Musical Acoustics & Instrument Design: When Engineering Meets Music

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ABSTRACT

This paper documents an instrument-building course co- developed by the School of Engineering and Applied Science and the Department of Music at Yale University. The course focuses on the fundamentals of musical acoustics, electronic sound production, and instrument design through traditional lecture-based learning as well as a hands-on experimentation and building. The structure of the course, the primary pedagogical objectives, the facilities, and examples of final projects realized by the students are discussed.

1. INTRODUCTION

ENAS344/MUSI371 Musical Acoustics & Instrument Design is an exploration of the acoustic principles of musical instruments using a highly interactive hands-on approach. This course is targeted towards undergraduate students with a wide range of backgrounds in music and engineering, providing an understanding of the physics of musical instruments, how they are designed, and a practical knowledge of the tools and technology used to build them. The course culminates in an innovative design project utilizing the Center for Engineering Innovation and Design (CEID) in which students produce novel musical instruments or relevant applications and interfaces.The students are therefore trained in, and make use of, the appropriate tools in the (CEID) for hands-on instrument study, design, prototyping, and building. Emphasis is put on string, wind, percussion, and electronic instruments, and topics include all aspects of sound from the origin of the vibration in the instrument to the perception by the listener.

2. A HANDS-ON APPROACH TO TEACHING MUSICAL ACOUSTICS

2.1 Spaces

The concept behind this course was born from a unique ecosystem present at Yale University formed by the Yale Center for Engineering, Innovation and Design at the School of Engineering and Applied Science and the Yale Music and Multimedia Technology Labs at the Department of Music.

Yale's Center for Engineering Innovation & Design (CEID) opened in the fall of 2012; it centralizes and expands the resources previously available to engineering students.

Figure 1. The studio at the Yale Center for Engineering, Innovation and Design

The idea behind the creation of the CEID was to foster a culture of engineering on campus and open up engineering to everyone. This unique space, open to the whole Yale community, features state-of-the-art prototyping technology, including 3D printers, a laser cutter, power tools, electronics workstations, machine and wood shops, computers and a wet lab. It has an open central studio space, a lecture area, and group study rooms with floor-to-ceiling whiteboards, all of which are open 24 hours a day. The CEID is a great teaching resource, but it is also a vibrant space filled with students working on extracurricular activities. Staff regularly organize workshops to teach students new skills and help them learn techniques as programming, computer-aided design, or electronic systems wiring, to name a few.

Yale's Music and Multimedia Technology Labs opened in the Fall of 1998. The YalMusT Labs serve a variety of constituencies - undergraduates, graduate students, professional students, staff and faculty. Its focus is drawn from the creative interaction between music, video, and technology, and the research, performance, and pedagogical impact of that focus. This space was key to the course's labs involving instrument recording and signal analysis. Concepts such Fourier transforms and spectral analysis of a signal were introduced in an interactive manner; the students learned not only those concepts but applied them to the instruments they had built in the previous lab sessions.

2.2 Lectures

The lecture component of the course involved traditional studies of instrument acoustics, electronic sound production, as well as guest lectures from instrument builders and historians. Lectures were held twice a week for 50 minutes. The acoustics component was broken down into three categories - bars, strings, and tubes - and involved investigations into the corresponding musical instruments. The electronic sound component involved lectures based on early electronic instruments, as well as investigations into digital synthesis techniques, human computer interaction, and micro-controllers. All along the semester, we put those lectures into perspective with insights in the history of musical instruments from the Yale Collection of Musical Instruments and guest performers.

2.3 Labs

Each lecture topic was accompanied by a corresponding three-hour practical lab. These lab sessions provided a structured introduction to traditional engineering tools such as 3D printers, basic electronics, power tools, laser cutters, wood working tools, and machining tools. Students were also introduced to basic computer-aided design (CAD) through labs in SolidWorks focusing on both the modeling of objects and material analysis. The labs were cumulative in content and difficulty, adding a new set of skills with each assignment.

Besides giving the students the necessarily building skills, the labs were intended to reinforce in a more concrete way the concepts introduced in a lecture. For instance, by asking the students to build a simple single string instrument, we reinforced and illustrated the concepts of frequency of a vibrating string and its link to a musical note, as well as the notions of equally-tempered and just scales by varying the fret positions.

3. INSTRUMENT DESIGN PROJECTS

This course concluded with a design project comparable to a classical engineering design challenge. In this section, we first describe the goals and expectations set at the beginning of the project. Then, we report on some typical examples of design projects realized in the fall of 2014.

3.1 Description

In the last 4-5 weeks of the term, each student was challenged to design and build a novel musical instrument or a unique modification/optimization of an existing musical instrument. The results of this final project went far beyond our best expectations. The students became independent and effectively applied the tools they learned earlier in the semester to realize their design. We believe that this pedagogical approach in conjunction with the ecosystem at CEID was a key component of the course success.

Below, we report on typical examples of design projects. A non-exhaustive list of the final designs also includes:

- *Fischer & Sons*, a keyboard inspired by the Fender-Rhodes piano, using the relay coils to pick up the oscillation of magnets fixed at the ends of wooden tines (as shown on fig.2);

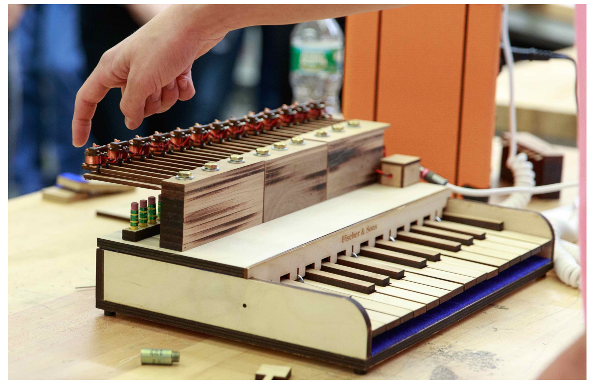

Figure 2. Fischer and Sons, a keyboard inspired by the Fender-Rhodes piano

- *GertrOud*, the electroacoustic Oud;
- *Absolute Muxima*, a touch-sensor double keyboard designed to play on different tuning systems;
- *Helmholtz's Harmonious Homebrew*, a keyboard activated bottle-blowing organ;
- *Godflow*, a software package developed around the inferface between Max/Ableton Live and the Thalmic Myo, a gesture control armband;
- *Viola Mechanista*, a keyboard operated bowed instrument;
- `GuitarTrack();`, a controller based input involving pitch tracking and capacitive touch sensing, adding, in an ergonomic fashion, versatility to real time electric guitar performance;
- *The Lothloritar* and more ...

3.2 Detailed Examples

3.2.1 Potenciello

The Potenciello (a compound word made of ”potentiometer” and ”cello”) stems out of the imagination of a freshman student. The student, a violin player himself, designed an instrument that would use the general ergonomic structure of a cello but relies on electronic sound production.

True to its cello design, the instrument is actuated by a bow which is covered with a timing belt whose grooves interlock with the grooves of a DC motor; when put in motion this DC motor delivers a voltage that can be read by a microcontroller (Teensy 3.1) which controls the amplitude of the sound produced. The frequency of the sound is provided by fingering

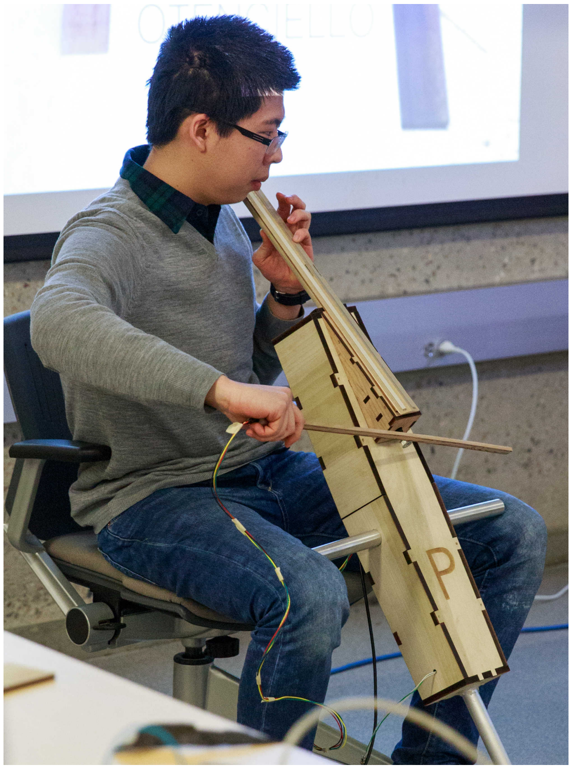

Figure 3. Student playing his Potenciello during his final performance, we can distinguish the main part of the instrument, the neck supporting the two SoftPot membrane potentiometer, the body housing the electronics and the motor, and the bow whose frog contains pressure sensor and accelerometer.

positions on two SoftPot membrane potentiometers by mapping the readout of voltage dividers.

As pictured on fig.3, the body houses the main components of the circuit and provides a structure for the instrument. The bottom face holds the DC motor. The wooden neck was designed in two parts (the fingerboard and the back), both manufactured on a ShopBot. A space between them accommodates the wires which run from the scroll to the body. The fingerboard is curved slightly to accommodate the two SoftPot membrane potentiometers. The 3D printed bow frog houses a force sensor which changes the timbre of the sound by changing the cutoff frequency of a low-pass filter and an accelerometer which allows the orientation of the bow to be detected, in order to simulate a change of string. Finally, the scroll was designed to fit over the top of the neck and 3D printed on a MakerBot. The scroll houses an LCD display, two rotary encoders, and connectors for the two SoftPot membrane potentiometers. Similar to classical string instruments, one function of the scroll in the Potenciello is to scroll through a Reference Pitch (i.e. frequency of A_4) and an Open String Pitch; rotating the scroll encoders is analogous to turning the tuning peg on a cello. Finally, the scroll also controls the waveform.

The Potenciello was developed as a lead instrument but the ability to play ”pizzicato” combined with the ability to tune the ”strings” without changing sound quality may also allow Potenciello to act like the bass in a jazz band. Finally, since the instrument can be fine-tuned to a different reference pitch without affecting its sound quality, it may be possible to play in ensembles using different tuning systems (such as pre-baroque ensembles).

3.2.2 Clip-B-Audio

Audio and visual arts are strongly entangled, the Clip-B-Audio project is an attempt to further this relationship. Simply put, the Clip-B-Audio is a pencil that draws music on a clipboard as shown on fig.4. Versatility and straightforwardness make this instrument a very playful one even for the beginner. The design of this instrument was guided by a few important goals. First, this instrument needed to be completely portable and have an ergonomic and small form factor. Next, the design should be kept as simple as possible. The real creativity would come from the music that people produced from their drawings. Lastly the instrument had to be fun and intuitive to use.

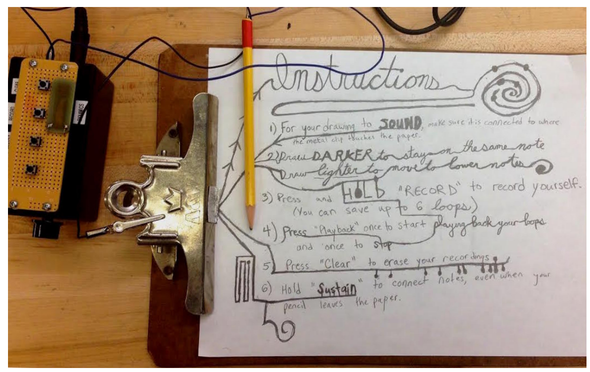

Figure 4. Clip-B-Audio, a pencil that draws music on a clipboard, we show here a set of instructions to the beginners that can be themselves played by the instrument.

Behind the scenes, the Clip-B-Audio uses the very simple idea of a voltage divider and the resistivity of graphite. The resistivity of a graphite line drawn on a piece of paper increases with its length, forming a voltage divider with a fixed resistor. A microcontroller (Teensy 3.1) reads out the voltage across the divider and maps it onto a frequency scale. The circuit is closed between the metallic part of the clipboard and the pencil itself. To reduce noise, the signal is filtered through a low-pass filter. One of the important features in the design of this instrument was to keep it compact; the student thus decided to use the Teensy audio library [1] for on-chip sound production.

A ”sustain” function was added to the instrument; the player could decide to sustain a note (the pencil would keep on playing a note even after the pencil left the page) by pressing a button. This allowed for greater musical control since a player could now make the sound staccato, slightly detached, or legato.

The Arduino Timed Action library on the Teensy 3.1 board was used, allowing creative expression through polyphony.

[1] http://www.pjrc.com/teensy/td_libs_Audio.html

It allows the player to record up to six tracks and play them back, all while drawing and playing current output from the pencil simultaneously. A dynamic touch sensor was added to the pencil in order to allow for a greater degree of musical expression, allowing the performer to change the timbre in an intuitive way. For the final prototype, the four buttons (record, playback, clear, sustain) were placed on the top of the box to improve playability and interactivity. An amplifier was installed at the audio output of the microcontroller as well as a volume knob, allowing headphones directly to the device. The Clip-B-Audio was designed with the idea in mind that anyone should be able to start using it and make music immediately. A new player can choose not to use the volume touch sensor, the sustain, or the recording features, while the advanced player can do much more to turn their drawing into a work of musical art. Furthermore, one can imagine the pencil inspiring visual artists to create new works of art with a musical component.

3.2.3 Siren Song

Invented by the French scientist Cagniard de la Tour, in 1819, the acoustic siren was one of the fundamental tools of 19th century science. Using this historical design, the Siren Song transposes it to light domain. Where the tone was produced by oscillations in the air pressure through the holes in the original design, the signal comes from the oscillations of the recorded light intensity through the very same holes in the design of SirenSong. The core of this instrument relies on a microcontroller (Teensy 3.1). Nevertheless, the rest of the design is true to its ancestor. The instrument is composed of three spinning discs with arrays of holes. These discs are connected to three DC stepper motors whose angular velocity is controlled by a Sparkfun EasyDriver stepper motor driver. The combination of number of holes in the disc and angular velocities of the three spinning discs provides the different pitches of the instrument.

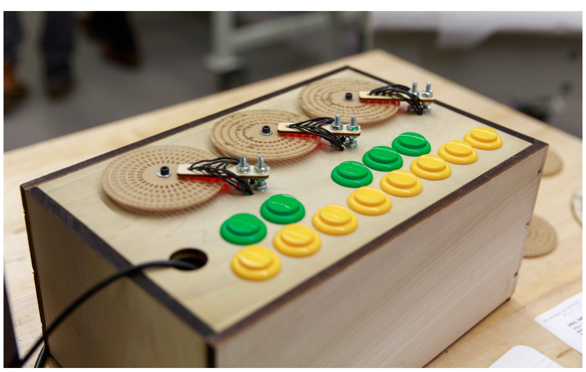

Figure 5. SirenSong

The signal is produced by the readout voltage of a voltage divider circuit containing a photoresistor; the photoresistors are installed across from red LEDs with rotating discs spinning in between as shown on fig.5 This produces an oscillation of the light received by the photoresistor. The oscillating voltage from the photoresistor – voltage divider is then sent out to an audio jack to be externally amplified.

This instrument is in essence a polyphonic keyboard using light as a sound producing device. The number of available pitches was set to 13 on this prototype. The voltages across the photoresistors were connected through the keyboard buttons in parallel and then combined to one single main audio output. Pressing a button would connect the corresponding voltage divider circuit and activate that tone. Arcade game buttons made for an attractive retro look and were layed out in a piano-like pattern in order to be intuitive for keyboard players. Discs and buttons were mounted on a plywood box made out of laser cut pieces; the instrument is powered by a recycled PC power supply enclosed and mounted in the box along with the motors and the PCB holding the microcontroller.

4. CONCLUSIONS

The goal of this course is to present musical acoustics and electronic sound production in a hands-on and interactive way. The class was realized in the unique ecosystem provided by the CEID, and in the collaboration between the school of Engineering and Applied Science, and the Department of Music. We see the effectiveness of this approach to teaching acoustics and instrument design in the fact that a diverse range of students were all able to fully meet every challenge of the course.

5. ACKNOWLEDGMENTS

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