Electronic Music Interaction: modern and alternative interactions with music devices

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***Abstract* — This project explores the theme of creating a virtuosic experience through high customizability, modularity, and simplicity. This theme was developed by pairing the fluidly-noted analog theremin, one of the first electronic musical instruments, to a highly adaptable set of MIDI-capable devices. These themes are further enhanced by the immediate usability of the devices to users on a different level. A primary motivation of this project was to engender a direct-feedback environment that facilitates the learning experience for a device that is considered to be a very difficult instrument to master. Thusly, these goals are accomplished by developing a pitch-to-MIDI converter, and a set of expandable easy-grid MIDI controller devices to accompany the theremin. The purpose of this paper is to illustrate the research and design approaches involved.**

***Index Terms* — Analog-digital conversion, audio systems, envelope detector, frequency modulation, musical interface design, performance instrument organization, signal processing.**

I. Introduction

Examining the use of ephemeral interactions with technology, the project focuses on integrating the theremin, a musical instrument that can be played without touch, to create a technological interaction that takes physical bodies as input, and provides a highly customizable interaction environment. To tie together this highly adaptable environment, we lit upon Hochenbaum's case study on the Chronome[1] that notes to provide a virtuosic experience without the years of mastery; one must find a balance between the complexity of an instrument and ease of use. Having found this highly pertinent to our endeavor we decided to use this as the hub of interaction between the MIDI-capable theremin and any other MIDI-capable performance instrument. We set to make each device modular, to expand upon this customizability, in that they can be placed together in many number of combinations to reflect one's personal mental organization. By creating the Expandome we wanted to even further push the easy-grid instrument to the next level. The theremin, as an infinitely variable instrument, that requires years of practice as well as a near perfect pitch ear to master, is an ideal candidate for our intermediary device, a pitch-to-MIDI converter. This device can take any analog instrument and allow pitch-mapping, and arpeggiated control, as well as direct feedback for practice. This complements our theme of ease-in-interaction in proficient playing, as well as gives any analog instrument social and adaptable input to our performance device hub.

II. Electonic Music Interacton Components

The Electronic Music Interaction (E.M.I.) device set consists of three major devices: uWave Theremin, SenseBox and Expandome. The block diagram in Fig. 1 below demonstrates how each device communicates with each other.

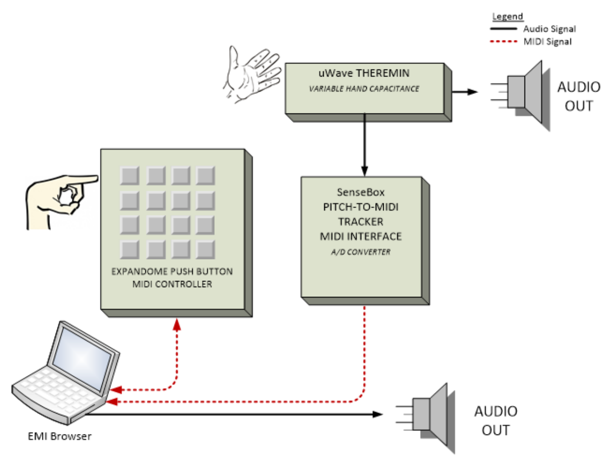


Fig. 1. E.M.I. Block Diagram demonstrating interconnections.

A. uWave Theremin

Patented in 1928[2], the theremin was the first electronic musical instrument. Although now a classical example, it has always been the most drastic break from any traditional instrument before or since. The theremin is played by moving both hands in the vicinity of two antennas. The player's hands creates a 'hand capacitance' between the antenna and true ground through one's hand, acting as a plate, and the antenna as the other plate. Typically, the left hand controls the volume, and the right hand the pitch. For the purpose of this project we will call our implementation of this device the uWave Theremin.

1. Antenna

Before we begin, it should be noted that most of the antenna equations that will be presented in this section also applies to the volume antenna. In playing the theremin, the pitch antenna is responsible for varying the pitch or frequency of the sound produced by the device. It is operated by placing the hand near the antenna thus changing the total capacitance seen by the pitch antenna circuit, which consists of inductors in series connected to the antenna. The antenna capacitance equation[3] is used to illustrate this:

$$C_A(\infty) = \frac{2\pi\epsilon_0 h}{\log\left(\frac{2h}{d}\right) - k} \tag{1}$$

Where C_A is the antenna's capacitance, h and d are height and diameter of the antenna respectively, ϵ_0 is the permittivity of free space (8.85 x 10-12 Fm^{-1}), and k is a constant depending on how far above the ground the antenna is mounted, which is about 0.4 for an antenna mounted almost at ground level[3]. The permittivity of free space, ϵ_0, gives a hint that the capacitance of the antennas will be affected by characteristics like humidity.

Equation 1 is the antenna's capacitance seen when the players hand is far away from the antenna; this equation also applies for the volume antenna. Using Equation 1 and an antenna with h = 0.45m (18 in) and d = 0.0095 m (3/8 in) and k being 0.4 we get C_A to be approximately 15.87 pF. The change in antenna capacitance when the players hand is in proximity is given by the following equation:

$$\Delta C_A \approx \frac{\pi\epsilon_0 h}{10\log\left(\frac{4x}{d}\right)} \tag{2}$$

Where x is the players hand distance from the antenna (it is assumed that this distance is greater than d)[3]. So, according to Equation 2, if a players hand is 4 m away from the antenna, a change in capacitance of only 0.43 pF is introduced to the antenna circuitry.

The pitch antenna will be vertically placed on the right hand side of the uWave Theremin as this configuration is more sensitive to the players hand far away from it, and less sensitive when the players hand is close by[4].

The pitch antenna of choice will be eighteen inches long and 3/8 in diameter. These dimensions were chosen largely due to aesthetic reasons, giving the uWave Theremin a compact look; however the length of the antenna will have an indirect effect on the hand-to-antenna capacitance by not only affecting the antennas capacitance, but also the hand-to-antenna range as demonstrated in equation 2. This will be important as it has an effect on the pitch antenna's reactance and the total impedance of the pitch circuit. Because of its relatively short length, it will be cascaded with multiple inductors to form a resonant frequency of about 260 kHz[4]. This frequency was chosen in order to reduce interference from other devices in the vicinity of the uWave Theremin. Since hand to antenna capacitance can vary on the order of 1pF to 15pF, the impedance of the pitch antenna circuit is drastically altered when the user brings his/her hand in proximity of the pitch antenna. The equivalent circuit of the antennas can be seen in Fig. 2.

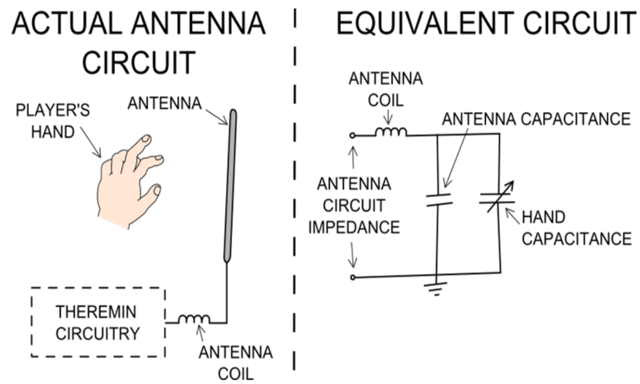


Fig. 2. Equivalent representation of hand and antenna capacitance.

2. Theremin Pitch Tone

Essentially, “the basic principle of the theremin is the heterodyne oscillator … A heterodyne oscillator is a radio signal technique in which new frequencies are created by combining or mixing two frequencies” [6]. Therefore, in order to create the pitch or sound we can hear, the uWave Theremin will be composed of multiple oscillators set to oscillate at two distinct frequencies. These two frequencies are slightly close to the resonant frequencies of the pitch circuits. These oscillators are the fixed pitch oscillator (FPO), the variable pitch oscillator (VPO) and the voltage oscillator. The fixed and variable oscillators will oscillate at a frequency (285 kHz) slightly higher than the pitch circuit's resonant frequency of 260 kHz. The VPO serves to create the variation in frequencies ranging from 0 to 3 kHz (about 3½ octaves above middle c)[4]. Its frequency will be reduced by the presence of the players hand on the pitch antenna.

In order to retrieve the beat frequency, a detector or demodulator is used. The detector is mainly composed of mixer, which can be in the form of a single diode, and a low-pass filter as seen in the block diagram below. The block diagram in figure 3 shows what the detector is consisted of and how it interacts with the VPO and FPO.

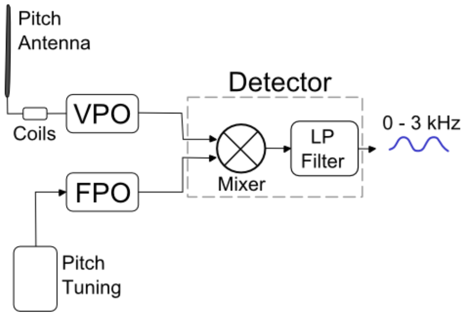


Fig. 3. Block Diagram showing the function of the Detector.

The result of the mixed signals is an amplitude modulated (AM) signal illustrated using the equation below.

$$V_{out} = \frac{A}{2}[\cos(\omega_1 - \omega_2)t - \cos(\omega_1 + \omega_2)t] \qquad (3)$$

A heterodyne frequency is one that has two component frequencies, $\omega_1 + \omega_2$ and $\omega_1 - \omega_2$. Since we only require the audible frequency from the heterodyne frequency, the output of the mixer seen in equation 3 is fed to a low-pass filter that has the output given in equation 4.

$$V_{out} = \frac{A}{2}\cos(\omega_1 - \omega_2)t \qquad (4)$$

As the player puts his hands close to the pitch antenna, the VPO's frequency is reduced and the output frequency increases and as the player puts his hand away from the antenna, the opposite occurs.

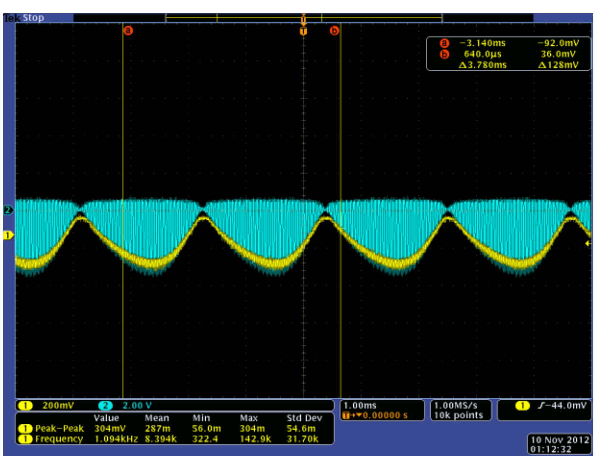


Fig. 4. Signals associated with the frequency detector.

Signal in blue is the heterodyned or mixed signal of the VPO and FPO. The signal in yellow is the output of the detector, which has a frequency equal to the subtraction of the VPO and FPO frequencies.

With the uWave theremin, we can expect the pitch antenna of the device to be responsive within 12 – 16 inch of the hand proximity with it. Below in figure 5 is a graph showing the hand distance versus scales of note A.

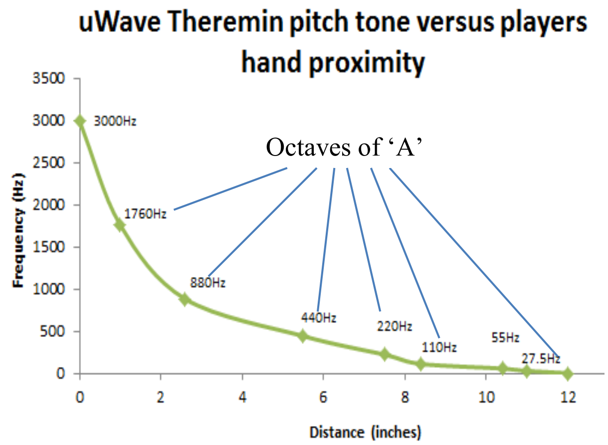


Fig. 5. Graph depicts the exponential increase in frequency as hand proximity increases.

3. Theremin Volume

As stated in Fred Mundell's investigation of the theremin, "the most common means of implementing this function is by effectively duplicating the pitch antenna oscillator, but having these operate at a higher frequency which does not interfere (has no important overlapping harmonics) with the pitch oscillator, and then converting the frequency variation from this oscillator to a varying voltage or current"[6]. This seems to be a similar case in Robert Moog's implementation in which he states that "as the player brings a hand near the volume antenna, the resonant frequency of the volume-antenna circuit is lowered, and the DC voltage is reduced"[4]. Also, in Robert Moog's implementation he sets the volume oscillator to oscillate at 450 kHz. This is in correspondence with Fred Mundell's comments about setting the volume oscillator to a frequency greater than the pitch oscillators and thus this condition was implemented in our design.

The rectified DC voltage from the volume oscillator and volume antenna circuitry will be sent to a volume controlled amplifier (VCA) in order to process the amplification factor of the pitch signal coming from the detector.

As the name implies, a voltage controlled amplifier is a type of amplifier that varies its gain factor depending on the control voltage/current given to it. As mentioned earlier, the volume oscillator and antenna circuitry will work with the VCA to amplify the small pitch signal coming from the detector. This is done by using the DC control voltage (CV) or current (varies with hand presence on the volume antenna) from the volume antenna/oscillator as the control voltage.

B. *SenseBox*

The SenseBox will receive two inputs from the uWave Theremin: pitch-preview and volume. This device takes an incoming audio signal and converts it to MIDI data messages. MIDI, which is short for Musical Instrument Digital Interface, is a standard protocol for communication between electronic musical instruments. The audio signal is analyzed by comparing its frequency to a lookup table of musical scale note pitches; the lookup table is based on the MIDI Tuning Standard (MTS) protocol found in the MIDI Manufacture Association website[7].

The incoming audio signal can be directly pitch-matched in the outgoing MIDI data or used as a controller via data messages. By allowing the infinitely fluid theremin to be mapped to data messages, we will be able to directly see how in-tune the player is. This is useful as direct training feedback. It also allows the theremin to not only be an instrument but dually gives it the capability of a MIDI controller. In the latter faculty, it will be able to control any virtual instruments. The heart of the SenseBox lies in the Atmega328p chip, which is our choice of microprocessor. The following sections will explain the analog-to-digital conversion methods, as well some of the feature SenseBox.

1. Pitch Conversion

Capturing the pitch data for MIDI involves integrating a threshold comparator. When the SenseBox receive signal from the uWave Theremin's pitch-preview output, the comparator will convert the incoming AC signal into square wave and will be fed into the microprocessor. The square wave output of the comparator is used to convert the analog signal into discrete and by doing so allow the microprocessor to sample the incoming signal. Fig. 6 demonstrates this phenomenon:

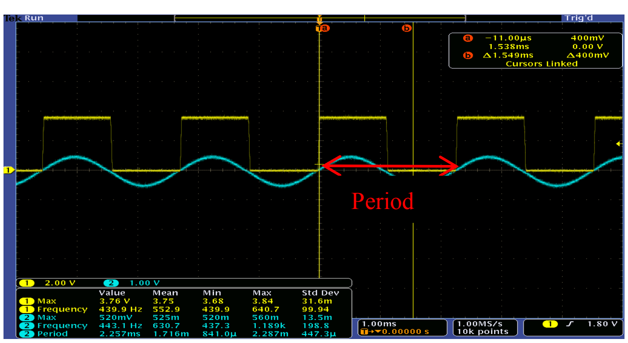


Fig. 6. Analog-to-digital conversion for pitch signal

The method of sampling the frequency is as so: the microprocessor will calculate how long the rising edge stays high and how long the falling edge stays low. After having enough samples, the microprocessor will then combine those two time values, which equals to a period, or frequency, and compare its frequency to a lookup table that is stored in the RAM flash memory. After finding the right the corresponding MIDI note value, it will output the corresponding MIDI data from the SenseBox to a destined MIDI device.

2. Volume Conversion

Capturing the volume data for MIDI involves integrating with an envelope function. Generally speaking, the envelope follower takes the raw audio waveform (usually in AC) and impulses a varying DC voltage, which represents the amplitude of the audio signal. Next, filtering is used to polish the output in order to filter out the low frequency. Principally, this method is used to capture solely the volume data. The signal will be placed into one of the analog inputs in the processor board.

3. Visual Aid Components

As mentioned before, playing with the theremin requires no physical contact with the user. Consequently, this means that the user is demanded to have great aural skills in order to play it proficiently. In fact, 1 in every 10,000 (1%) Americans have perfect pitch - an ability to identify the letter-name of a sounded note [8].

Thus, by installing an LCD (Liquid Crystal Display) in our SenseBox, it will deliver a visual assistance for the user to show where the notes are. Furthermore, the LCD will display current mode operation, volume value, and incoming/outgoing MIDI data. Fig. 7 demonstrates a typical LCD screenshot:

Fig. 7. LCD display demonstrating pitch mode and MIDI data

Although this will not eliminate all the strenuous hours of practice to become a skilled thereminist, the LCD display will be a good training tool to utilize.

In addition to installing an LCD panel for visual aid, an 8 bit-shift register will be included in the project. The 8 bits in the shift register will be grouped in two: volume and pitch LEDs. Three of the LEDs will represent the intensity of the volume coming from the uWave Theremin; it depicts if the user is producing a small, medium, or large volume by moving the user's hand relative to the volume antenna of the uWave Theremin. The remaining five LEDs (which consist of two reds, two yellow, and one green LED's) will represent how accurate the pitch is in-tuned from the user's hand with respect to the pitch antenna. Fig. 8 demonstrates the setup:

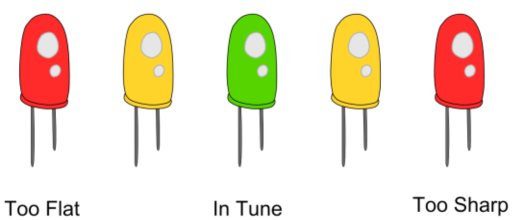


Fig. 8. LED pitch accuracy

When the SenseBox is receiving pitch data from the theremin, it will tell the user if the current pitch is either in tune, too flat or too sharp from the desired pitch. Markings on the readout drift left if the current note is too flat and right if the note too is sharp. If the current pitch is matched to the desired pitch frequency, the green LED in the middle will turn on. The reference pitch for our tuning system is based on the frequency of 440Hz (440Hz is the musical note A, above middle C).

4. Mode Operations

The SenseBox will feature two main mode operations: PITCH and CONTROL mode.

The PITCH is the basic function of the SenseBox, which extracts volume and pitch data from the uWave Theremin and output the corresponding MIDI data. The CONTROL mode is similar to PITCH mode, but instead of outputting musical note information, it will output control data. This is used if the user wishes to control the parameters of the destined MIDI device that is outputting to from the SenseBox. For this device, we will use both a typical Digital Audio Workstation (DAW) and the Pure Data environment for both MIDI and OSC testing.

Additionally, two extra modes are being taken into consideration for the implementation of the SenseBox: ARP1 and ARP2. Both functions allow the user to 'arpeggiate' certain musical chords with the uWave Theremin by pressing and holding keys on an external MIDI keyboard controller. An arpeggio is a musical technique where notes in chords are played sequentially rather than played simultaneously. This will give the SenseBox a "harp-like" sound when performing.

ARP1 Mode will read input from a MIDI keyboard and 'arpeggiate' the chord based on how many keys are pressed from the external MIDI keyboard. Table. 1 describes the available chords in ARP1 Mode:

ARP1 Mode Function	
Notes held on keyboard	**Types of Chord**
1 (Root note)	Major Chord
2	Min Chord
3	Dominant Chord
4	Minor 7th Chord

Table 1. Arp mode function table

To elaborate further, the first key will indicate the root note of the chord and will automatically choose its major chord to 'arpeggiate'. To choose other available chords, the user must press any key above the root note. For instance, if the user presses note A on the keyboard and press two notes above it, the user will 'arpeggiate' A Dominant Chord.

ARP2 Mode will read input from a MIDI keyboard and 'arpeggiate' based on any chord combination held on the keyboard. For example, if the user presses note A, C# and E, the SenseBox will 'arpeggiate' only those three notes in all of the available octave. Currently this particular mode is designed to 'arpeggiate' up to 12 notes. Both modes are still in the beta-test phase—modifications still need to be made before fully functional.

The SenseBox will include a 4 position rotary switch for the user to choose the available mode operation.

C. Expandome

The Expandome is a modular OSC-capable MIDI-controller that can be connected in a variety of orientations to reflect the user's preference. This device is an iterative design based upon the Arduinome[9], which was in turn based on the Monome[10]. In future work, the RGB capabilities and velocity sensitive buttons of the Chronome[11] will also be integrated into the project. The Expandome devices have an n x m backlit push-button grid. The 8x8 device is the primary Expandome that will connect directly to the computer, while the smaller devices may be added to expand the grid to allow the user to add beats and custom functions. The smaller Expandome devices are sized as 4x4 and 4x8 n x m devices. The Expandome's primary interaction is through the backlit pushbutton grid. This project, when working in concert with our EMI Browser, has some built-in setup functions, but can be used with any Monome/Arduinome app written in Pure Data[12] or other Max[13]-like environment. The device implements a barebones Arduino clone as the microprocessing unit. An easily integrated feature is the inclusion of an SD card for additional reading functionality and memory. This expansion will allow the hot-swapping of beats, as well as additional programs or setups beyond the default firmware. With this feature, files can be saved and manipulated to fit a variety of performance setups.

1. Back-lit Pushbutton Grid Button Pad, PCB and LEDs

The Expandome device's most visible feature is its backlit LED grid. The 4x4 button pads are made by SparkFun[14] as seen in Fig. 9. 'Each 4x4 button pad is made from translucent silicone rubber and is LED compatible. Each button has a conductive circle backing so that a switch can be created with exposed PCB traces. Button force is between 190 and 210 grams activation force.' These can be combined to create any grid size for our *n* x *m* devices. The button pads are also PCBs made by SparkFun. They are compatible for both standard LEDs and RBG LEDs. The RGB capability allows for easy coded additions to the firmware.

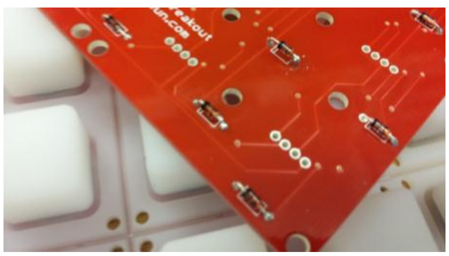


Fig 9. The most evident feature of the Expandome device is the backlit-pushbutton grid.

Each Expandome device features an array of LEDs which will be controlled by the microprocessor in conjunction with an LED Drivers and two shift registers, parallel-to-serial and vice versa respectively. The LEDs are the visual part of the project that allows the board to illuminate and indicate that a button has been pressed (or other programmed visualization) and the associated beat is played. In the reference designs it was discussed that there are numerous choices of LEDs that exist and are to be considered for power and desired illumination and color. The design will use multiple colors to make each device uniquely segmented when combined in a larger grid, as seen in Fig 10.

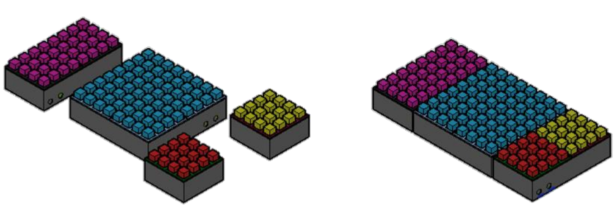


Fig. 10. Modularity and an integration example of the Expandome devices.

Initial limitations set at the time of research allowed for 3mm, 500mcd - 2000mcd, about 50° or better viewing angle, below 4.5V forward voltage and below 20mA current draw. For reference, the primary Expandome uses blue LEDs from Jameco[15], which have a 20mA draw and a 45° viewing angle.

2. Microprocessors and ICs

The 8x8 Expandome device will be designated as the Master device when connected to multiple Expandome devices. This expandable group will require additional input and output pins to reside on the Master device to allow communication to other devices. In addition to the need for more I/O connections, the Master device will require additional memory. For this reason, the 8x8 device will use the ATmega328 which has 14 digital input/output pins and has 32kB of flash memory. Both microprocessors will be incorporated into the PCB design circuit and require 5V DC power. The smaller devices need only a ATmega168 or higher.

Unique device recognition by other devices as a MIDI/OSC device is achieved by updating the FT232 chip's serial number to an iteration of "exp-###". This is also completely back-compatible with the Arduinome's "a40h-###" styled serial protocol recognition if flashed otherwise.

The 74HC164 and 74HC165 shift registers will be used to provide 8-bit serial-in/parallel-out and parallel-in/serial-out shift registers, respectively.

The use of an LED display driver is necessary to interface the microprocessor with the LEDs used on the Expandome module. The MAX7219CBG, manufactured by Maxim Integrated Products, is an integrated circuit which has an 8-digit LED display driver that has the capability to provide interface between the microprocessor and up to 64 individual LEDs. This integrated circuit also gives the capability to control brightness through analog and digital control. The MAX7219 requires +5V. For a single LED matrix, it is possible to use the +5V power supply from the microcontroller circuit, but more than three Expandome devices will require additional units to have secondary power over USB if an 8x8 device, or have batteries inserted if a 4x4 or 4x8 device.

3. Software and EMI Browser

An EMI browser is in development to allow additional functionality as well as utilization of an expansion bay for an SD card for general memory expansion. It allows for quick prototyping of programs and is a unique user interface that is another iterative development on the Arduinome's easy-grid concept. This browser parses through the file structure and automatically enumerates every file that begins with the letter 'e' and that takes the form of 'e####.lua'. Quick edits are now actually quick, no flashing onto any Atmel chips. The EMI Browser, and subprograms, are written using Löve Lua[16], a 2D game library for Lua. Screenshots from the Löve EMI browser are shown in Fig. 11. Concurrently developed, is an EMI Browser made in the Processing[17] environment that largely contains the same functionality.

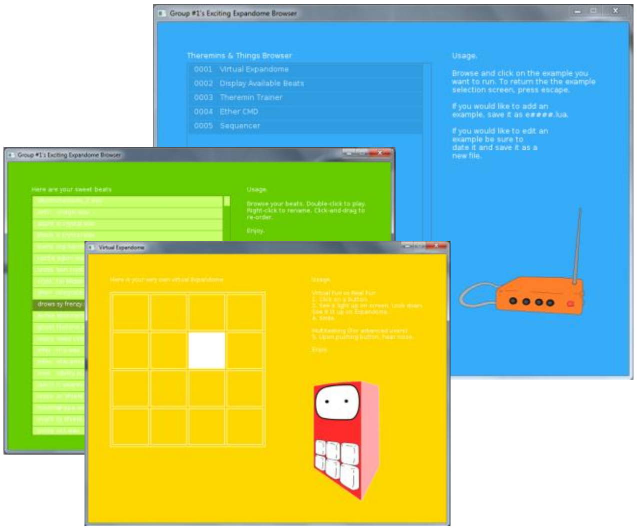


Fig. 11. Some pages from the EMI Browser

The EMI Browser by default has pages for a SenseBox console, virtual Expandome, and a theremin trainer on both the Löve and Processing implementations. The Löve browser has additional SD card hot-swap capabilities as well as a code debug mode called Ether CMD.

The SenseBox and Expandome devices are both Digital Audio Workstation capable. Any standard DAW will be able to interact with the devices. The EMI Browser comes with some example Pure Data setups that allow an extra flexible compatibility layer. Due to OSC's ability to be sent over UDP, the theme of ease-in-expansion is additionally reinforced. A wide variety of apps and programs are able to interface with this group of devices including, but not limited to, Androidome[18], Control[19], and TouchOSC[20]. Future work will delve further into Libpd[21] as well as uOSC[22] for embeddable devices.

4. Full Implementation

Each device is capable of working solely on its own. However, each was created with the others in mind. Below, in Fig. 12. is the depiction of the uWave theremin, the SenseBox, and four Expandome devices in an example orientation. The MIDI IO ports were places so that each device can connect flush with the next.

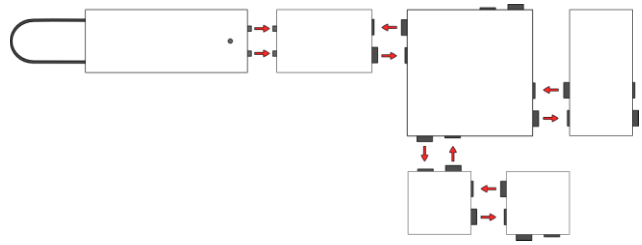


Fig 12. Overhead view of interconnections

By allowing the devices to be placed in any orientation desired, whether compact, long, or even spread out via cabling, a new interaction environment is possible. A solo artist or an entire group can take advantage of instruments with such faculties.

VII. Conclusion

The initial goal of making a highly adaptable set of musical instruments has been pursued with the uWave theremin, SenseBox, and the Expandome easy-grid MIDI controller. These devices were developed with a design mentality to provide a virtuosic experience with ease and to complement a musician's mental organization.

Three initial designs were examined and molded to work in concert: the theremin invented by Léon Theremin, the Pitch to MIDI Tracker inspired by Stephen Hobley, and the Monome and Arduinome developed by the Monome and Flipmu groups respectively. The final results are purposeful iterative designs that expand the capabilities of the originals in novel ways.

In summary, we submit our set of adaptable performance instruments to the community of design for further iterative development and hope that the philosophy of open collaboration engenders further work in new and innovative instruments and interfaces.

Each device that was investigated and implemented brought unique findings about the world of Electrical Engineering. In the case of the uWave Theremin, knowledge was increased in regard to understanding how sensitive devices can be when operated with high frequencies. Understanding how much factors play in the stability of the device's antennas helped gain knowledge of this. Also, being able to work with oscillators that were used to produce musical notes played a part in the team's knowledge of analog devices.

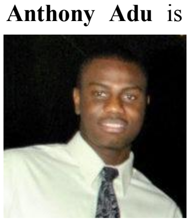
Another source of knowledge that was gained during this project was learning more about analog-to-digital conversation. In our project, a MIDI device was created to convert analog signals from the uWave Theremin into a digital format known as MIDI. Learning more about MIDI protocols helped us gain more familiarity with music theory and MIDI applications. In addition it helped incorporate new understanding of MIDI with a microcontroller using the Arduino language. It was also learned that with the help of the SenseBox, which is a pitch-to-MIDI converter, the uWave Theremin can be used for many other applications other than music.

With the help of the Expandome, the player has the ablilty to interact with the uWave Theremin and SenseBox in a way that allows for customizability adequate enough for unique performances.

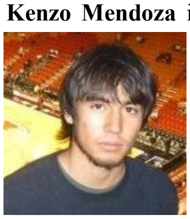
This project has enabled us to take an old but powerful technology which requires quite a few skills and dedication to operate, and made it a little easier and more intuitive for people with minimal musical understanding to enjoy. This was achieved by using the supporting devices, the SenseBox and the Expandomes to produce a feedback system the user can rely on during performance. With that being said, this senior design project sets a good example of what the purpose of engineering is, which takes a problem or a need and produces a solution.

With today's modern technology, this project proved that a vintage instrument, such as the theremin can be modified and accompanied by other electronic devices, such as the Expandome, to create an all-in-one contemporary instrument. Using the SenseBox, the EMI System integrates a feedback loop which allows new users of the uWave Theremin to easily learn how to control the pitch and volume of the uWave instrument. Throughout the course of this project, the group has learned a great deal about areas of Electrical Engineering that include oscillators, detectors, heterodyning, frequency modulation, analog-to-digital signal conversion and communication protocols by means of implementation in the E.M.I. System.

BIOGRAPHY



Anthony Adu is graduating from the University of Central Florida with a Bachelor of Science in Electrical Engineering. He is interested in continuing his education with a Masters degree in Electrical Engineering/Electromagnetics at UCF. He is also weighing the option of working full time first before continuing his education.



Kenzo Mendoza is graduating from the University of Central Florida with a Bachelor of Science in Electrical Engineering. He is interested in earning a Master degree in Electrical Engineering in the future, but as of now he is concentrating in traveling around the world. He is hoping to enter the JET Program in 2013, which is a teacher-assistant volunteer program at Japan.

Thomas Spalding is graduating from the University of Central Florida with a Bachelor of Science in Electrical Engineering. He hopes to pursue further research in grad school towards Electrical Engineering topics. His interests include open-source programming, musical instrument design, embedded systems, analog and digital filter design, and microwave engineering.

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