Active Acoustic Instruments for Electronic Chamber Music

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ABSTRACT
This paper presents an ongoing project for augmenting acoustic instruments with active acoustics. Active acoustics are defined as audio-rate vibration driven into the instruments physical structure, inducing air-borne sound output. The instrument's acoustic sound is thus doubled by an electronic soundscape radiating from the same source. The article is centered on a case study on two guitars, one with hexaphonic sound capture and the other with monophonic pickup. The article discusses the design, implementation, acoustics, sound capture and processing of an active acoustic instrument, as well as gestural control using the Leap Motion sensor. Extensions towards other instruments are presented, in connection with related artistic projects and "electronic chamber music" aesthetics.

Author Keywords
Augmented Instrument, Active Acoustics, Structure-borne sound, Guitar.

ACM Classification
Applied computing~Sound and music computing, Hardware~Sensors and actuators, Computing methodologies~Mixed / augmented reality

1. INTRODUCTION
The present article constitutes a progress report of an ongoing technological and artistic research project for augmenting acoustic instruments with active acoustics. The term "active acoustics" is employed here to signify the use of structure-borne sound drivers to drive electronic sounds into the physical structures of an acoustic instrument, inducing air-borne vibration, analogously to a diaphragm loudspeaker. A new layer of electronic sound can thus be created in parallel to the instrument's acoustic output. The article discusses the design, implementation, control and artistic use of such system on the guitar, as well as introduces an extension of the research towards the harpsichord, the double bass and a double-skinned tomtom drum.

The research presented in this article is a case of hybrid lutherie aiming to create an augmented instrument, i.e. an existing instrument with expanded sonic possibilities. Our design targets a self-contained instrument, ideally embedding all the input, processing and output devices within the instrument itself. The rationale is to retain as much as possible the functional and integrity of an acoustic instrument both as an object as well as a sound source, bypassing external loudspeakers and control devices.

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The project is at the crossroads of acoustic lutherie, structure-borne sound, signal processing (feature extraction, audio processing and synthesis), acoustics and gesture recognition. It is closely linked to a series of artistic works exploring the aesthetics of "electronic chamber music" and electronic sound diffusion via alternative loudspeaker systems. The methodological framework is that of Research-Creation, where technological development and artistic creation are brought into a mutually nourishing loop [2].

2. PREVIOUS WORK
Instrument augmentation is a continuous and diverse thread in electronic musicianship, at least since Gordon Mumma's seminal "Hornpipe" (1967) and related projects [18]. Tod Machover's "Hyperinstruments" introduced augmentations utilizing digital audio and control data [17], serving as an impulse to many subsequent augmentation projects, such as [1], and [25]. Dan Overholt has been sustaining a research effort on the "Overtone Violin" for over a decade [19]. The development of the electric guitar with its countless experimentations can also be seen as a process of augmentation [8]. The guitar has more recently gained academic attention and been the object of a number of systematic augmentation projects [10], [13], [21].

Structure-borne sound and its applications for transforming diverse surfaces and objects into speakers constitutes an upcoming trend, especially present in a multitude of recent works in the "sound arts" area. The step towards incorporating active acoustics to music practice and performance has been pioneered by Overholt in 2011 [20]. The Ircam is currently conducting a larger research project on creating instruments with active acoustics [22] A first commercial application of active acoustics on the guitar body achieved quickstarter funding and is starting shipping in 2016 [23].

The present project is part of the emerging research on active acoustics. Important previous work has been conducted in active control of modal resonances by Benacchio [2] and Chollet et al., [7], and in feedback control by Griffin et al. [11] and Berdahl [3]. Electromagnetic exciters and sustainers for steel strings are established and are getting more sophisticated as the Vo-96 Acoustic Synthesizer and the Wond by Paul Vo [24].

The originality of our approach in regard to other existing projects stems from a "holistic" approach to design, integrating hexaphonics, gesture recognition and feature extraction hardware and software, as well as the expansion of the research towards other instruments. Our project is also closely tied to music composition and performance, akin to Britt's work on an actuated acoustic piano [5].

3. DESIGN

In this section we present a case study of active acoustics augmentation on the guitar. Expansions to other instruments are presented in 5.1.

3.1 Design principle

The long-term design goal of our project is self-defined by the following design brief: an augmentation using active acoustics should produce a self-contained electro-acoustic hybrid instrument, that is, a single object for input, sound processing and output. The “interface” and the “instrument” should be inseparable. The augmentations should not hinder the existing playing techniques nor alter the acoustic sound, but still enable new sonic possibilities. The electronic sound output should offer a balanced, full spectrum quality, with a coherent acoustic image: acoustic and electronic sounds should seem to emanate from the same source and radiate in a similar manner. Electronic sounds should be modulable via gestural control, tightly integrated into the instrument’s gesture-sound couplings. In performance, there should be no need for an external technician to operate the instrument.

We are approaching this ambitious design goal in parts, under five topics: a) acoustics and sound driver placement, b) mono vs. hexaphonic sound capture, c) audio signal processing, d) miniaturization, and e) gestural control.

3.2 Initial Acoustic Studies

Sound driver choice and placement constitute a critical issue in the design of an instrument with active acoustics. In a previous study, we have conducted a series of tests on a selection of commercially available structure-borne sound drivers on the basis of size, weight, power and sound quality [14], leading to the choice of Hiwave / Tectonic 32C30-4B sound driver for a guitar-type application. The 32C30-4B driver is a robust 30W, ø 5cm unit which, when attached to a tonewood surface is capable of delivering full range (100-20000Hz) audio. With careful placement of two drivers we have achieved an audio quality that satisfies the needs of our application.

Previous impulse response - based acoustic studies have been carried out on a Breedlove c20 steel-stringed acoustic guitar, and reported in [15]. At that time, the most balanced sonic outcome was found to result from two sound drivers placed under the soundboard, one near the bridge and the other near the neck, emphasizing respectively low and treble frequencies.

On the basis of this previous work, we concluded that our acoustic measurements give only a partial insight into the complex acoustics of a guitar-plus-sound driver system. We thus sought further counsel from the Helsinki - based Master Luthier Uwe Florath, assuming that the professional “hands on” expertise of a senior acoustic guitar craftsman would prove helpful in optimizing driver placement. From a luthier’s point of view, the main concern was the preservation of the guitar’s acoustic properties while mounting the sound drivers. A single 32C30-4B driver weights 130g, whereas a high quality guitar soundboard weights approximately 180 – 230 grams depending on the wood. Two sound drivers constitute an excessive load for the soundboard, severely restricting its vibrational possibilities, and thus the sonic output. Moreover, the area around the bridge is the part where the most modal resonances occur on the guitar and thus critical for the instrument’s sound quality.

In order to preserve the original acoustic qualities of the instrument, we decided to abandon the attachment of drivers on the soundboard altogether. This choice left us with three main options: the guitar’s back panel, side panels, or a supplementary element such as an extra back panel (“double back”) featured in some guitar designs. All of these three options were investigated with Uwe Florath’s experience in guitar acoustics. The side panels are small in dimension and rigid due to their bindings, thus emphasizing high frequency content. The extra back panel is an acoustically promising direction but it would need a custom-made guitar design which is not at our reach at this stage of the project. Finally, the back panel proved to be the best starting point for driver placement, with sufficient low frequency response and a functional perceptual blending with the guitar’s acoustic sound. Through listening tests we chose to use two drivers attached to the back and side panels, as shown in Figure 1.

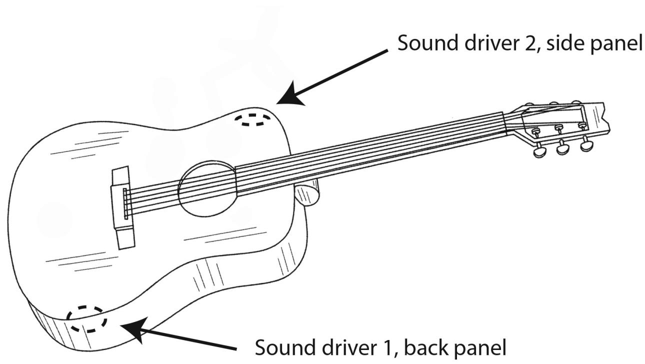

Figure 1. Driver placement on the back and side panels of the guitar

The main part of the sound is created by a driver placed off-centered on the largest area of free-vibrating wood at the back of the guitar. The location corresponds to the most active modal region of the backboard and it is the optimal area for obtaining a well-rounded acoustic response from a single sound driver outside the soundboard. The exact location is found by ear and it varies from one instrument to the other. The response turns out to be slightly emphasizing the low-mid modal resonances of the guitar.

A second driver is attached to the side of the guitar, where the vibrating surface is much smaller and rigid. This location is very efficient for producing treble frequencies and balancing the mid-heavy sound driver on the backboard. In addition, the second driver is at a 90º angle in regard to the first transducer. As both surfaces radiate sound as dipole sources (with a high-pass filter effect growing with the angle, detailed in [16]), the overall radiation pattern for the electronic sound output is omnidirectional with a complex frequency radiation pattern, effectively mimicking the instruments natural acoustic radiation. Adding the second “treble” driver on the side panel greatly adds to the perceived aural presence of the instrument.

3.3 Implementation

We have implemented two prototypes of guitars with active acoustics, informed by the previously presented acoustic study:

1) Steel-stringed Breedlove c20 “folk” guitar with a Übertar hexaphonic pickup.

2) Nylon-sringed J. Perez classical guitar with a monophonic piezoelectric contact microphone.

The rationale for developing two active acoustic guitar projects in parallel is the result of dividing a complex research problem into two parts. Our ideal instrument would be self-contained, with built-in miniature electronics, sound drivers, hexaphonic signal processing capabilities and Leap Motion video analysis for control input, all packed into one instrument. For the time being, there is no readily available miniature computer which could process real-time high-quality hexaphonic audio, nor the Leap Motion's hand recognition software.

As a result, we pursue our research in two distinct tracks: the first one (Breedlove steel-stringed guitar) in hexaphonic audio, with advanced signal processing and the Leap Motion sensor providing a channel for gestural control input. In this experiment, we use a modular outboard system comprising hexaphonic preamplification, audio interface, and a laptop running Max/MSP. While compromising the miniaturization we are able to see the real potential of the system, arguing that miniature computers are steadily gaining in processing power and might soon be able to run real-time hexaphonic audio as well as advanced computer vision algorithms.

For the second experiment we emphasize the miniaturization and compromise with audio channel count, processing power and gesture recognition. For the Perez classical guitar, we run Pure Data on a Raspberry Pi2 microcomputer with a mono guitar signal, onboard Fishman preamplification and small-size Class-D amplification for the sound drivers.

Running two parallel experiments enables us to conduct comparative research and gain insight on three focal points for the study of active acoustics on guitar: comparing how two types of acoustic guitars (steel-stringed vs. nylon-stringed) adapt to the augmentation with active acoustics, the perspectives of mounted miniature electronics vs. outboard modular system with multifold computing power, and monophonic signal acquisition from the guitar vs. hexaphonic signals. Figures 2 and 3 depict the system schemas implemented for both guitars.

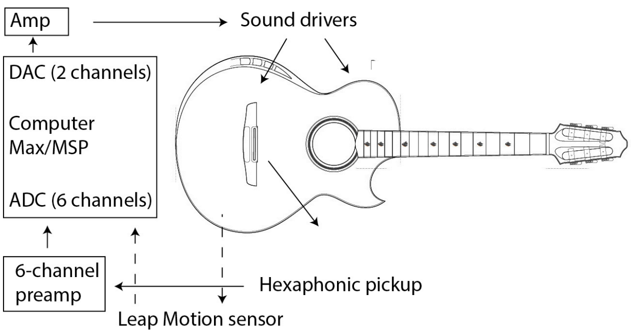

Figure 2. System schema for Guitar 1, with hexaphonic pickup and Leap Motion sensor.

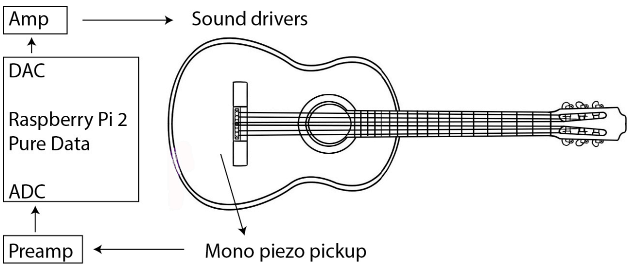

Figure 3. System schema Guitar 2, with mono pickup and sound processing on Raspberry Pi.

3.4 Gestural Control

The Leap Motion is a small tabletop hand-tracking device based on two IR-cameras generating 3D position data for the two hands and the fingers. Having experimented with a range of different sensors as well as the Kinect camera on the guitar, we were immediately struck by the Leap Motion's pertinence for the guitar's playing position and environment. The Leap Motion tracks hand and finger movements in great detail, fairly reliably, and works in the 15 to 40cm range. In addition, the device is small, light and it can easily be mounted on the guitar without obstructing playability nor the natural acoustics. A well-performing Max/MSP skeletal tracking external [leapmotion.mxo] has been made available by the Ircam in 2014. The external provides 42 channels of hand-tracking data, of which we found the high-level gesture recognition features most immediately usable, such as "pinch", "grab" and hand rotation. Having explored augmentation with different sensors on the guitar in depth [13], gestural control via the Leap Motion appears to be a promising perspective, as the level of precision in hand and finger tracking is unprecedently high. However, more time in exploring mappings is necessary to fully utilize its potential, for example following Han and Gold's approach [12]. We use it for the right (plucking) hand, for linking aerial hand gestures above the strings to sound processing, as shown in figure 4. These gestures occur after the strings are plucked and the hand has time to move away from the strings. They are readily available, often already present as "gestural ornaments" in the normal playing, accompanying sustained tones.

Figure 4. Leap Motion sensor incorporated into the guitar playing environment. Right hand and finger gestures above the strings can be used to control sound processing, adding new gesture-sound couplings to the instrument.

3.5 Audio Processing

Our approach to audio processing on the active acoustic guitar is based on an analysis of the guitar's existing sonic palette and what it is missing in terms of timbral and musical possibilities. As a plucked string instrument, the guitar tends to produce harmonic tones with rapidly decaying envelopes within a frequency range between approximately 80 and 1000Hz. The guitar does not readily produce sustained or inharmonic tones, low bass or high pitches, nor complex timbres. The possibilities for modifying the timbre after attack are very limited. Following this reasoning, our sonic augmentations aim to bring new sonic possibilities for the guitar, namely sustained tones, timbral modifications after the attack, complex timbres as well as frequency content beyond the guitar's natural register.

For the computer-run hexaphonic augmentation on a steel-stringed guitar we have implemented four max/MSP patches: 1)

A hexaphonic spectral delay with feedback and highpass filter parameters mapped to the Leap Motion's pinch and rotation gesture detection. 2) A hexaphonic granular sampler-synthesizer where each string produces its grain clouds, amplitude controlled by the individual finger motions via the Leap Motion. 3) A hexaphonic cross-synthesis patch mixing the string signals with air-like sound samples for creating complex, noisy timbres. 4) A signal-driven hexaphonic feedback effect where the input signal sets the frequency of a resonant bandpass filter, producing an overdrive and feedback on the specific frequencies that are being played.

For the Raspberry Pi-run monophonic processing, we have used the Satellite CCRMA Raspbian image, containing Pure Data Extended [4]. We have tested guitar-processing patchs inspired by the Extended Guitar project [4], such as spectral delay, pitch-tracking FM synthesis and adaptive ring modulation with success. No gesture-tracking strategy has been yet attempted on the Raspberry.

4. DISCUSSION

The combination of active acoustics, miniature computers and robust gesture tracking hardware enable the perspective of an integrated, self-contained hybrid electroacoustic instrument. In the following, we present a discussion on the research questions enumerated in 3.1.

At the current stage of the project, we have succeeded in finding an optimal combination of sound drivers and their placement, producing a high-quality audio output as well as a rich, "acoustic instrument-like" sound radiation.

For sound capture, we have not yet found the ideal hardware. There are not many Hexaphonic pickups on the market and most of them are electromagnetic, intended for use on electric guitars, ruling out nylon-string classical guitars. The Ubertar electromagnetic hexa pickup chosen for our project suffers from noise and crosstalk. On the other hand, our tests with a hexaphonic piezo sensor (Graphtecth Ghost model) leads to compromises with the original acoustics of the instrument due to a poorly designed bridge system. High-quality, non-invasive hexaphonic audio capture remains a central issue for our project.

Hexaphonic vs. monophonic audio processing is another central question for guitar augmentation. Traditional guitar pickups output a summed mono signal from the six strings and the entire "guitar effects" paradigm is based on mono processing. Hexaphonic pickups enable not only individual processing for each string, but also precise feature extraction enabling to track the individual sounds and their related gestures. On the other hand, hexaphonic effects processing has yet to prove its efficiency in producing engaging sonic results. Hexaphonic processing is complex to manipulate, but also complex for the ear and the player. Based on our personal guitar playing experience, the guitar is cognised as a unified instrument rather than as a collection of six individual voices. In our case, we have come to support a combined approach: hexaphonic input is very useful for feature extraction and implementing adaptive audio effects, whereas mono (or stereo) processing is often musically efficient and supported by our monophonic active acoustic system on the guitar.

Looping processed audio back to the guitar's body creates a feedback loop, which must be kept in check. We have used two strategies to counter feedback: firstly detecting the most preeminent resonant modes of the guitar enables to neutralize them by filtering. Second, gain levels should be calibrated on the instrument's acoustic output. On the electromagnetic hexaphonic pickup and on "acoustic-like" gain levels our system does not give rise to feedback loops. However, the piezo system used o the classical guitar is prone to feedback, which reduces the types and frequency content of the processing used. Drastic eq cutting on the most protuberant modes are needed to keep the feedback in check. We are currently investigating alternative pickup placements to decouple the feedback loop.

Another type of feedback is the tactile sensation of the guitar vibrating against the body and hands. One advantage of an active acoustic system is that the electronic sounds driven into the instrument's body acquire a tactile dimension. The player can access multimodal (aural and tactile) feedback from the electronic sounds, enhancing the experience connectedness to the instrument.

Lastly, an important aspect of augmenting an acoustic instrument is its own sonic presence: the electronic sounds are bound to coexist with the acoustic output, at least as long as the instrument is being played and not used solely as a loudspeaker. A new dimension would be gained if it were possible to vary the instrument's acoustic output levels, allowing for the emphasis on acoustics or electronics as a variable musical parameter.

Figure 5. Performing with the active acoustic guitar; the sound drivers are not visible and all sounds emanate from the guitar itself. Leap Motion sensor is used for hand gesture tracking mapped to sound processing.

5. ELECTRONIC CHAMBER MUSIC

Instrument augmentation using active acoustics enables to create hybrid electroacoustic instruments where the electronic and acoustic sounds emanate from the same source. The acoustic image of such an instrument preserves a coherency in terms of sound source and radiation pattern, bypassing the loudspeaker-instrument dichotomy which appears when acoustic sound sources are amplified by external speakers (usually placed far from the original source in order to minimize feedback). The kind of structure-borne sound applications we are working with do not produce loud sound pressure levels: instrument construction and materials, sound driver specifications and feedback issues set strict limits to the gain levels. Active acoustics is thus more a technique for acoustic sound alteration than amplification.

Adding up these considerations advocates the use of active acoustics in a low-volume mixed music context, where electronics blend into acoustic music. In this setting, active acoustics may provide a pertinent way for mixing acoustics and electronics in a new way. Writing for traditional instruments is the core of contemporary composers' expertise, and it comes with little surprise that number of composers are interested in instruments augmented with active acoustics. Existing instrumentarium, instrumental skill and writing conventions can be employed in this context, whereas with novel electronic instruments areas such as scoring, virtuosity and performance practice must often be considered on a case-by-case basis.

We have termed our approach of music creation with active acoustics as "electronic chamber music" and have produced a series of works investigating its potential such as "Full Contact" for cello and electronics (2013), and "Tapage Nocturne" for double bass and electronics (2015). Related recent works from preeminent contemporary composers include Robert Platz's "Closed loop" for active acoustic guitar (2014), Sarah Nemtsov's "Running out of Tune" for two harpsichords and transducers (2013), as well as Adam Basanta's "This Machine Breathes to the Rhythms of its own Heartbeat" for piano and surface transducers (2014).

Both of the guitars presented in this article have been used in experimental chamber music practice and will be used in concert setting onwards from summer 2016. Our experience points towards a specificity of active acoustic guitars as opposed to the electric guitar effects. The standard effects produce rather unconvincing results, sounding like a poor imitation of an electric guitar. However, spectral processing (spectral delays, cross-synthesis, convolution) and adaptive effects (pitch-following filtering) and granular processing create a true enlargement of the instrument's acoustic output. The key factor appears to be to look for sound processes that produce contrast to the guitar's original acoustic sound.

5.1 Extensions towards other Instruments

Our project is to extend the research initially conducted on the guitar towards other instruments. At the moment, two projects are being developed in parallel adding active acoustics to a drum and double-bass. Each project is different by its aesthetical and technological motivations and problems.

The drum is a two-skin tomtom, where the upper skin is played by the hands and bears a contact microphone, while the lower skin is occupied by the sound driver. We use attack detection and envelope follower in max/MSP to map the incoming percussive audio to a Reaktor synthesizer patch. A large variety of sounds can be achieved, completely altering the drum's acoustic output.

The double bass project is conducted with Nathan Thomson, an Australian-born bass player with a long experience with African music. The research points towards the use of active acoustics to induce characteristic buzz sounds used in Tanzanian Ilimba (thumb-piano) instruments, acoustic distortions created by metal resonators and cobwebs – highly defined and desirable in the Tanzanian musical context.

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