AEMI: The Actuated Embedded Musical Instrument

Nick Hwang
Louisiana State University and Agricultural and Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_dissertations

Part of the Music Commons

Recommended Citation
https://digitalcommons.lsu.edu/gradschool_dissertations/4407

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Doctoral Dissertations by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
AEMI: The Actuated Embedded Musical Instrument

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The School of Music

By
Nick Hwang
B.A., University of Florida, 2005
M.M., Louisiana State University, 2008
December 2016
This dissertation is dedicated to the memory of my grandfather Jiu-Lin Hsieh.
ACKNOWLEDGEMENTS

I would like to thank Dr. Stephen David Beck for his consistent insight, direction, encouragement, and patience throughout this dissertation, and also for the time and effort he put into my education and the opportunities the numerous to teach, present, and perform he provided. Dr. Jesse Allison has been extremely helpful throughout this process with his invaluable of knowledge of NIME and his insights on electronics and programming. Dr. Dinos Constantinides has always encouraged me to be the best composer I can be. Dr. Griffin Campbell’s approach to musicality in all things has forced me to examine the creation of an instrument from many as perspectives as possible. Dr. Joe Skillen has given me invaluable insight on the intricacies on academia.

I want to also thank Jonathan Corey Knoll, Andy Larson, Jeff Albert, and William Conlin. Their unique musicality has always affected the way I think, write, and make music. Their constant encouragement despite living in different parts of the United States has been a source of finishing motivation. Danny Holmes served as a great sounding board in the initial instrument fabrication stages. Tom Lapann has been a constant collaborator, with his artful insight in creating all of our past projects, including AEMI.

I would like to thank my parents and siblings for their love and support.

Finally, I would like to thank my wife, Olivia Watkins Hwang, for her steadfast encouragement through the entire process. Her organization and grammarian advice were essential to this dissertation.
TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................ iii

ABSTRACT ............................................................................................................................. v

PART I: Composition of concerto for AEMI and orchestra ................................................. 1
  A. PERFORMANCE NOTES ................................................................................................. 1
  Instrumentation .................................................................................................................. 1
  Notes on Orchestra Layout ............................................................................................... 2
  AEMI Notation ................................................................................................................... 3
  Orchestral Notation .......................................................................................................... 4
  About the Composition .................................................................................................... 32

PART II: AEMI – the Actuated Embedded Musical Instrument ...................................... 37
  CHAPTER 1. OTHER INSTRUMENTS AND THEIR INFLUENCES ON AEMI ........ 37
    Introduction ..................................................................................................................... 37
    Resonant Bodies: Overtone Fiddle, Chameleon Guitar ................................................... 37
    Capacitance and Interfaces ............................................................................................ 39
    Analogs and Models: EWI and EVI ............................................................................... 46
    Conclusion ...................................................................................................................... 47

  CHAPTER 2. DESIGN AND CREATION OF THE INSTRUMENT ......................... 49
    Introduction ..................................................................................................................... 49
    Actuated and Embedded ............................................................................................... 50
    Body Form ..................................................................................................................... 50
    Upper Control ............................................................................................................... 53
    Circuitry Chamber ......................................................................................................... 54
    Raspberry Pi ................................................................................................................... 56
    Arduino ........................................................................................................................... 56
    Fingerboard .................................................................................................................... 57
    Conclusion ...................................................................................................................... 61

  CHAPTER 3. SONIC FEATURES OF AEMI ............................................................. 62
    Introduction ..................................................................................................................... 62
    Musical Decisions .......................................................................................................... 62
    Sound Design and Signal Processing ............................................................................ 65
    C:M Ratio ...................................................................................................................... 66
    Loudness and Filtering ................................................................................................. 68
    Articulations ................................................................................................................... 70
    Portamento and Multipressing ...................................................................................... 70
    Conclusion ...................................................................................................................... 71

FUTURE DEVELOPMENTS ............................................................................................. 71

CONCLUSIONS ................................................................................................................ 72

LINKS .................................................................................................................................. 73

BIBLIOGRAPHY ................................................................................................................. 74

VITA .................................................................................................................................... 77
ABSTRACT

This dissertation is a combination of acoustic and electronic musical creation, acoustic instruments and digital instruments, and a combination of all of these areas. Part I is an original composition for orchestra with the new instrument set as soloist. Part II is an examination of the development and influences of creating a new electronic musical instrument.

Part I is a composition for AEMI (the Actuated Embedded Musical Instrument) and orchestra, entitled “Meditation on Solids, Liquids, and Gas.” This composition is a dialogue between the orchestra and instrument, set as an exchange of ideas; sometimes ideas lead to conflict, others lead to resolution. This also serves as a way to feature some of the musical capabilities of this new instrument.

Part II is an examination of AEMI and its influences. Chapter 1 includes a discussion of existing instruments whose similar features influenced the development of AEMI: the Theremin, Manta, JD-1, Buchla controller, EVI and EWI, and Chameleon Guitar. While AEMI instrument does not have the same performance mechanics as the Theremin, Evi, or Ewi, understanding the physicality issues of an instrument, like the Theremin, provided insights into creating a versatile instrument that can be easily learned yet have virtuosic character. Ultimately, embedding expressivity, such as subtlety and nuance into the instrument, would be one of the most difficult aspects of creating an instrument and would demand the largest amount of work.

Chapter 2 describes the aesthetics, technical aspects, difficulties, and musical abilities of the instrument. Attempts to combine acoustic and electronic music are not novel, the incorporation of acoustically driven resonance by electronic embedded
instruments is new. The electroacoustic nature of this instrument is different than most electronic instruments. The controller and user interface is electronically driven, and its speakers/acoustic drivers are embedded within the instrument. This discussion may provide insights to musicians, composers, and instrument makers involved in the finding of new avenues of musical expression.
PART I: COMPOSITION OF CONCERTO FOR AEMI AND ORCHESTRA

A. PERFORMANCE NOTES

Instrumentation

2 Flutes [Fl.]
2 Oboes [Ob.]
2 Clarinets in Bb [Cl.]
2 Bassoons [Bsn.]
4 Horns in F [Hn.]
2 Trumpets in C [Tpt.]
2 Tenor Trombones [Tbn.]
Tuba [Tba.]
2 Percussion [Perc.]
   1. Timpani (4 standard size)
   2. Bass Drum, Vibraphone

AEMI [AEMI]

Strings [Vln. I, II, Vla., Vc., Db.,]

Note: Score in written in C. Contrabasses sound one octave below.
Notes on Orchestra Layout

The ideal layout for the orchestra should have the numbering scheme be center-aligned, as an intentional orchestration written in the composition involves a cascade of material between instrument families as well as inter-family gestures.

The AEMI performer should be in front of the orchestra.

Figure 1 – Ideal Layout of Orchestra
AEMI Notation

The black-filled squares indicate which triggers to press. Triggers 1, 2, and 3 correspond to the performer’s (left hand) index, middle, and ring finger respectively. The performer determines how far to press down on a trigger based on the traditionally notated dynamic marking.

Figure 2 - Filter Graphics

Portamento is notated in two ways:

1. Stemless notes (usually when performing a sequence of portamentos), a dashed slur may accompany sequences to provide visual aid.

2. Straight Lines to resultant pitch (usually when performing a single portamento).
Orchestral Notation

Bracket notation represents performer-based aleatory:

1. Pitches of which the performer may perform any from the collection, in any order. If stemless, any durations can be used. May recycle material.
2. Perform tremolo (only in the strings) for any portion of the note/note grouping it appears above.
3. Performer choice of rests with possible notes. Any combination in any order for the duration of the entire selection.

<table>
<thead>
<tr>
<th>1º -&gt; 8º: ALL</th>
<th>Orchestration gesture where the notated line should be performed from first chair to eighth, resulting in all chairs continuing.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1º -&gt; 8º: One</td>
<td>Orchestration gesture where the notated line should be performed from first chair to eighth, resulting in only the 8th chair continuing.</td>
</tr>
</tbody>
</table>

- A wavy line suggests the amount of vibrato should be performed (by rocking the instrument gently).

| Continue performing the previous measure’s material. |

Table 1 - Further Notations
Score in C

Mediations on Solids, Liquids, and Gas

Nick Hwang

©2016 Nick Hwang
Mediations on Solids, Liquids, and Gas

\[ q = 60 \], Subdued, yet flowing

Frozen, icy, static \( q = 40 \)

\[ q = 30, \] Solo

Frozen, icy, static \( q = 40 \)

\[ q = 30, \] Solo

Frozen, icy, static \( q = 40 \)

\[ q = 30, \] Solo

Frozen, icy, static \( q = 40 \)

\[ q = 30, \] Solo

Frozen, icy, static \( q = 40 \)

\[ q = 30, \] Solo
Mediations on Solids, Liquids, and Gas
Mediations on Solids, Liquids, and Gas
Mediations on Solids, Liquids, and Gas
Mediations on Solids, Liquids, and Gas
Mediations on Solids, Liquids, and Gas
Mediations on Solids, Liquids, and Gas

Fl.

Ob.

Bb Cl.

Bsn.

Vln. I

Vln. II

C Tpt.

Tuba

Vib.

Vc.

Vla.

Cl.

Ob.

No mute

Slowing, evaporating: \( \frac{q}{50} \).

\[ \text{1°} \rightarrow 8°: \text{All} \]

\[ \text{1°} \rightarrow 12°: \text{All} \]
Mediations on Solids, Liquids, and Gas
Unmetered (\(\sim q = 60\))

Vibraphone and AEMI parts should be loosely coordinated, playing at a similar pace. Wait for the other instrument and continue loosely at double bars.
* Stop and wait for other instrument

** Begin together, but coordinately loosely with similar pacing
Fl.
Ob.
Bb Cl.
Bar.
Hn. 1, 3
Hn. 2, 4
C Tpt.
Tbn.
Tuba
Timp.
Perc.
Vib.
AEMI
Vln. I
Vln. II
Vla.
Vc.
Cb.

Rich, thick ~ \( \frac{q}{3} \) = 60

Molto vibrato

Con sord.
About the Composition

One component of the dissertation is a musical composition, a concerto, involving a new musical instrument of my design (AEMI) accompanied by a full orchestra. The composition is approximately 18 minutes in length. The instrumentation of the orchestra includes two flutes, two oboes, two clarinets, two bassoons, four horns, two trumpets, two trombones, one tuba, two percussionists (including, timpani, bass drum, and vibraphone), AEMI, and a standard strings section. In orchestral shorthand, this is 2,2,2,2,4,2,2,1 (timpani, vibraphone) percussion, strings. Aside from AEMI, the orchestra does not utilize any form of electronic sounds.

A concerto, though varied in history, is a multi-movement musical composition in which the individual movements feature different moods, styles, sentiment, or tempo. The combination of an electronic instrument with an orchestra is still atypical in the 21\textsuperscript{st} century, and the concerto format proves to be a good setting to explore the contrasts in the rich color and timbre palette of the orchestra with that of the instrument. Featuring a solo instrument in different situations (of playing against and together with an orchestra) has been a common practice from the Baroque through the modern era.

The composition has one movement. Within the single movement, three varying

\begin{footnotesize}
\begin{enumerate}
\end{enumerate}
\end{footnotesize}
moods and themes are explored; the themes interrupt one another. These themes are inspired by the three states of water – liquid, solid, and gas. Also explored are geometric and organic concepts in nature and in building AEMI. These concepts are carried through to the composition. AEMI’s shape is loosely based on a water droplet and it is fitting that the first composition written for it reflects that image. The score of the composition is not the sole product of the dissertation, but an artifact and vehicle by which the orchestra, AEMI, and musical composition are realized. Additional artifacts from this dissertation are the physical instrument, performer gesture instruction, and notational system for the instrument.

The first theme used in the composition is inspired by the liquid state of water. While this theme is expressed with a motivic switchback melodic pattern, the orchestration furthers the concept of a liquid state wherein instrument families begin to play and carry the theme from one instrument family to the next. The goal of this theme is to demonstrate the flow of water from the back of the orchestra to the front. A secondary motive of the liquid state is the use of sweeping portamento – a feature ability of AEMI. The composition relies on portamento in this theme with the strings and timpani.

The harmonies in the liquid state are based off the octatonic scale. The octatonic scale is built on alternating semi-tone and whole-tone intervals. This scale lends a fluid flexibility to move between augmented and diminished harmonies in the liquid theme. The octatonic scale used in this theme is the (0-1) octatonic built from C natural.

The second theme of the composition is the solid state of water. This concept is expressed by using large orchestral moments of stasis, which outline melodic material in
AEMI’s part. An orchestration constraint that was utilized for the composition was the employment of the digits in the number pi, up to the tenth digit beyond the decimal. The use of Pi is further incorporation of geometric and natural aesthetics. For each digit, the composition limits the number of orchestra families and their individual notes. In addition to AEMI’s solo, AEMI is paired with the vibraphone. The vibraphone is tied not to a digit within pi and is more freely written. At one point in this theme, the vibraphone and AEMI parts pull apart from the orchestra and play in an unmetered duet. The vibraphone is used in this theme for its cold, metallic timbre to create a link between AEMI and the other instruments in the orchestra. The largely unchanging orchestral moments, the pre-determined digits of pi, and sometimes stark orchestration serve to express the solid, icy nature of water.

The harmonies in the solid state theme are built off the melodic material of AEMI. In this section, AEMI begins using a diatonic harmony and slowly alters its pitches to be more chromatic in nature. It also continues to incorporate portamento as this theme develops.

The third theme of the composition is the gaseous state of water. This is expressed through pointillistic aleatory within the strings and also through a largely upward-seeking tremolo within the winds. The strings largely use pizzicato to create a cloud-like texture against a fast, wavering melodic line of AEMI. This creates individual particles of sound spatialized across the orchestra family. Additional instructions, at points, increase and decrease the number of performers in family affecting the density of sound.
Points of aleatory/indeterminacy within the composition are notated with given pitches from which performers may play as many or as few as they choose in any order for any duration without rest. The composition also employs bracket notations to demonstrate the possible pitches for performers. Moments in the score exist where marked rests are included within the brackets. These moments are indented to create a thinner texture. These rest and note durations are left to the performer.

The third theme has harmonies based on the (0-2) octatonic scale and AEMI is largely chromatic while employing wide portamento sweeps.

Along with the introduction of a new musical instrument to the orchestra, an extended system of musical notation for AEMI was also created. Two main non-traditional features of AEMI are the controls for loudness through the use of three triggers on the cross-bar section and the ability to portamento by pressing two touchpads simultaneously. The notation for the use of the triggers is a graphic with three boxes representing the individual triggers that should be pressed. The degree to which the musician will press a trigger indicated by the graphic is determined by the musician playing AEMI; this judgement is made based upon the traditionally notated dynamic marking. Portamento notation is illustrated by a defined series of notes. The first note is a traditional note with stem; the second note does not have a stem. The musician can choose to portamento from the first to the second note or continue to portamento to additional notes.

An additional adaptation of notation used in my composition is the use of vibrato

\[ 5 \] (0-2) Octatonic Scale: (C, D, D#, F, F#, G#, A, B)
notation expressed through a wavy line. The larger the wave, the broader a vibrato expected. The performer rocks AEMI to perform vibrato. A faster rocking motion results in a broader vibrato.

With each iteration, the themes develop in length and complexity. At one point, a duet between AEMI and the vibraphone create a stark section of the composition, which is followed by a dense, flowing return to the liquid state. The composition concludes as the texture evaporates with a final return of the gas state.

A traditional first movement of a concerto begins by following the Classical Sonata Form, using the alternating ritornello segments between the orchestra and the soloist. The alternating nature of this form between the orchestra and soloist creates the sense of contrast and struggle. The alternating themes within the composition borrow from the traditional ritornello form. The choice to combine all three themes into one larger movement is based on the interchangeability of water in nature. The contrast between AEMI and the orchestra decreases at times, with imitative motives between the them. The incorporation of the orchestra demonstrates both the uniqueness in tone of the new instrument as well as its ability to play alongside acoustic instruments.

---

PART II: AEMI – THE ACTUATED EMBEDDED MUSICAL INSTRUMENT

CHAPTER 1. OTHER INSTRUMENTS AND THEIR INFLUENCES ON AEMI

Introduction

In conceptualizing a new instrument, research was conducted on various musical instruments developed over the course of the 20th and 21st centuries that utilized one or more features were researched, including: the actuation of resonant bodies, embedded computers, and intuitive interfaces (particularly capacitive touch). It is arguable that these features are essential to a musical instrument that is portable, that provides for a more physically dynamic performance, and allows the sound to be customized through computer programming.

The result of this exploration is a new musical instrument, which is called the Actuated Embedded Musical Instrument or AEMI. In conceptualizing AEMI, the use of tactile transducers was one way of imbuing the instrument with natural characteristics, obfuscating the electronics, and giving the performer physical feedback-like playing of a traditional acoustic instrument.

Below is an examination of instruments that influenced the development of AEMI.

Resonant Bodies: Overtone Fiddle, Chameleon Guitar

Dan Overholt’s Overtone Fiddle7 and Amit Zoran, Stephen Welch, and William Hunt’s Chameleon Guitar8 have taken existing instruments (violin and guitar respectively) and augmented them in physical and electronic ways. The Overtone Fiddle

uses vibration-sensing pickups on the bridge of the violin and sensors on the bow which allow an attached CUI32 microcomputer to process sounds and interpret performance gestures for newly processed sounds. These new sounds created on the CUI32 are propagated by an attached tactile transducer within the violin and also on an attached resonance chamber within its own separate transducer. An iPod Touch also attached to a violin allows for in-performance wireless control of the CUI32’s digital signal processing. In performance settings, this instrument produces impressive sonic results, and does so with an absence of loudspeakers. Marshall and Wanderlay found that performers have an increased level of engagement when they can ‘feel’ the vibrotactile feedback like those produced by acoustic instruments.\(^9\) Marshall and Wanderlay describe how a performer would encounter vibrotactile feedback: “In an acoustic instrument the sound production mechanism also produces the vibrations that the performer feels.”

Twenty years ago, Miller Puckette called for creative ways electronics could enhance performances (to performers) with feedback.\(^{10}\) This is now known as the study of haptics. This type of haptic\(^{11}\) feedback is one level of engagement mainly felt by the performer. The embodiment of sound and absence of loudspeakers makes it an engaging example of an acoustic-electric instrument.

---


\(^{10}\) Miller Puckette and Zack Settel, "Nonobvious Roles for Electronics in Performance Enhancement" (paper presented at the Proceedings of the International Computer Music Conference, 1993). “But in instruments which create sound physically, there are usually physical cues returning from the mechanism to the player. A good example is the piano, whose accelerating hammers can be felt by the player's finger as force.”

\(^{11}\) Edgar Berdahl, Hans-Christoph Steiner, and Collin Oldham, "Practical Hardware and Algorithms for Creating Haptic Musical Instruments" (paper presented at the NIME, 2008).
The Chameleon Guitar\textsuperscript{12} begins with an existing instrument and then augments its ability to remove and replace resonance boards. In addition to the ability to interchange acoustic resonators, Zoran, Welch, and Hunt’s paper explores the many different ways the shape and type of wood, finishes used, and means of attachment (bracing) affect the sound and modes of vibration. They discuss different methods of examination.\textsuperscript{13} Understanding the different types of vibrational modes in relation to shape and sizes of woods is an important element to AEMI, but one that has not been carried out yet. Future research with the current model would involve acoustic response. Other iterations of AEMI would involve different types of woods, thicknesses, and finishes.

Capacitance and Interfaces

In 1960 Don Buchla\textsuperscript{14} began building electronic instruments when composer Morton Subotnik commissioned him to create an instrument for live electronics music and composing. Buchla began making modular synthesizers in 1963 and pioneered the touch-sensing keyboard to control his modular synthesizers. The model 112 keyboard (1963) had 12 equally spaced touch plates that could be set to individual notes (independent of octave, orientation, or tonality) to control his modular synthesizers. They output a pair of control voltages with an extra output based on touch pressure. The model 114 had 10 keys and a single control-voltage output. Other examples of non-organ style touch controllers include Serge Tcherepnin’s the Touch Activated Keyboard Sequencer (TKB), the Sputnik Multi-Touch Keyboard Controller, and Make Noise’s Pressure

\begin{footnotes}
\footnote{Zoran and Paradiso.}
\footnote{Laser vibrometry, computer modeling, Finite Element Method are used to track and predict vibrational modes on their guitar soundboards.}
\footnote{Buchla 110 touch keyboard: \url{http://www.synthmuseum.com/buchla/buc11201.html}}
\end{footnotes}
Buchla’s later 200-series (‘The Electric Music Box’) modular synthesizers used keyboard style layout. The Buchla model 217 featured a two and half-octave range, in keyboard-style layout, with pressure sensitivity.

Image 1 - Buchla Model 217 Touch Keyboard

The Buchla model 219 Compound Touch-Controlled Voltage Source featured 48 touch- and pressure-sensitive surfaces, from C to B. The 219 was polyphonic up to four voices. Other touch interfaces included a separate eight tunable-pad section.

In 1990, Buchla produced the Thunder MIDI (musical instrument digital interface) controller which feature 25 velocity and pressure-sensitive pads, with the possibility of dividing the pads into two or three sections, allowing up to 42 different notes with note-on/off and aftertouch MIDI data. The Thunder’s layout is non-idiomatic and features parallelograms in a diverting from the center of the control area.

---

Jeff Snyder’s *Manta*\(^\text{17}\) and *JD-1*\(^\text{18}\) are instruments/controllers that have influenced the development of AEMI. The Manta features a six-by-eight lattice of hexagonal touch pads. Its pads employ velocity detection through the use of machine-learning techniques and examining the frames prior to ‘note on’ detection. The JD-1 has 32 keys laid out in a traditional diatonic keyboard pattern. The keys are capacitive-touch sensors and they do not move. Both the Manta and JD-1 are able to detect the surface area covered by the performer and output proportionally. The original JD-1 keyboard layout was a flat, printed circuit board, similar to that of the Buchla controllers, but Snyder felt that the raised and separated keys gave performers better feedback. AEMI’s fingerboard layout is in an arched diatonic layout, and remains flat on a printed circuit board. AEMI’s fingerboard detects presses and releases. The order of keys simultaneously pressed is determined in the PureData code and is used for portamento effect between pitches.

One of the earliest capacitive instruments was the Theremin. Originally called the Étherophon\(^\text{19}\) then Thermenvoks, it is a monophonic electronic instrument developed by Russian inventor, musician, physicist, and spy Leon Theremin (Lev Sergeyevich Termen). Trained in physics and music, Theremin, who ran one of the Red Army’s radio stations, combined his interest in radio interference and electromagnetic field capacitance to create the music instrument. One of Theremin’s original desires was to create a device

---


that detects the presence of humans through capacitance.

First demonstrated in the Kremlin in 1922, Theremin impressed Vladimir Lenin by inviting him to play Glinka’s *The Lark*. In 1927, the Soviet authorities granted Theremin permission to tour France, Germany, and England. After travelling to New York later that year, Theremin performed a recital at the Metropolitan Opera on January 31, 1928 entitled *Music from the Ether*.

The uniqueness of the Theremin results from both its electronic, gesture-based control and its performance capabilities. Despite having a few control knobs and dials, the Theremin has no moving parts during a performance. The movement of a performer’s hands around two magnetic fields generated from the instrument controlled the instrument’s frequency and amplitude.

The Theremin has a rectangular wooden enclosure called the cabinet, which houses all the circuitry. Two antennae extending from the cabinet determine the pitch (frequency) and the loudness (amplitude) of the Theremin. The pitch-control antenna extends vertically from the cabinet, and the volume antenna extends horizontally from one edge of the cabinet, back into the same side of the cabinet.

As the performer’s hand approaches the pitch-control antenna from the side, the pitch frequency increases. The performer’s performative gesture is largely horizontal—toward and away from the antenna. The loudness-control antenna, which bends back into the cabinet, lies on the horizontal plane. As the performer’s hand approaches the antenna from above, the loudness decreases. The loudness gesture is largely on a vertical axis. In

---

videos of performances with the Theremin, subtle movements of the performer have an apparent effect on resultant sound.

A radio frequency oscillating circuit within the cabinet creates an electromagnetic field around the pitch-control antenna. Because of the human body’s natural capacitance, moving the hands closer to or away from the antenna disrupts this oscillator’s electromagnetic field, changing its frequency.\textsuperscript{22} This oscillator, which transmits through the pitch-control antenna, is a variable oscillator. A knob on the side of the cabinet controls the frequency of a separate oscillator—the fixed oscillator. A radio signal process called \textit{heterodyning} mixes the frequencies of the variable and fixed oscillators. The difference of the frequencies results in the final output frequency by the Theremin.\textsuperscript{23}

A similar variable oscillator is attached to the horizontal loudness-control antenna. As capacitance changes with the performer’s proximity, the resulting change in voltage through the oscillator affects the output amplitude of the instrument.

Two aspects of the Theremin stood out the most when developing AEMI: its simplicity in controls and its obvious physicality. When considering controls for AEMI, it was desirable to keep its controls visually simple and to involve physicality as a performance gesture. These goals are satisfied by obfuscating electronics, creating the main body of the instrument from wood, and creating vibrato by lightly shaking the instrument.

Thaddeus Cahill created the Telharmonium in 1897 – one of the first electronic

\textsuperscript{22} The antenna and the human act as two capacitive ‘plates,’ with the air between them as the dielectric. The distance between the antenna and the human cause a change in voltage in the variable oscillator, thus affecting the oscillator frequency.

\textsuperscript{23} The process of \textit{heterodyning} is similar to the process of ring modulation where two side-bands, different tones, or \textit{heterodynes} result.
instruments. Also known as the ‘Dynamophone,’ audio frequencies were created by the spinning of dynamos\(^{24}\) (an electrical generator that produces direct current with the use of a commutator). The instrument had acoustic horns that amplified the sound and had the capability to transmit audio through telephone wire. This method, used around 1916, was utilized well before the existence modern methods of amplification and mass transmission. Cahill planned to have the music from the Telharmonium piped to private homes and commercial stores. The keyboard interface was pressure sensitive and had more than one manual. Two musicians (four hands) were typically needed to perform on the instrument. The instrument had seven octaves, with 36 notes per octave.

First demonstrated in Baltimore, Maryland, Cahill created a second version in Holyoke, Massachusetts. The instrument itself was of immense size — 200 tons and 60-feet long. In 1906, this version was moved to New York City by way of railroad. One version of the instrument was said to be destroyed; part of it was thrown into the Hudson River.

Freidrich Trautwein invented the Trautonium, a monophonic electronic instrument first shown in Berlin, Germany in 1930. With the help of Oskar Sala, different versions of the Trautonium were created radio (1935), concert (1938), and Mixtur-Trautonium.

The original Trautonium had a fingerboard that consisted of a resistance wire stretched over a metal rail. The performer would press down on the wire making contact with metal rail, completing the circuit. Markings in a chromatic scale pattern along the

\(^{24}\) “The dynamos themselves each needed to generate the circa 10 kW required to drive the transducers of thousands of listeners who subscribed over telephone lines.” Joe Paradiso, "New Ways to Play: Electronic Music Interfaces," *IEEE Spectrum* 34, no. 12 (1997).
metal rail showed the performer positions to make contact. The positions on the wire vary
the resistance connected to the frequency of an oscillator. This variable resistor method is
used within the triggers of AEMI. The performer is able to achieve glissando/portamento
by gliding their finger across the metal rail while pressing down on the resistance wire.

The range of the Trautonium was three octaves which could be transposed by
flipping a switch. Additional controls amplified harmonics along the fundamental note
and non-harmonic partials could be added through filtering. The single foot pedal
controlled the loudness.

Maurice Martenot created the Ondes Martenot in 1928. This instrument featured a
metal ring attached to a ribbon loop. The performer placed the ring on the forefinger of
their right hand, and as they moved their right hand horizontally about the keyboard, the
ribbon adjusted a variable capacitor connected to a heterodyned audio oscillator (similar
method to that of the Theremin). The original version had a keyboard which simply was a
visual aid for the performer, as the ring’s position in relation to the keyboard determined
the resultant pitch. Early models had non-mechanical keyboards. Later versions of the
Ondes Martenot incorporated the keyboard to allow more modes of performance. While
the use of the ribbon allowed for glissando from one pitch to another, the keyboard could
be shifted laterally by a few centimeters, allowing for vibrato of the depressed pitch.

Simply moving the ribbon or pressing a key on the keyboard did not produce a
tone. A small drawer housed controls used by the performers to determine note on/off,
timbre, articulation, and dynamics. The performer could also select a number of fixed
filters such as “Hollow,” “Tutti,” “Wave,” “Gambe,” “Nasillard,” and “Octavaient.”

25 Vail, 35.
The relationship of pitch determination with the right hand and note on/off, timbre, and dynamics on the Ondes Martenot is reflected on AEMI.

The Ondes Martenot had three types of sound ‘diffusers’ from which AEMI inherited their unique qualities. The principal diffuser, ‘Haut-parleur,’ was a traditional looking loudspeaker with cabinet. The resonator ‘Palme’ diffuser consisted of a resonance chamber with a sound hole with either tuned metal strings or springs. The resonance chamber is driven by a transducer, and the added sympathetic vibrations of the strings/springs add an timbral quality to the overall sound. The third ‘Metallique’ diffuser consists of a metallic gong actuated by a transducer housed in a cabinet. The performer is able to select which diffusers sound from the left-side drawer.

The use of capacitive touch became an important aspect of control for pitch selection in AEMI. Capacitive touch on AEMI allowed for a non-mechanical interface. Unlike many of the Buchla and Snyder controllers, which could also register touch velocity and area of surface touched, AEMI’s capacitive touch fingerboard only detects touch ‘on’ and ‘off.’ The piano-style layout of the touchpads allowed for an inherited understanding for the performer. AEMI also uses the separate control system, like the Ondes Martenot, for pitch selection, note duration, and timbre/filtering.

Analogs and Models: EWI and EVI

Nyle Steiner’s Electronic Wind Instrument (EWI) and Electronic Valve Instrument (EVI)26 are electronic versions of existing model instruments with performance gestures: trumpet and saxophone fingerings. Invented in the 1970s, the instrument has taken on

many features, including capacitive touch, bite pressure for portamento, accelerometers for vibrato, and air pressure sensor for loudness. Newer versions access MIDI sound libraries to imitate different instruments. In 1987, Akai started manufacturing version of the EWI and its current model “comes loaded with more than 3GB of built-in high-quality sounds.” The success of these two instruments has been helped by the interface models they used, as performers could use the trumpet or the Boehm saxophone fingering systems. The success of these two instruments is also linked to having non-obstructive mappings for their non-performative controls which gave them the sense of ‘inevitability’ (embodied metaphors or ‘hooks’) that Tod Machover wrote about in his paper “Instruments, Interactivity, and Inevitability.”

Conclusion

Developing AEMI allowed for an attempt at providing a performer with an electro-acoustic instrument with intuitive controls while still allowing for a sense of expression and feedback. By embedding the electronics within the chamber of the instrument, the performer and the body of the instrument are the focus of the performance.

At the same time, the use of loud speakers is avoided by relying on the resonance of AEMI’s body to generate the sound heard by the listener. In this way, AEMI maintains a strong visual tie to classical instruments typically played in an orchestral setting.

There is a strong sense of physical feedback for the performer through the vibration

of the instrument and visual feedback for the listener through familiar performative
gesture. The performer should be able to ‘play’ the instrument with expression and
gesture, spanning the often troubling gap of automation and “one-gesture-to-one-acoustic
event.”

---

30 David Wessel and Matthew Wright, "Problems and Prospects for Intimate Musical
CHAPTER 2. DESIGN AND CREATION OF THE INSTRUMENT

Introduction

In the following sections, the physical construction, electronic components, and hardware aspects to AEMI are discussed. Research and development concerns in creating an instrument extend from basic form factor, nuanced moving parts, back-end control programming, and mapping controls for performance. Sound synthesis and design concerns are discussed in Chapter 3.

Construction and programming of the instrument involves realizing the hard structure of the instrument (shaping, milling, fastening) and embedding the instrument with the electronic controls. Part of the development of the instrument involved comparing the capabilities to program and sustain a stand-alone, powered, and self-amplified electronic instrument with embedded speakers\textsuperscript{31} and drivers\textsuperscript{32} with digital signal processing off a microcomputer. The BeagleBoard was originally considered, followed up Raspberry Pi, then finally RaspberryPi 2 Model B. Arduino\textsuperscript{33} prototyping boards are used as the interface between controller-input devices and the embedded microcomputer. Tactile transducers attached to the inside of the resonant cavity are used, giving the instrument its own acoustic properties outside of the synthesized audio from the embedded computer.

\textsuperscript{31} Example of considered speakers: Hi-wave- Balanced Mode Radiators (http://www.hi-wave.com/products/audio-bmars.php)
Actuated and Embedded

AEMI uses a tactile transducer to transfer energy from an audio amplifier into mechanical energy (movement). The movement of the flat plate of the transducer is attached to the front- and back-outer layers. The movement of the wood (vibrations) then propagates to the air. The transducer drives the synthesized audio from PureData coding within the RaspberryPi onto the front and back layers of the resonant chamber. The actuation of the material gives the AEMI an acoustic property, in contrast to an electronic instrument reliant on loudspeakers.

AEMI uses embedded electronic components, including RaspberryPi 2 for audio processing, Arduino Nano for sensor collection, a three-axis accelerometer, two capacitive-touch chips (MPR121), three game controller triggers, and a T-model amplifier. Raspberry Pi and BeagleBone microcomputer boards are two notable brands that have gained traction in the computer-music and DIY communities. An external knob along the side of AEMI adjusts the amplifier output (affecting the overall loudness) and a removable back panel gives access to embedded circuitry.

Body Form

The basic body shape for AEMI came from an organic aesthetic goal to mimic the shape of a water droplet using a combination of circles and ovals. Circles were important

---

34 The Merriam-Webster dictionary defines ‘actuated’ “1. to put into mechanical action or motion; 2. to move to action” and ‘transducer’ “a device that is actuated by power from one system and supplies power usually in another form to a second system <a loudspeaker is a transducer that transforms electrical signals into sound energy>.”
35 Dayton DAEX58FP Flat Pack 58mm Exciter 25W 8 Ohm
36 The work of Edgar Berdahl (SatelliteCCRMA) and Andrew McPherson (Bela)
in the design, which was initially an aesthetic decision and afforded the three main
structures: a circular resonance chamber, a circular cut away (which is called the ‘upper
control’ section), and an ovoid fingerboard section. The resonance chamber houses the
two transducers. The ‘upper control’ section is composed of the sensors, embedded
microcomputer, amplifier, and trigger crossbar. The fingerboard section is a layer
mounted on wooden offsets above the front of the resonance chamber.

The first iteration fabrication method involved creating a fiberglass shell through a
lay-up process: creating a positive mold made from MDF (medium-density fiberboard)
and a negative mold around that MDF. The fiberglass lay-up method—using layers of
fiberglass and several coatings of resin—created a sturdy shell, but did not result in a
smooth interior. The backing of some acoustic guitars use a similar method with
fiberglass. This original design that involved the fiberglass resonant shell attaching to the
“upper-control” portion made of wood. Problems arose when attempting to affix the
wood portion to fiberglass. The fiberglass lower portion was markedly lighter than the
upper portion and would have created balancing issues.

The second iteration method involved cutting away the body of the instrument from
a large form of MDF with the use of a CNC (computer numerical control) mill. The CNC
process would have allowed for the resonance chambers to be hollowed out. This method
of fabrication would have allowed for a unibody-type structure with a limited number of
visible seams and a precisely cut interior. While gluing of several layers of MDF was
successful, the resources for the CNC became unavailable at the time of fabrication.
MDF is usually denser than plywood and the overall weight of the instrument would be
substantially greater than its current model.
The third iteration method of creating the body of the instrument uses layered laser cutouts of quarter-inch thick plywood. The laser cut designs were created with a vector graphics program, and the laser cut individual layers from sheets of wood. The inner layers of the instrument create the outer and inner walls to two main chambers: the resonance chamber and the circuitry chamber. The outer layers enclose the inner layers and form the flat front and back. Wood glue fixes the layers to each other. Threaded metal rods inserted into laser cut guide holes help alignment during the gluing process. These rods were later removed after the remaining layers were glued.

Image 2 - Gluing Layers with Clamps and Metal Guide Rods

The precision of the laser allowed for smoothly cut edges on the interior and exterior of the instrument; it also allowed for smaller precision cuts, including creating
the interior housing components, mounting and structural guide holes, and other smaller parts. Unlike the two previous, this method allowed the entire of the body of the instrument to be wood. The resulting dimensions of the instrument are 32-inches tall, 18-inches wide, and 3.5-inches deep.

**Upper Control**

The “upper-control” portion of the instrument is a circular cutaway with a crossbar horizontally spanning it. There are three spring-loaded, trigger-style game controllers of analog output attached across the bar. The performer plays this portion of AEMI in a manner that is similar to that of a euphonium musician by pressing down on three values.

These triggers on AEMI, however, send continuous data and sonically shape the timbre of the instrument through a set of three filters. When only the first trigger is pressed, a low-pass filter is used. The second trigger opens a notch/resonance filter (with a traveling center frequency based on the current pitch), and the third trigger opens a high-pass filter. While the instrument has a two-octave range, an adept AEMI performer could use the triggers to help exaggerate or create the illusion of a broader *tessitura* (musical range).

In the original design, the rotation of the cross bar (to which the triggers are now attached) controlled the loudness of the instrument. Spring-loaded cams supplied
resistance against the performer’s rotation, allowing the instrument’s loudness to naturally return to silence. The resistance allowed the performer to physically embody their effort while increasing the loudness of AEMI. This design scheme was abandoned because of the fatiguing nature of using spring-loaded resistance.

The current version of the crossbar section uses bicycle grip tape to wrap around the trigger apparatus and a Styrofoam backing. The Styrofoam added to the back of the triggers creates a healthy girth for the performer to grasp without fatiguing while squeezing the triggers. The grip tape is used to keep all the components bound together and to supply a non-slip texture around the crossbar.

![Diagram of AEMI Circuitry](image)

Image 4 - Basic Organization of AEMI

Circuitry Chamber

The circuitry chamber houses the embedded electronic components of AEMI. A three-axis accelerometer in the circuitry chamber of the instrument measures the difference in G-forces (instantaneous acceleration) of the instrument. To achieve a vibrato effect, the performer gently shakes (rocks) the body of the instrument and pivots the instrument on their upper leg. Having the accelerometer placed near the top and pivot
point toward the bottom of the instrument (on the performer’s lap) allows for more noticeable measurement.

The Arduino Nano receives sensor data from the capacitive touch, loudness/filter triggers, and accelerometer. The Arduino sends data to the RaspberryPi with a version of SatelliteCCRMA\textsuperscript{38} by Edgar Berdahl running PureData. A PureData patch maps to sensor data to sound synthesis coding. Audio output from the RaspberryPi runs to the amplifier and out to two flat-paneled tactile transducers within the resonance chambers.

Image 5 - Circuitry Chamber, View from Back

A covered opening on the back layer allows access to the embedded circuitry chamber only. This access point allows to adjustments to circuitry and the ability to

update software running on the RaspberryPi (including the PureData patches), as well as the Arduino sketches.

**RaspberryPi**

AEMI uses a RaspberryPi 2 as its embedded\(^{39}\) microcomputer. Running Satellite CCRMA,\(^ {40}\) a version of Linux, a preset PureData (PD) patch loads at boot and begins serial communication via USB with the Arduino at 9600 baud rate. Earlier tests with high bauds, with hopes of reducing latency, seemed to overwhelm to PD. The Pure Data coding used to parse incoming sensor data from the Arduino is custom written and simply backups a concatenated string with whitespace character datatypes as delimiters. Each parsed character is recast into an integer value and routed as pitch on/off, accelerometer, or trigger data.

**Arduino**

Arduino Nano 3.0 receives sensor data from a group of game triggers (variable resistance), a three-axis accelerometer, and two capacitive-touch circuits, each reading 12 touch pads. Programming for the Arduino is preloaded via USB in the form of a ‘sketch,’ which tells Arduino to often times offset, scale, and concatenate the data before it is sent to the RaspberryPi via USB through serial protocol.

The three-axis ADXL326 accelerometer is used to track the performer shaking/rocking AEMI. It has a small form factor and outputs three analog measurements.

\(^{39}\) Edgar Berdahl, "How to Make Embedded Acoustic Instruments" (paper presented at the NIME, 2014).

\(^{40}\) Berdahl and Ju. An software bundle containing Ubuntu Linux, Arduino, and audio applications (PureData, Faust, ChucK).
The capacitive touch controllers (MPR121)\textsuperscript{41} allow for up to 12 pads, used I2C communication, auto programming, and has adjustable thresholds. Two controllers are used to detect 24 pads (see Images 8 and 9). With the code library used on the Arduino, on or off touches are detected. Different settings are possible, but they are currently unused.

The game triggers (COM-10314) used in the crossbar section were originally purchased through Sparkfun.com\textsuperscript{42} but are now discontinued. No datasheet is available. They each have a 10k potentiometer that is adjusted by using the spring-loaded trigger, affecting the voltage divider circuit ranging “from about 2k - 9k ohm” (See Image 2).

The instrument draws power from a single 12VDC power cable attached to the amplifier. A USB cable is soldered to the power and ground pins of the amplifier to supply 5 volts, 2 amps to the RaspberryPi via its micro-USB socket. The Raspberry Pi then supplies power to the Arduino Nano through a Mini-B USB cable. This cable is used to send serial data from the Arduino back to the Raspberry Pi.

**Fingerboard**

The fingerboard portion of AEMI rests on an ovoid wooden layer elevated from the front layer by laser-cut offsets with a scroll pattern modeled off a violin’s bridge. The fingerboard portion features a capacitive-touch pad array and is AEMI’s pitch selection interface, built from printed circuit board. The circular touch pads are arranged in a keyboard-style layout similar to a piano. A slight arc in the layout is meant to allow

\textsuperscript{41} https://www.sparkfun.com/datasheets/Components/MPR121.pdf
\textsuperscript{42} https://www.sparkfun.com/products/retired/10314
performers to pivot their right forearm while keeping their elbow still. The one octave pattern is repeated directly above the other, in a stacked octave manner. In its current state, the touch interface could easily be substituted for a different layout of 24 pads, but the goal of the instrument is to have a fixed, non-interchangeable interface. Jeff Snyder, regarding his Manta touchpad controller, aptly describes that in the age of dynamic touch interfaces, a fixed layout “encourages the development of muscle memory on the instrument.”\footnote{Snyder.}

The fingerboard is designed so that the performer touches the metal traces, giving the performer some tactile feedback. The touchpad was the toughest aspect of AEMI to design, as it was the most important aspect of the instrument—pitch selection. As there are so many existing models for pitch interfaces, the touch areas size, shape, and layout were agonized over. Below are two earlier examples of layouts and insets for the touch areas.

Image 6 - Alternating Water Droplet Key Shapes in Dual-Level Pattern
Earlier interface designs involved relief overlays that elevated the areas around the touchpad or elevated the touchpad areas themselves. For example, early versions of the touch interface used the acrylic overlays for the touchpads, giving them a smooth glass-like surface similar to iPhones or iPads, creating tactile contrast with surrounding wood portions.

The current version uses circular pads with no elevation in a diatonic-piano pattern on printed circuit board. The design method started out on a vector graphics program and then moved into Fritzing, an open-source platform that allows designers ‘to create electronic projects.’ Within Fritzing, the original layout design of the fingerboard was converted into an electronic schematic to coordinate with the Arduino board, MPR121, accelerometer, and trigger sensor wiring. The eventual exported file of Fritzing included several layers of Gerber files for the creation of printed circuit boards. Below are

44 http://www.apple.com/
46 Gerber format is the de facto standard in printed circuit board printing, which allows for the
screenshots from within Fritzing where the traces from the copper touch pads would lead to dedicated copper pins, which leads to the MPR121.

Image 8 - Designing the Fingerboard in Fritzing

Image 8 is a screenshot from the Fritzing environment. There are two parts to this design: Arduino components and fingerboard. After receiving the boards from the producers, I cut the board to separate the two sides. The left side of the image is where the Arduino and other components would be soldered. That board and its components are housed in the circuitry chamber. The right side shows the design of the fingerboard. Ribbon cables connect the copper pins from the fingerboard through an opening on the front plate to the left-side board. The Fritzing environment allows the ability to design the layout, determine drill holes, port traces to both sides, and import existing components.

Image 9 - Printed Circuit Board with Arduino and MPR121 Components Attached
Conclusion

Numerous construction methods and materials were experimented with and the use of laser cutting and vector graphic design afforded rapid iterations. The current iteration utilizes 10 layers of plywood glued and compressed to create a single hollow body. The embedded circuitry involves a RaspberryPi 2 using an image of Satellite CCRMA with PureData programming synthesizing the audio output. The fingerboard construction relies on a customized, printed circuit board with 24 touchpads for pitch selection. I also utilized three game-style triggers for loudness and timbre control. A three-axis accelerometer provides motion-controlled vibrato.
CHAPTER 3. SONIC FEATURES OF AEMI

Introduction

In this chapter, the sonic and musical considerations of AEMI are discussed. Many modern composers and musicians have utilized a combination of the acoustic and electronic instruments. Through the study and application of both approaches, composers may find that one informs the other. That understanding was applied in the creation of AEMI — the embodiment of the instrument is a combination of electronic circuitry and sensors, digital audio design/signal processing, analog resonance, and acoustic propagation.

Musical Decisions

Certain levels of constraints were utilized in designing AEMI including, setting an unalterable pitch range, number of selectable pitches, its monophony, and synthesis style. The rationale employed was to model AEMI on traditional acoustic instruments. As many existing acoustic instruments have a variety of timbral ranges, i.e., the clarinet’s chalumeau, throat tones, clarion, and altissimo, AEMI also includes performer-enacted variations in timbre. And within those constraints, performers may would develop “stylistic variations both in spite of and because of the constrained design,” as Gurevich, Stapleton, and Marcquez-Borbon observed. But along with those constraints, the same questions of Tod Machover’s ‘inevitability’ may be asked. The trend of

49 Machover.
modular programming and synthesis techniques, often via MIDI (musical instrument digital interface), in the second half of the 20th century allowed for these instruments to have almost infinite sonic capabilities without changing the performer interface. AEMI, like most acoustic instruments, has a limited user interface, limited sonic abilities, and a limited musical range. Still, with these constraints, performers may be capable of making the instrument expressive.

Electronic instruments often rely on loudspeakers to transmit sound aurally. In contrast, AEMI uses tactile transducers to vibrate the wooden material of its body, which adds a layer of physicality to the transmission and a natural coloring to the tone of the instrument, as the transduction material has its own inherent physical acoustic properties. This timbral component from the wooden material is considered while formulating the sound synthesis.

‘Acoustic viability’50 is the concept that explains how electronic composers and sound designers apply the laws of physics throughout the process of designing electronic instruments, electroacoustic music, or sonic environments, “by creating connections of performance and timbre to the synthesis processes.” Application of acoustic viability aids electronic composers and sound designers in creating better instruments. Modeling can also aid designers to create more expressive and believable electronic instruments. An example of this practice could be that an object of larger volume and mass might have a lower, louder sound.

Physical modeling is the practice of quantifying properties of existing acoustic

instruments/resonant bodies, and expressing those features. Physical modeling used in sound synthesis is often used to generate ‘models’ or algorithms that predict resultant sounds, based on “the premise that the closer the simulation, the better understood the system is.” Physical modeling and acoustic viability are similar, in that, based on the understanding of the laws of physics and the application of their theories, they may have similar resultant sounds, but they may be used for different goals. Both concepts show that resonant bodies react differently when varying energy is applied to a system. Physical modeling may not intentionally imitate actual physical systems, but based on existing data, also interpolate a non-existent system. And, while acoustic viability may also start with understanding of physics, a non-mathematical resultant could satisfy the creator.

AEMI’s physical material naturally colors its tone and the synthesis method attempts to map as many control points to synthesis factors. The following sections discuss sonic aesthetics and the mappings of performances controls to resultant sounds through the synthesis code in PD, based on the concepts of acoustic viability. In this context, the concept of acoustic viability is used to describe the timbre of the instrument.

The choice of pitch range was based on musical aesthetics and frequency range that had less-overt buzzing in the material. More in-depth research on the acoustic response and resonance frequency of AEMI has been planned for a future date.

Many performer-expressed control parameters affect the timbre of AEMI: loudness, pitch, and range. In Hunt, Wanderley, and Paradis’s *The importance of parameter*

mapping in electronic instrument design," they discuss possible mapping strategies of control parameters onto electronic instruments and compare them to existing acoustic instruments. A ‘complex’ mapping of loudness and timbre controls is used, where the combination of many mappings affecting the both overall loudness and timbre. Similar to most acoustic instruments, these parameters affect the timbre differently and a performer would find more expressivity using them. They also discuss the concept of multi-layered mappings (layers that maybe abstract, like “brightness” or “energy”).

Sound Design and Signal Processing

The digital signal processing was coded with PureData running on the RaspberryPi. The underlying model of synthesis was FM synthesis, which allowed for rich spectra. Important parameters in FM synthesis are the frequency of the carrier, amplitude of the carrier, frequency of the modulator, and amplitude of the modulator. The name of the parameters may appear different, with different authors re-naming the parameter to describe their function. For example, in simple FM, deviation is synonymous to ‘amplitude of the modulator,’ both describe the frequency deviation (width) in frequency of the resulting modulation. As the amplitude of the modulator increases, the width of the vibrato increases. Future signal processing adjustments will take into account the natural coloration from the wooden material and nodes of vibration.

C:M Ratio

In FM instruments, the spectral components are controlled through the relationship of the parameters listed above. A characteristic of FM is the existence of sidebands that occur above and below the carrier’s spectral component. The distance of the sidebands from the carrier can be described as a basic relationship $F_c \pm n F_m$, where $F_c$ is carrier frequency, $F_m$ is modulator frequency, and $n$ is number of sidebands. ‘Carson’s (bandwidth) rule’ describes how the sidebands will “extend outwards to twice the sum of the frequency deviation and the modulation frequency, $B = 2(\Delta f + f_m)$.”55

The relationship of relative frequencies of the carrier frequency to the sidebands/partials is commonly described as the carrier to modulator ratio (C:M ratio) or ‘harmonicity.’56 If the $c:m$ ratio reduces to a rational number, the relationship is described as harmonic. If the $c:m$ ratio reduces to an irrational number, the relationship is described as inharmonic. Most wind instruments have partials that are harmonic in nature. Many noise-based instruments, like percussion instruments, have inharmonic spectra. While C:M ratio and harmonicity describe the same relationship of carrier frequency to modulator frequency, $C:M$ is typically shown with the colon delimiter. Harmonicity is typically shown as a single decimal quotient value.

Another mathematical relationship important to FM is the modulation index. Described as the ‘deviation/Fm’ or modulation amplitude/modulation frequency, this relationship shows that the relative amplitude of sidebands increases as the ratio

55 Farnell, 301.
increases, resulting in a richer spectrum. A lower modulation index creates a simpler spectrum. Bessel functions are used to determine the amplitude of the sidebands. “In practice they scale the sideband amplitude according to the modulation index, so as we increase the index the sidebands wobble up and down in a fairly complex way.”

AEMI uses a ‘Simple FM’ model with single modulating oscillator with a $C:M$ ratio of 0.5 and a sliding modulating index of 1 to 200. Another modulating oscillator is used to create a slight vibrato, with a ‘one-to-one’ mapping of accelerometer is linked to vibrato depth. The slight rocking of the instrument which affects the accelerometer inside the circuitry chamber, allows for both mechanical and performative motions for vibrato of other instruments like the singing saw and trumpet.

Charles Dodges describes a dynamic modulation index in terms of minimum and maximum values: respectively, IMIN and IMAX. Harkening back to acoustic viability’s application of ‘increased energy implies difference in sound,’ AEMI’s modulation index is based on the sum of all three trigger values, scales between 1 and 200. When the performer increases the ‘loudness’ of the instrument, a mapping to increase modulation index, is to intended imitate an increase of ‘energy’ into the instrument.

---

57 Farnell, 300. “The amplitude of the $n$th FM sideband is determined by the $n+1$th Bessel function of the modulation index.”
58 C. Dodge, and T. Jerse., Computer Music: Synthesis, Composition and Performance (New York: Schirmer, 1997), 123. Modulation Index as function of the overall loudness (trigger values) between IMIN and IMAX.
‘Pitch’ selection on AEMI is made through the capacitive touch pads on the fingerboard section of the instrument. The pitch range is between C4 and B5 (MIDI note 60 to 72). Within PD, the pitch value is converted to frequency value; the tuning would otherwise be equal temperament. The pitch selected determines the carrier frequency of the Simple FM model.

Loudness and Filtering

The three triggers in on crossbar of the upper control section control the loudness and filtering one step down the signal chain of synthesis. When one or more triggers are pressed, the maximum value of all the triggers is used to control loudness of the instrument. If the performer were to press all three triggers, the greatest value out of all three would set the loudness.
The three triggers are set to three independent filters: a lowpass, bandpass, and highpass. In terms of signal chain, these filters are located below the synthesis module and before overall loudness. The lowpass and highpass (one pole) filters have fixed roll-off frequencies of 250 and 1000 hertz, while the bandpass has a sliding center frequency based on the current frequency/pitch selected. The Q (quality factor) of the bandpass is currently set to 10, but with future versions, variability will be based on the center trigger’s value. Q is typically described as the sensitivity of the filter with the equation $Q = \frac{\text{Center Frequency}}{\text{Bandwidth}}$.\(^{59}\) Bandwidth in a bandpass filter represents the lower- and upper-cutoff frequencies. Another way to describe Q is the sharpness of the bandpass filter, where a higher Q would result in a narrower bandwidth.

The use of these filters was an attempt to create a variable formant-like character for the instrument, which enriches the timbral quality through controllable parameters. Formants can be fixed in instruments because of their physical bodies creating resonance, but not always. “Formant peaks are characteristics of the vowels spoken by the human voice and the tones radiated by any musical instruments.”\(^{60}\) Although already using a physical material of wood to color the sounds, ability to alter the sound through processing would deepen the expression of the instrument. And while the greatest trigger value dictates the overall volume of the instrument, any other trigger-pressed affects the timbre with other amplified partials. This mapping is what Hunt might describe as a ‘conceptual one-to-one mapping’\(^{61}\) of trigger to loudness, but also a complex coupling of timbre to loudness.

\(^{59}\) Ibid., 173.
\(^{60}\) Roads, 263.
\(^{61}\) Hunt, Wanderley, and Paradis.
Articulations

A small envelop of filtered noise creates an ‘initial transient’ or ‘chiff’ on each attack of a note. The duration of this transient is function of the loudness of the note, supplied by maximum trigger value. When the performer selects a pitch and has one or more of the loudness/filter triggers presses, the highest trigger value becomes a multiplier on the duration, between 5ms and 25ms. Future versions should make the spectral content more contextual with the selected pitch/frequency. (See end of document for links to PureData code.)

Different types of articulation are achieved when the performer places separation between pitches. The sharpness of the articulations is expressed through the initial transients relative to the loudness controlled by the triggers. Legato articulation occurs when two or more successive notes in a phrase follow one other smoothly creating an overall dynamic gesture — one that increases in loudness, decreases, or does what Richard Dobson describes as the musical term *mesa di voce* (an increase in volume followed by a decrease). Given the capability noted above of indexing pressed pitches and portamento (mentioned below), a practiced performer would be able to achieve legato phrasing with very little portamento. Absent in the legato notes are the initial noise transient audible in other articulated notes.

Portamento and Multipressing

Part of the sound design of the AEMI is the ability to portamento from one note to

---


63 Ibid., 171.
the next. Many instruments like the trombone, stringed instruments, Ondes Martenot, and Theramin are able to portamento easily.

AEMI is monophonic, so when the performer presses more than one pitch, the instrument executes a portamento from the first pressed pitch to the second. In order to technically achieve this, pitch-selection ordering (or indexing) was necessary. If the performer releases either pitch during a portamento, the pitch still pressed becomes the primary pitch, and the instrument quickly slews to that pressed pitch. Anytime the performer has two pitches selected and releases one of the presses, the remaining pitch become the primary press. Any secondary press becomes the resultant portamento destination.

Conclusion

AEMI uses FM synthesis with simple mapping for pitch selection and complex mapping for timbre. An application of acoustic viability allows for the performer to express dynamic timbre through loudness, which varies the tone (C:M ratio), and filtering. Portamento is achieved through indexing multipresses on the fingerboard.

FUTURE DEVELOPMENTS

While AEMI is a functioning instrument capable of being played in an orchestral setting, areas of further research include the use of traditional tone woods and the resulting inherent characteristics thereof. Additionally, there are plans to adjust the distance between the touch pads on the fingerboard to more easily allow performers to transition between notes.

Future plans also include installing indicator lights for signaling data transmissions.
between components; a mounted RJ45 jack to allow software updates to the RaspberryPi and Arduino; simpler internal cabling; and a power jack and switch. The eventual goal for AEMI is to be battery-powered, which will allow greater freedom of movement. The battery for AEMI would sustain the RaspberryPi, the Arduino Nano, the amplifier, and the input sensors (capacitive touch sensors, variable resistor triggers, and accelerometer). Arduino Nano is now retired, according to Arduino. Future versions of AEMI may rely on a different Arduino board.

Future software capabilities include custom sound synthesis through third-party mappings. A performer may want to re-map the trigger values to a different part of the sound synthesis. A performer could also have the capability to remap the range or tuning of the instrument. This will allow performers to adjust the applicable sound and timbre of AEMI.

**CONCLUSIONS**

The creation of AEMI was an attempt to combine previous acoustic and electronic works and research, along with an understanding of instrument design. The goal was to create a dynamic instrument that engages the performer and the listener with intuitive feedback. AEMI is a physical bridge between acoustic and electronic music, performance, and composition. The composition provides listeners an opportunity to engage with an unfamiliar instrument in a familiar setting. The composition also allows AEMI to demonstrate its unique timbre and features as a soloist.

I hope this work brings insight into my process and goals, inspires further work into composition for new instruments, and draws future performers to play AEMI.
LINKS
A link to versions of the PureData patches, Arduino sketch, laser cut schematics, videos, and other downloadable files are located: https://github.com/rioter00/AEMI.
BIBLIOGRAPHY


VITA

Nick Hwang (www.NickHwang.com), from St. Petersburg, Florida, is working toward a PhD in Music Composition at LSU where he studied with Stephen David Beck, Dinos Constantinides, and Jesse Allison. He has earned his Master’s degree from LSU and Bachelor’s degree from the University of Florida.

Hwang currently teaches at the University of Wisconsin-Whitewater in the Media Arts and Game Development program. He has had his music performed internationally and in the United States.