reproduction hardware and software. Expected student learning outcomes were assessed using written reports and oral presentations as well as an evaluation of each student's contribution to the project.

Introduction

The piano that Mozart, Haydn, and the young Beethoven used to compose the music of the classical era (often referred to as a "fortepiano") was very different from the modern concert grand instrument of Steinway, Bösendorfer, *et al*. in a number of important ways. Physically, it was much smaller (about 3' x 7' vs. 5' x 9') lighter (188 lbs vs 900 lbs. The keys were 1/3 shorter and the keystroke half as long, and the keys had a much lighter and more delicate feel. There were only 63 keys, vs. the 88-key modern piano. There were no foot pedals, although many used knee-actuated levers for the same purpose. These differences made for a very different tactile experience when playing the instrument. More important were the differences in sound produced by the instrument. The sound was very light and precise, with lower maximum volume. The sustain (the time needed for the volume to decay) was very short. As a result, the piano of the late 18th century sounded and felt very different from the modern version.

Visually it was also very different. Figure 1 shows the piano used by Mozart during the last ten years of his life.[1] It was built by Anton Walter and is now housed in the Mozarteum museum in Salzburg. The most striking feature, aside from its small size, is the color reversal of the keys; the naturals are black and the accidentals are white.

Figure 1. Mozart's fortepiano,[1] now housed in the Mozarteum in Salzburg.

The major differences may be seen and heard at Reference 2.

These differences had a major impact on the way classical composers composed, and it is difficult to understand music of the late 18th and early 19th centuries completely without understanding (and hearing) these differences. 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 and Haydn.

This paper describes a 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 a target cost of $2,000. The keybox and soundboard are accurate reproductions of the original, but the expensive, labor-intensive parts of the key action were made using 3D printing. In place of the strings, an electronic key velocity sensing system was developed that couples to a physical-model-based digital sound generation system. To reproduce the complex behavior of the original soundboard, a high-power acoustic transducer used for home theater applications was coupled to a dimensionally correct plywood soundboard. To evaluate the efficacy of the hybrid system, acoustic spectrograms were compared to those from an actual replica 18th century fortepiano. The system was also evaluated by a professional fortepianist. The system compared quite favorably in terms of sound quality and had essentially identical haptic characteristics.

The prototype of the hybrid fortepiano was developed by three senior students over a 9-month (three-quarter) academic year. The musical backgrounds of the three students were varied; one was trained in guitar while the other two had no formal musical training. Two of the students were in the top 25% of their class academically. The students undertook the project primarily due its challenging nature. However, as the project progressed the students became much more involved in the historical and musical aspects of the project.

The objective of the senior design sequence is to train students to use the knowledge and skills gained during their academic career to conceptualize, design, and develop a practical product. A key component of this development is the demonstration of a working prototype of the product. Expected student learning outcomes included an ability to use the knowledge and tools of the discipline relating to acoustic measurement and analysis, 3D printing and prototyping, microcontroller-based sensing, analysis, and communications, an ability to design, fabricate, analyze, and optimize a complex physical system in terms of cost and performance, and an ability to communicate effectively in written, oral, and graphical forms.

Assessment was performed using written reports and oral presentations as well as an evaluation of each student's contribution to the project. Oral presentations were assessed at the end of the first and last quarter and written reports at the end of each quarter. Both written reports and oral presentations were assessed by all faculty members and a number of outside assessors from regional industries. The assessment of individual student contributions was performed by the project advisor and co-advisor.

Technical Challenges

There were a number of technical challenges that had to be addressed in the development of the electronic fortepiano. The major ones included replicating the proper feel of the keyboard, accurately, sensing key presses and velocities, and reproducing the proper sound of the instrument.

Approach

In this section we describe the students' approach to addressing each of the technical challenges.

The key action is the major cost driver for the project because there are 63 of them and because each has a large number of small parts that, in the original, had to be hand fabricated. The main difficulty in reproducing the keyboard feel is related to the complex key action, particularly the escapement system (the system that allows the key hammer to fly freely toward the string just before striking it). The escapement in a fortepiano is quite complex, as can be seen in Figure 2. The key action can be broken down into several steps. 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. In the next step, which occurs when the hammer is just below the string, 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.
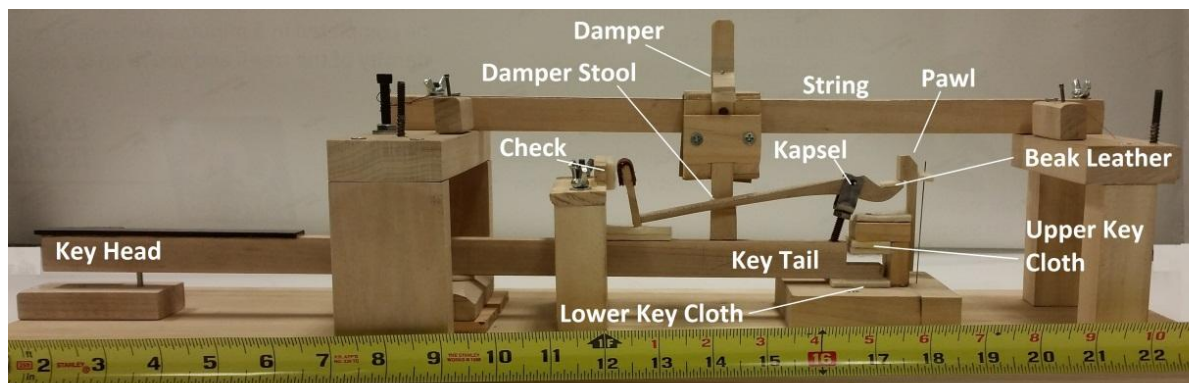

Figure 2. Fortepiano Key Mechanism.

The first step in reproducing the feel of the key action was to fabricate a full-scale replica of the key action using the actual materials and dimensions of the original system. This replica is what was shown in **Figure 2**. The dimensions and materials were determined from full-scale drawings of a 1795 Anton Walter fortepiano obtained from the Germanisches National Museum in Nuremberg.[4]

To verify that the replica accurately reproduced the correct feel, the students identified a local world-renowned fortepianist, Dr. Matthew Bengtson.[3] Dr. Bengtson owns a hand-made replica of a 1785 Walter fortepiano and is familiar with many replicas throughout the world. He agreed that feel of the key was representative of many instruments that he has played.

Using the verified key replica it was determined that the key action was too complex or too costly to be reproduced by any combination of springs, actuators, etc. It was therefore decided to build the full key action but to fabricate as many components as possible using 3D printing to lower the cost. The only important exceptions were the kapsels, which had to be made of metal, and the keys themselves. The cost of 3D printing the keys was prohibitive due to the large quantity of material needed. DIY injection plastic molding was also considered but was determined to be more expensive than simply cutting the keys from wood using simple band saw jigs. The components that were fabricated using 3D printing are shown in **Figure 3**. The gate and sensor standoff that was used to measure the hammer velocity are also shown.
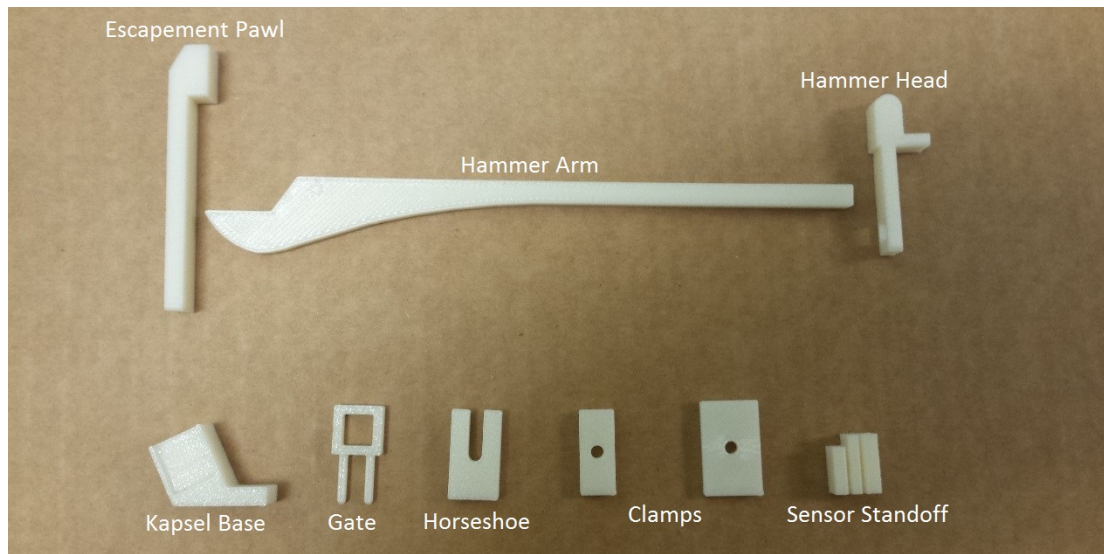
Figure 3. 3D-printed components.

The tone of a note is affected by the velocity with which the string is struck, so accurately measuring this velocity is essential to generating the correct sound. In addition, velocity information from all 63 keys must be transmitted to the sound generation subsystem in a timely manner.

Several alternative methods for measuring key velocity were considered, including switches, accelerometers, magnetic sensors, and optical sensors. In terms of accuracy, cost, and ease of implementation the optical method for measuring velocity appeared to be the most promising. It has the added advantage 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 must 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.

A single optical sensor is used for each key. The sensor 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.

To achieve the required speed, a dedicated microcontroller is used for each key. The microcontrollers calculate their respective hammer speeds and communicate over a common custom-designed bus using the Musical Instrument Digital Interface (MIDI) protocol.[5] The protocol doesn't transmit actual audio data, but rather note information that can be used to produce the proper sound via a synthesizer. The protocol also defines connectors and digital instrumentation. It is used to allow connectivity between digital instruments, computers, and synthesizers.

The mapping of actual key velocity to MIDI velocity is implemented differently in different digital instruments, and the result is interpreted differently by various synthesizers. Research performed at Carnegie Mellon showed that most keyboards map the range using a square root function.[6] For our implementation we used a linear mapping, due to ease of programming and speed of execution, although this can be modified later in software.

The final challenge was the accurate interpretation of the MIDI signals and the accurate generation of the acoustic signal. Commercially available electronic pianos do not fully capture the sound of the modern piano.[7,8] This is due to the complex interaction between the strings, bridge, and soundboard as well as inharmicity in the strings. An added complication is that the sound at any moment is dependent on the recent history of key strokes as much as the key(s) being immediately struck. Figure 4 shows a spectrogram of the sound generated by Dr. Bengtson's Walter piano as note C4 is repeatedly struck. The spectrogram shows the interaction between resonant modes in the soundboard. Modes are seen to exchange energy, sometimes disappearing then reappearing at a later time. The spectrogram was created using a Blackman window of length 2048, an overlap of 1792, FFT length of 8192, and sample rate of 44,100 Hz.
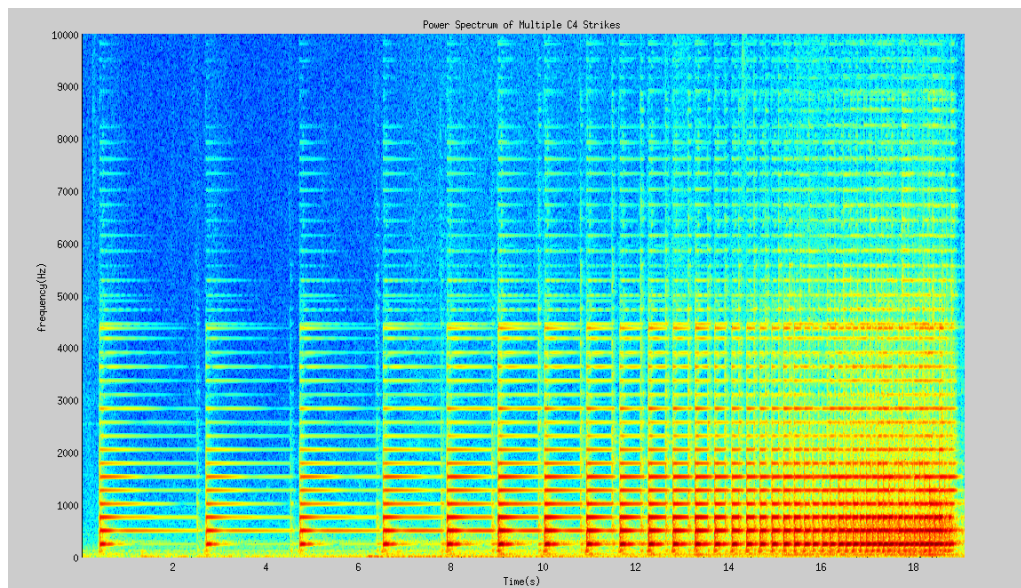
Figure 4. C4 Audio Signal Spectrogram.

Modern electric pianos rely on high-quality audio samples prerecorded real pianos as the keys are struck with different velocities. The samples are then interpolated to produce a range of velocities. As a result, they cannot reproduce this complex behavior.

Two techniques were employed to reproduce this complex behavior. First, software was obtained from Pianoteq[9] that uses a physical model to generate an acoustic signal from MIDI information. The physical modeling approach determines the resulting tone based on mathematically modeling all of the physical interactions that occur in the instrument. This is a complicated process to implement due to the complexity of the mechanical system as well as the non-ideal physical behavior of the instrument. Although it is more challenging, the result is a much more expressive and accurate reproduction of the instrument itself.

Models are available for a number of 18th 19th and 20th century pianos, including a 1795 Walter. Second, to reproduce the complex mixing of modal energy an actual soundboard was constructed. Two smaller prototypes were first constructed as a test. The first used solid spruce cut and joined as in Mozart's piano. The second use spruce plywood. The use of plywood in soundboards is controversial, although many experts argue that well-constructed spruce plywood soundboards perform as well as many solid wood boards.[10] Both prototypes produced complex and pleasing tones and there was no discernable difference in sound quality between the two. Since the plywood soundboard was considerably cheaper to produce, a full-size version was fabricated.

To energize the soundboard the acoustic signal was amplified using a conventional stereo power amplifier and sent to a Clark Synthesis Tactile Sound TST229 Silver Transducer [11] mounted on the soundboard. This transducer is used for home theater applications. It offers a tactile frequency range from 15 Hz to 800 Hz and an audible frequency range from 35 Hz to 17 KHz. (This device has been discontinued and replaced by the Clark Synthesis TST239 Silver Transducer.)

Figure 5 shows a functional diagram of the complete fortepiano system. The front end of the system comprises the instrument's keyboard and sensing electronics, and the back end is responsible for the sound production. The physical keyboard is the part of the front-end system that the user interacts with (i.e. the piano keys). The velocity sensing subsystem is responsible for monitoring the keys and recording the key presses. This information is then processed by the microcontroller system to calculate the velocity values. The resulting values are then converted to the MIDI format and transmitted to the audio-production back end.

On the back end, the MIDI signal is sent to a computer system hosting the Pianoteq software. The MIDI data is then used by the sound synthesis stage to produce the corresponding notes. The audio signal is transmitted to an amplifier that connects with the soundboard output transducer, which produces the audible sound heard by the listener.
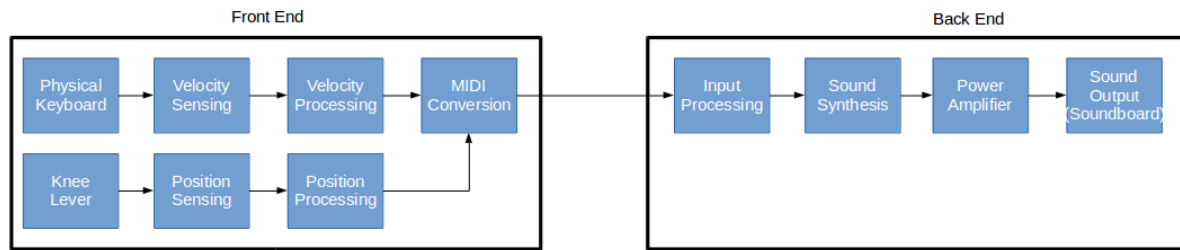
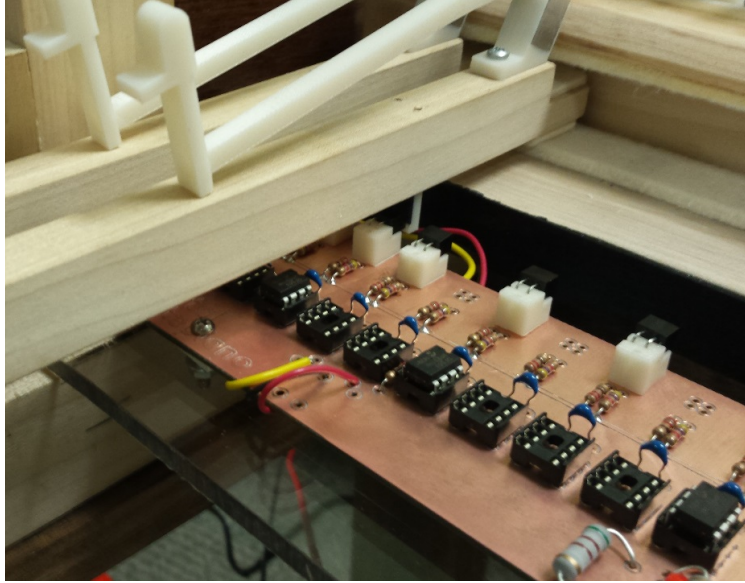**Figure 5. Functional diagram of the complete hybrid system.**

Results

Figure 6 shows the completed fortepiano prototype. The dark disk on the soundboard is the acoustic transducer. Figure 7 shows a close-up of the keybox with several keys removed to reveal the underlying electronics.


Figure 6. Completed Fortepiano prototype.

Figure 7. Mounted and Partially Populated Control Board.

The keys were tested after assembly to check their responsiveness and any possible bus conflict issues. (Prior testing had only been performed on a single key in isolation, and not using the circuit board.) The instrument was able to play all the notes individually and as chords. The latter was a major concern in terms of timing issues. This validated both the circuit board and logic design.

Figure 8 shows the spectrogram of the power distribution for a 430 Hz sine wave played through the transducer, not mounted to the soundboard. Figure 9 shows the same signal played through the transducer mounted to the soundboard. The spectrum is not merely stronger when using the soundboard; the spectral distribution is different as well. This phenomenon was also tested subjectively. Our group agreed that the sound felt more natural and warm when played through the soundboard compared to normal speakers.
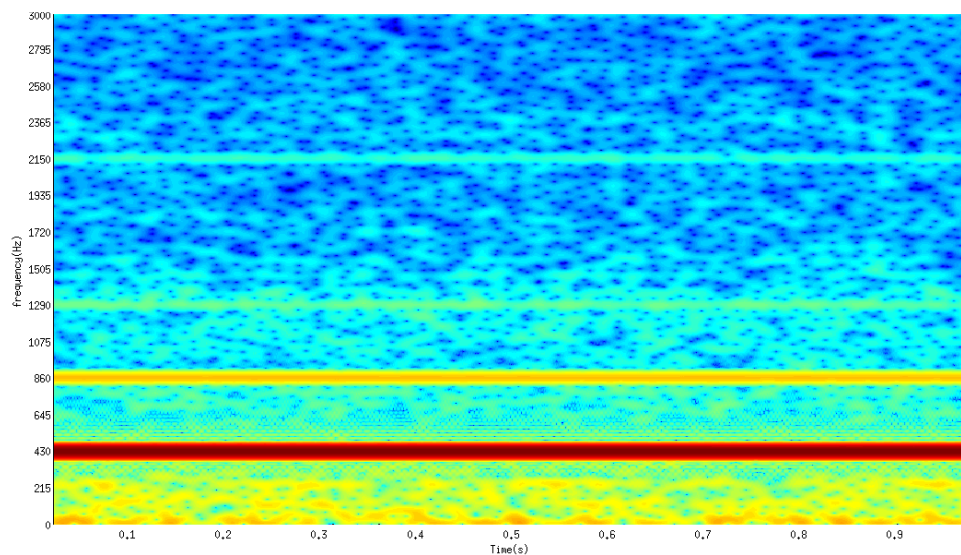
Figure 8. Spectrogram using the transducer without soundboard for a 430 Hz sine wave.
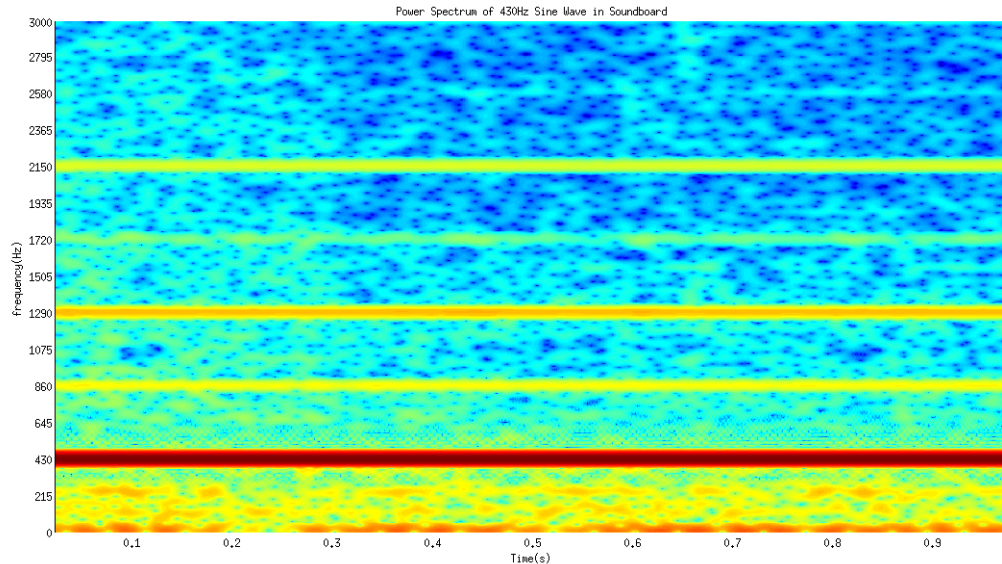
Figure 9. Spectrogram using the transducer with soundboard for a 430 Hz sine wave.

The prototype cost $2,450 to fabricate, including labor. The cost also included a one-time cost of $280 for jig fabrication and software development. We anticipate that the cost would be substantially lower in a production version.

Assessment

Assessment was performed using written reports and oral presentations as well as an evaluation of each student's contribution to the project. Oral presentations were assessed at the end of the first and last quarter and written reports at the end of each quarter. Both written reports and oral presentations were assessed by all faculty members and a number of outside assessors from regional industries. The assessment of individual student contributions was performed by the project advisor and co-advisor.

The students' performance was assessed using a set of performance indicators that are also used to assess the program's student a-k outcomes. Each indicator is assessed according to a Likert-type scale and the results weighted to emphasize technical qualities of the work and scaled to produce a score from 0 to 100 in order to determine the students' final grades. Using this method the students received score of 93.5 and 90.4 for the oral and written contributions, respectively. The average of 92 ranked them as the best of eight senior design teams, scoring nearly 4 points higher than the second-ranked group. The students' high scores were due primarily to the difficulty of the project, the high quality of the successfully completed prototype, and the high quality of the students' oral presentation and final report. During the course of the project the students used a great deal of the knowledge gained during their academic careers, but also accrued new knowledge and skills in acoustic signal processing and digital networking.

Conclusions

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.

This paper described a senior design project aimed at developing a hybrid fortepiano that captures the feel and sound of an 18th century instrument but at much lower cost than currently available hand-crafted replicas. Using 3D printing we were able to produce many of the complex mechanical parts more quickly and more affordably than handcrafting. Using modern sensing, physical modeling, and sound reproduction techniques we were able to replace the complex and expensive bridge and string system. The result was a working prototype that captures much of the qualities of the original instrument on which Mozart and others composed their music over two centuries ago.

Bibliography

1. Retrieved from http://www.squarepianos.com/_images/otherpix/WAMflug.jpg. Accessed 30 January 2016.
2. Retrieved from https://www.youtube.com/watch?v=ixKath2K0Mw. Accessed 31 January 2016.
3. Retrieved from http://www.mattbengtson.com. Accessed 1 February 2016.
4. Retrieved from http://www.gnm.de/en/. Accessed 1 February 2016.
5. Retrieved from https://www.midi.org. Accessed 1 February 2016.
6. Dannenberg, Roger. "The Interpretation of MIDI Velocity." *Proceedings of the 2006 International Computer Music Conference* (2006): 193-96.
7. Bengtson, M. Private communication.
8. Bilson, M. Private communication.
9. Retrieved from https://www.pianoteq.com/home. Accessed 1 February 2016.
10. Retrieved from http://www.harpkit.com/category/lib_soundboards.html. Accessed 1 February 2016.
11. Retrieved from http://www.parts-express.com/tactile-sound-tst229-silver-transducer--300-860. Accessed 1 February 2016.