How to Make Embedded Acoustic Instruments

Edgar Berdahl
Louisiana State University
Baton Rouge, LA, 70803, USA, and
Technical University of Berlin
10587 Berlin, Germany
edgarberdahl@lsu.edu

ABSTRACT

An *embedded acoustic instrument* is an *embedded musical instrument* that provides a direct acoustic output. This paper describes how to make embedded acoustic instruments using laser cutting for digital fabrication. Several tips are given for improving the acoustic quality including: employing maximally stiff material, placing loudspeaker drivers in the corners of enclosure faces, increasing the stiffness of "loudspeaker" faces by doubling their thickness, choosing side-lengths with non-integer ratios, and incorporating bracing. Various versions of an open design of the "LapBox" are provided to help community members replicate and extend the work. A procedure is suggested for testing and optimizing the acoustic quality.

Keywords

embedded acoustic instrument, embedded musical instrument, Satellite CCRMA

1. INTRODUCTION

1.1 Embedded Instruments

Since the beginning of NIME, most prototypes have contained only a small amount of integer-based computation for processing sensor data or none at all. The sensor data was transmitted to an external computer, which carried out all of the computationally intensive tasks including sound synthesis. However, in the past few years, native embedded floating-point computation has become inexpensive enough to more widely benefit the NIME community [2]. This trend has enabled makers of new musical instruments and sound art installations to embed computation into their designs. For example, the Satellite CCRMA project has aimed to help the community install embedded computation into musical instruments and sound art installations. The Satellite CCRMA image can be used with the Raspberry Pi embedded computer, which costs only approximately \$35 to \$40 USD [3].

Embedded computation has many advantages including reducing the number of cables required for operation and helping prototypes remain operable for a longer period of time with less maintenance. In many prototypes, an audio out connector allows the output audio to be connected to an external sound system [8, 4, 12]. Proprietary platforms have been used for prototyping embedded musical instruments as well including the Variax [5] and the Chameleon Guitar [19].

In contrast, an intriguing question is how to provide an embedded musical instrument with a direct, cleanly controllable acoustic output. This question is the topic of the present paper, which aims to also share the technology with the community.

1.2 Embedded Acoustic Instruments

The concept of the most basic embedded acoustic instrument is represented in Figure 1, which shows human hands manipulating sensors that are connected via a sensor interface to an embedded computation unit. A sound synthesizer implemented in software creates an output audio signal based on the sensor data. Finally, an audio amplifier makes the output audio signal intense enough to power an internal transducer (see Figure 1). The sound radiates directly from the transducer while the enclosure can help support the sound radiation by partially or wholly baffling the driver and/or providing a port, etc. In general, lumped element models can be employed to help guide the size and geometry of the design [17].

In practice, different overall configurations may be desirable. For example, a differently shaped enclosure, more loudspeaker drivers, more sensors, etc., may be useful in a specific context. Here the intent is merely to describe what is meant by the term embedded acoustic instrument.

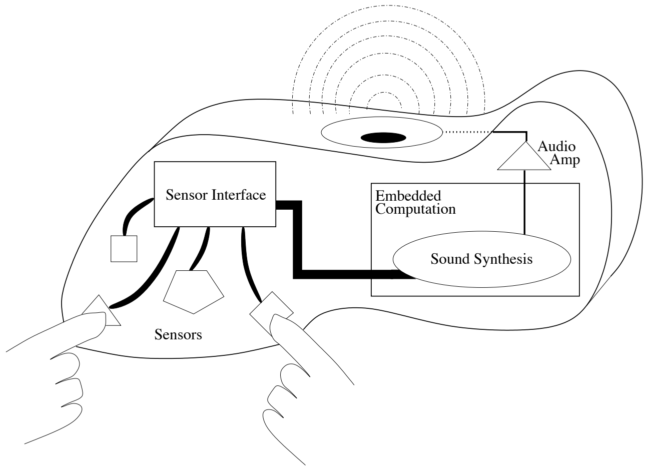

Figure 1: Embedded acoustic instrument concept.

Community members interested in building embedded acoustic instruments will want to first experiment with the simplest designs in order to efficiently learn the craft. Therefore, the approach taken in this work aims at providing the community with a simple design that is easy to test, replicate, and extend. For this reason, the paper aims at pre-

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senting these concepts in the most general sense.

1.3 Radiation Pattern

It is possible to build embedded acoustic instruments that radiate sound in many different ways. Therefore, it is interesting to consider how traditional acoustic instruments radiate sound. Measured radiation patterns tend to be quite complex, but a few approximate generalizations can be made. Gongs and cymbals radiate sound approximately in a dipole pattern, with very little sound radiating in the plane of the instrument. Brass instruments tend to radiate the highest frequencies directionally out of the horn with a widening pattern at lower frequencies. Acoustic stringed instruments generally radiate sound in an even more complex pattern [7].

On the one hand, highly directionally dependent acoustic instruments will present challenges in anechoic environments or environments with very little reverberation. For example, when performing outside with such an instrument, each performer will likely want to aim to have all audience members lie within a somewhat homogeneous region of the instrument's radiation pattern. On the other hand, most indoor performance venues provide for a reverberant environment that can help diffuse the sound throughout the entire listening space. Therefore one can posit that a highly directionally dependent radiation pattern may be satisfactory in such a reverberant environment.

Acoustical simulations of classical music concert performances provide some specific insights into performance environments with reverberation [14]. In reverberant performance halls, the sound radiated from an instrument can either travel directly to a listener's ears and/or it can reflect off of one or more surfaces before reaching the listener's ears. In either case, the listener has the possibility of hearing the instrument, no matter where it is placed on stage. The ratio between the strength of the direct sound and the strength of the reflected diffuse sound will affect how reverberant the sound is perceived to be [11]. Furthermore, if two instruments on a stage have significantly differing radiation patterns, then the room will typically filter the sound differently as it makes its way to a listener's ears. In particular, the *timbre* of the two instruments will be affected differently. The same holds true between entire instrument sections, assuming that in each section, the instruments have similar radiation patterns and are oriented similarly [14]. Thus, when listening to a traditional orchestra, in which the different *kinds* of musical instruments have individualized radiation patterns, each instrument *section*'s timbre will be shaped differently and individually by the room, providing the listener with a "rainbow" of timbreally shaped sounds [14].

If one wishes to follow the lead of orchestral history when designing new embedded acoustic instruments, one should consider endowing each embedded acoustic instrument design with its own individualized radiation pattern. This is easy to do using even a small number of loudspeaker drivers. For this reason, the examples associated with this paper are based on designs using two independently controlled loudspeaker drivers.

1.4 Related Instruments

Some related prior instruments and concepts are discussed here in order to provide for a more thorough historical perspective. In 1991, David Wessel suggested making digital instruments with concentrated arrays of independently controllable loudspeakers to enable programmable control of a digital instrument's radiation pattern. He suggested that this approach could make it easier to mix traditional acoustic musical instruments and electroacoustic instruments in live performance [18]. This concept is embodied by the Bowed-Sensor-Speaker-Array (BoSSA), by Dan Trueman and Perry Cook [16]. The BoSSA enclosure approximates a sphere and has twelve independently controllable loudspeakers, which are nearly evenly distributed over the surface.

The technology has since been integrated into six-channel loudspeakers that sit on the floor in laptop orchestras and have become used by many institutions [15]. However, controlling the radiation pattern to more accurately simulate specific radiation characteristics is difficult and could require 120 independently controllable loudspeaker drivers or more [20, 1]. Thus for simplicity in the present work, the examples associated with this paper are based on designs using two independently controlled loudspeaker drivers to provide each performer of an embedded acoustic instrument with an individual sound source, as with the laptop orchestra. However, in the future, it could nonetheless be interesting to experiment with incorporating larger numbers of channels into embedded acoustic instruments.

Actuated acoustic instruments are also worth mentioning. They radiate sound more similarly to acoustic musical instruments but have a more fixed radiation pattern [13]. However, in contrast, the focus of embedded acoustic instruments lies in being able to create a wide range of timbres that would ideally be unrestricted by the enclosure geometry. This is why embedded acoustic instruments typically actuate sound waves directly using loudspeaker-type transducers.

2. DIGITAL FABRICATION

2.1 Overview

In order to make acoustic embedded instruments most accessible to the community, the authors have decided to pursue a digital fabrication approach for making enclosures. While the author looks forward to the possibility of employing 3D printing techniques for making enclosures, and while the lead author has a 3D printer at his institute, it has been decided to employ a 2D laser cutting technique for this work instead. One significant advantage of laser cutting is that the material is much less expensive, enabling students to engage more easily in creating acoustic embedded instruments in a classroom context. Also, it is hypothesized that musicians might have an affinity for laser-cut wood as final designs can moderately resemble some kinds of traditional acoustic musical instruments. Finally, wood glue is convenient to work with, is non-toxic, provides a strong bond, and is quite environmentally friendly. Figure 2 shows five faces of an enclosure laid out on a table in preparation for gluing them together.

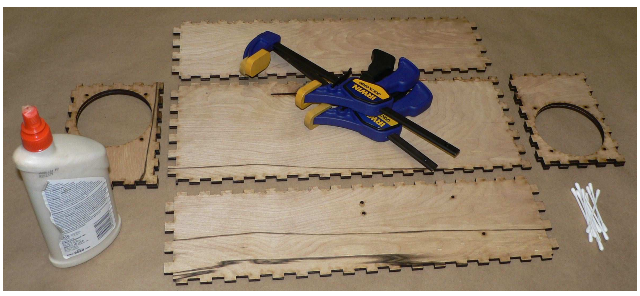

Figure 2: Preparations for gluing together pieces of laser-cut plywood to make an enclosure.

Approximately ten prototype enclosures for embedded acoustic instruments have been fabricated and tested. The lessons learned are summarized here. The most significant challenge to making lightweight enclosures out of laser-cut wood is nonlinear rattling of the enclosure pieces or the electronic parts mounted to them. This occurs primarily due to structural resonances in the enclosure. The following steps can be taken to prevent rattle:

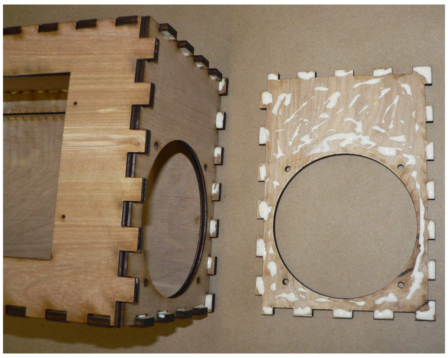

Figure 3: The thickness of faces containing loudspeaker drivers can be doubled simply by gluing two layers of laser-cut plywood together.

- Use sufficiently stiff pieces of wood such as 0.2" (5mm) thick plywood or medium density fiberboard (MDF).
- Install the loudspeaker drivers in faces with less area. Place the drivers in the corners of these faces.
- Double the thickness of faces containing loudspeakers, such as shown in Figure 3.
- Make the enclosure small so that the thickness of the sides is as large as possible compared to the enclosure side lengths.
- Choose the side lengths for the box so that the ratios of the various side lengths have non-integer relationships.
- Use "plane" braces that are glued to four different sides of the enclosure to help reduce the strength of structural vibrations [9][17].

2.2 Acoustic Testing

Acoustic testing is absolutely essential, especially for learning how to build acoustic embedded instruments. We recommend, as early as possible, screwing the loudspeaker drivers to the enclosure parts and then controlling the drivers with a loud sinusoid in order to check for possible rattling. Only then is it convenient to systematically eliminate rattling. Indeed, if an enclosure is rattling at a specific frequency, then one can manipulate the enclosure while it is rattling in order to find the problem. For example, one might wish to hold certain faces more rigid, move cables, tighten screws, loosen screws, and/or add feet, etc. until the rattling is eliminated.

Due to the necessity of acoustic testing, it may be desirable to build acoustic embedded instruments within a studio or other soundproofed room. The enclosure should be tested again after each additional part is added to eliminate sources of rattling.

A Pure Data (pd) patch is included with the archive distributed with this work. This patch is shown in Figure 4, which reveals how to search for resonance frequencies that contribute to rattling. The process is as follows:

1. Choose a frequency near the lowest structural resonance frequencies of the enclosure,
2. increase the amplitude until the sinusoid is very loud,
3. sweep the frequency to search for resonance frequencies that rattle, and
4. for each rattle frequency, manipulate the enclosure and components until the rattling is eliminated.

Repeat the process described above after adding each additional component.

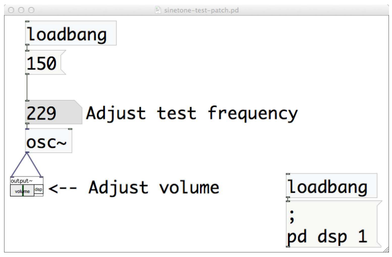

Figure 4: Pd patch for searching for resonance frequencies contributing to rattling.

2.3 Carefully Check Freely Vibrating Wires and Other Parts

Wires and all electronic parts need to be mounted very carefully so that structural vibrations they make will not cause any rattling. It may be necessary to sandwich thin layers of foam between the enclosure and circuit boards being firmly screwed to the enclosure. Similarly, if the loudspeaker drivers come with foam gaskets, then they should be employed when fixing the loudspeaker drivers to the enclosure. For parts that cannot be screwed to the enclosure, hot glue is recommended for early prototyping. For example, hot glued parts can sometimes be more precisely re-placed later after viewing wire lengths etc. in order to route cables to help prevent them from rattling.

3. THE LAPBOX

3.1 Selecting Dimensions

The *LapBox* enclosure was designed so that it would be easy for students to assemble and modify to make embedded acoustic instruments (see Figures 2 and 3). Due to its simplicity and tutorial value, a simple dovetail enclosure was used. Its dimensions were chosen considering the criteria described in Section 2.1. Louden's ratio of 1:1.4:1.9 was selected [6, 10]. However, it was decided to multiply the longest side length by two in order to obtain a relatively small box with the ratios 1:1.4:3.8 that could fit in the lap of a performer as shown in Figure 5. A picture of a related embedded acoustic instrument with ratios 1:0.7:3.8 is shown in Figure 6.

3.2 Open Baffle By Default

The *LapBox* is acoustically open by default on the bottom face (not shown). Although this can reduce the strength of the bass response below 200Hz, it is pedagogically useful. In this case, students can always quickly get inside the instrument if necessary in order to make modifications. However, the project files include a template for a bottom panel cover, which can be attached using Velcro or wood screws in order to acoustically close the instrument. In this case, it is advisable to insert some acoustic foam into the enclosure to help dampen "air" resonances inside the enclosure.

Figure 5: *LapBox* revision 3, with force-sensing resistors placed on the sides in the shape of the human hand.

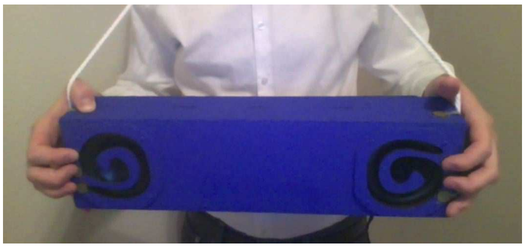

Figure 6: "The *SuperSonicSoaker* soaks you with sound." It is a derivative of the *LapBox* revision 4 that is designed to be held by a strap going around the neck.

4. CONCLUSIONS

Embedded acoustic instruments are an emerging and intriguing area of research and musical practice. Specific advice was given regarding enhancing the sound quality of embedded acoustic instruments. The authors hope that by placing the *LapBox* design within the public domain, the advancement of the field can be accelerated. More detailed, step-by-step instructions regarding making the *LapBox*, the above-described pd patch, parts lists, and example templates for laser cutting can be found at the project website: `https://ccrma.stanford.edu/~eberdahl/EAI/index.html`

5. ACKNOWLEDGMENTS

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