Multi-point vibrotactile feedback for an expressive musical interface

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ABSTRACT

This paper describes the design of a hardware/software system for rendering multi-point, localized vibrotactile feedback in a multi-touch musical interface. A prototype was developed, based on the Madrona Labs Soundplane, which was chosen for it provides easy access to multi-touch data, including force, and its easily expandable layered construction. The proposed solution makes use of several piezo actuator discs, densely arranged in a honeycomb pattern on a thin PCB layer. Based on off-the-shelf components, custom amplifying and routing electronics were designed to drive each piezo element with standard audio signals. Features, as well as electronic and mechanical issues of the current prototype are discussed.

Author Keywords

Haptic musical interface, Vibrotactile feedback, Multi-point, Piezo actuators

ACM Classification

H.5.2 [Information Interfaces and Presentation] User Interfaces — Haptic I/O, H.5.5 [Information Interfaces and Presentation] Sound and Music Computing — Systems

1. INTRODUCTION

Looking at current musical interfaces, that of tactile feedback seems like a minor issue as compared to ergonomics or gesture mapping. Nevertheless, several recent studies (e.g. [25, 24, 4, 21, 8]) suggest that the development of musical skills strongly relies on tactile and kinesthetic cues: These would inform sophisticated control strategies that allow experienced musicians to achieve top performance levels (for example in terms of precise timing and accurate intonation), and enable expressivity and self-monitoring.

Indeed, while performing on acoustic or electro-acoustic musical instruments, an intense haptic experience is unavoidable, as well as highly relevant to the musical performance itself. Interaction with digital musical interfaces is also generally mediated by touch, however, while such interfaces can track input gestures, they generally provide haptic feedback only as by-product of their built-in mechanics, if any. This lack of physical experience at the performer's side alters the action-perception loop [19] that is normally established in tactual interactions with traditional instruments.

Touch is the most intimate of the senses, and indeed a more intimate connection with digital musical interfaces should strongly rely on the haptic modality. Qualitative aspects [11], as well as musical performance indicators [13] appear also to be affected by the haptic response of an instrument.

Following the increasing availability of low-cost sensors, actuators and computing systems, several prototype musical interfaces offering haptic feedback have been developed in the last few decades. Some of them simulate the haptic behavior of an acoustic or electro-acoustic counterpart (e.g. [7, 12, 22]), while some others aim at implementing new paradigms (e.g. [3, 20, 26, 1]), inspired to different extent by traditional musical instruments.

In [14] a wearable vibrotactile system is described, to render compositions made expressly for the sense of touch.

Research on haptic interfaces also exists, where feedback is used to teach, facilitate or enhance playing techniques [26, 16], or to help follow a score [15].

As for commercial products, only a few examples of haptic musical interfaces or instruments are currently found. The Yamaha AvantGrand digital pianos[1] offer vibrotactile feedback through transducers embedded in the instrument body, simulating the effect of strings and soundboard vibrating, and pedal depression. Syntact[2] is a contact-free interface, which provides contactless tactile feedback through an array of ultrasonic transducers.

The use of multi-touch surfaces in music started some years ago with the JazzMutant Lemur touchscreen controller and the reacTable, and the trend is now exploding with iPads and other tablets. While the possibility to design custom GUIs has opened to great flexibility in live electronics and interactive installations, such devices still cannot convey a rich haptic experience to the performer.

Aiming at investigating how performance in basic musical gestures may be affected by audio-tactile feedback, in a previous experiment some of the present authors took into account a finger-pressing task [17]: Somewhat similarly to what happens when learning a musical instruments, by relying on kinesthetic memory, subjects had to memorize and reproduce different pressing force targets with the best accuracy. Results show that audio-tactile augmentation allowed subjects to achieve the target forces with improved accuracy. The psychophysics of active touch for broadband vibrotactile stimuli was also investigated in [27, 30]. In another study [10] the perceived quality of a digital piano aug-

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[1] `http://europe.yamaha.com/en/products/musical-instruments/keyboards/hybridpianos/avantgrand/`

[2] Still unreleased as of January 2015, `http://www.ultrasonic-audio.com/products/syntact.html`

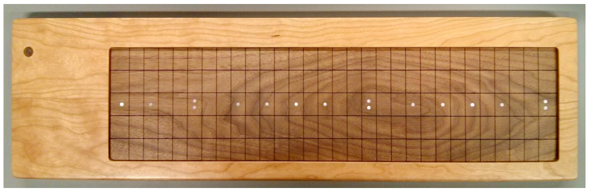

Figure 1: The Madrona Labs Soundplane

mented with vibrotactile actuators was tested according to different auditory and tactile feedback conditions. A partial preference for the combination of audio and vibrotactile feedback was found.

In this perspective, we argue that the addition of rich haptic feedback to future musical interfaces would enhance several aspects of musical practice, such as improved user experience, control and expressivity. For this reason, we decided to design an advanced vibrotactile feedback system to be used in a musical interface. Such augmented interface would then serve as a open and versatile framework, allowing experimentation with different audio-tactile mappings, and testing the effectiveness of vibrotactile feedback in musical practice.

2. DESIGN

Vibrotactile feedback as found in the current generation of touch-screen devices is affected by several limitations. Such devices usually make use of either an Eccentric Rotating Mass (ERM) motor or a Linear Resonant Actuator (LRA) coupled with the device body, which therefore vibrates as a whole. Also, these actuator technologies can only produce simple vibratory signals: ERM motors produce vibrations whose frequency and amplitude cannot be set independently, and show a considerable lag in response time; LRA conversely have improved response time, however they only vibrate at a fixed resonant frequency, not affected by the amplitude. Furthermore, with regard to touch input, current touch-screen systems cannot detect finger pressure[3], and often do not offer response times suitable for real-time musical applications.

As opposed to what described above, our goal was to implement distributed and localized vibrotactile feedback, with as little limitations as possible on the vibration signal in terms of temporal dynamics and spectral envelope. Being a very demanding objective, we started evaluating existing multi-touch interfaces that could be adapted to our purpose by adding a newly developed haptic layer. After doing some research, our choice fell on the Madrona Labs Soundplane.

2.1 The Madrona Labs Soundplane

The Soundplane, pictured in Figure 1, is an elegant-looking wooden musical interface that was first described in [18], and is now a commercially available product[4]. It provides a large multi-touch and pressure-sensitive surface based on capacitive sensing, and it offers high tracking speed.

The interface allows easy disassembly and is potentially open to hacking, which was required for our purpose. Moreover, Do-It-Yourself instructions are provided for building the original prototype version, with details on the used materials and construction solutions, as well as source code and patches for Max[5]. An online forum is also available to exchange advices for hacking and fine tuning. Furthermore, when we contacted the Soundplane inventor and mentioned our goal, he showed interest in the idea of implementing a haptic layer.

The interface patented capacitive sensing technology makes use of several carrier antennas, each sending a signal at a different fixed frequency. Separated by a dielectric layer, transversal pickup antennas catch these signals, which are modulated by changes of thickness in the dielectric layer due to pressure on the Soundplane surface.

In the commercial version, the generation of carrier signals and the decoding of the modulated signals are done internally by a DSP chip, while a USB connection sends three-dimensional touch data (x, y: surface coordinates, z: pressure intensity) to a host computer. Conversely, in the "analog" 8×8 DIY version all the digital signal processing is done in software by a host computer: Eight carrier signals are generated in Max and sent from the analog outputs of an audio interface, while the eight modulated signals are acquired by its inputs and decoded by a Max external to extract three-dimensional touch data.

It is worth noting that, despite its wooden finish, the Soundplane surface does not feel nor it behaves like a stiff wooden panel. Indeed its tiled touch pads are engraved and independent of each other, and they rest on a natural rubber layer enabling a certain extent of compression when pressed.

2.2 Construction

In what follows, we will refer to our haptic Soundplane prototype as the "HSoundplane".

The original Soundplane multi-layered design consists of a top tiled surface – a sandwich construction made of wood veneer, stuck to a thin Plexiglas plate and a natural rubber foil – resting on top of the capacitive sensing layer described above (made of carrier antennas, dielectric and pickup antennas). Since these components are simply laid upon each other and kept in place with little pegs built into the wooden casing, it is quite simple to disassemble the structure and replace some of the elements.

Ideally, vibrotactile actuators should be placed as close as possible to the touch location, in that way maximizing the vibration energy conveyed to the fingers. In our case that would actually mean that actuators should be embedded in the top surface, just below the wood veneer. As a compromise we chose to place our haptic layer between the top surface and the sensing components. However, such solution poses some serious challenges: the original flexibility, flatness and thickness of the layers above the sensing components has to be maintained as much as possible, so as to preserve the sensitivity and calibration uniformity of the Soundplane.

A review of actuator technologies suitable for musical applications is found in [20]. To implement a haptic layer for the Soundplane we chose a solution based on low-cost piezoelectric transducer elements, having the following cumulative advantages: below their resonant frequency, they have a response suitable to the vibrotactile range (5–1000 Hz [29]); they offer fast response times; they can be driven by audio signals; they are thin (down to a few tenths of a millimeter); they allow scaling up due to their size and cheap price.

In order to provide differentiated haptic information to multiple touch points, a large amount of densely distributed, individually driven piezo elements is necessary. To maximize the density of actuators, they have been arranged in a honeycomb pattern, which required to cut their original round shape into hexagons. As shown in Figure 2, the actuators were arranged so as to match the tiled pads on

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[3] With the exception of the just announced Force Touch technology by Apple.

[4] `http://madronalabs.com/`

[5] `http://cycling74.com/`

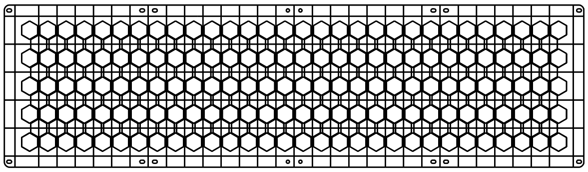

Figure 2: Arrangement of piezo actuators in a honeycomb pattern, matching the Soundplane tiled surface.

the Soundplane surface (see Figure 1): interleaved columns made of 5 or 4 piezo elements correspond respectively to a column of pads, or to intersections between them. It is worth noticing that this solution even exceeds the number of pads at the Soundplane surface, thus allowing for continuous feedback in sliding gestures even when crossing different pads.

To retain as much as possible the flexibility of the original surface – in this way allowing the sensors below to detect individual finger pressures – the piezo elements were wired via a *ad-hoc* designed flexible PCB with SMD soldering techniques (see Section 2.3).

To let the actuators vibrate, despite being sandwiched between the top surface and the sensing layer, the PCB with piezo elements was laid on top of an additional thin rubber foil, *ad-hoc* designed with holes corresponding to each piezo element. This solution also guaranteed to leave the overall flexibility unaltered.

However thin, the addition of the actuators layer alters the overall thickness of the hardware. For this reason we had to re-design the original top surface (a sandwich made of wood veneer, Plexiglas and natural rubber) replacing it with a thinner version. As a result, the thickness of the new top surface plus the actuators layer matches that of the original surface. In this way we could fit the new instrumentation into the original Soundplane wooden case.

Figure 3 shows an exploded view of the HSoundplane construction, consisting of nine layers.

2.3 Electronics

In order to provide effective vibrotactile feedback at the HSoundplane surface, some key considerations have to be made. On the one hand, the use of input audio signals gives great advantages in terms of versatility and richness of feedback. On the other hand, the voltage needed to drive piezo actuators – in our case up to 200 V – is not compatible with standard audio equipment. Moreover, as mentioned in Section 2.2, the piezo elements have been placed under each pad (32 × 5) and at each intersection (31 × 4), which makes for a total number of 284 elements, thus posing a non-trivial challenge from an electrical standpoint.

These observations lead to the following requirements, so as to drive all the piezo actuators. Being in the analog domain, having one separate audio signal per actuator would be clearly overkill, therefore we considered using a maximum of one channel per column of pads, that is 32 separate audio channels, which can be easily provided by e.g. a MADI interface. This already results in a limitation, for it implies that each group of 5 + 4 piezos – corresponding to a column of 5 pads and 4 intersections – would be fed by a single signal (see Section 2.3.2 for more details). To reach all of the actuators, each of the 32 channels has to be multiplexed with a 1:9 ratio (in this way slightly exceeding the overall number of actuators). Moreover, to comply with the electrical specifications of piezo elements, each audio signal has to be amplified by about a factor 100.

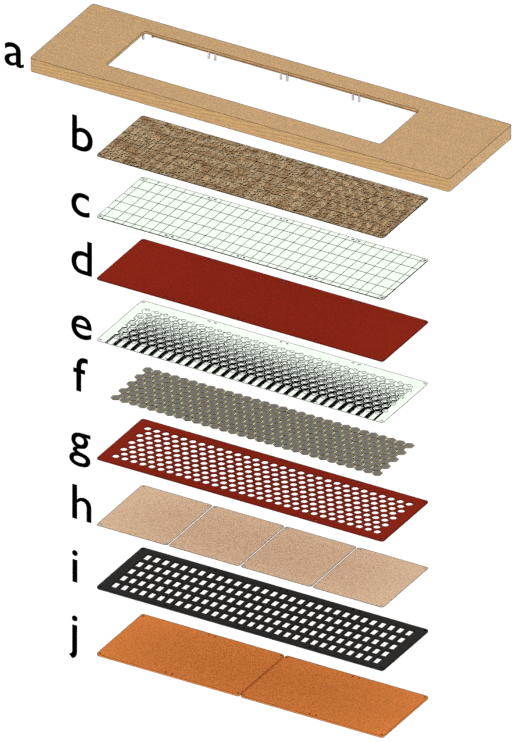

Figure 3: Multi-layered construction of the HSoundplane: a) wooden case; b) new touch surface (wood veneer, 0.5 mm); c) new Plexiglas plate (1 mm); d) new natural rubber foil (1.3 mm); e) flexible PCB (0.3 mm); f) piezo elements (0.2 mm); g) natural rubber holed foil (1.3 mm); h) carrier antennas (original); i) dielectric (original); j) pickup antennas (original).

Multiplexing continuous analog signals can be a delicate issue, since the end user must not notice any disturbance or delay in the feedback. Moreover, amplifying the already multiplexed signals would imply a huge number of amplifiers, while amplifying the original signals would require high voltage multiplexers, which are available in a limited choice, are expensive and more difficult to drive.

2.3.1 *Complete setup*

To satisfy the requirements and solve the issues pointed out above, we came up with a solution based on three key components: 1) Texas Instruments DRV2667 piezo drivers, that can be directly fed by audio input and drive a signal up to 200 V; 2) serial-to-parallel shift registers with output latches of the 74HC595 family; 3) high voltage MOSFET relays.

For the sake of simplicity, the whole output stage of the HSoundplane was divided into four identical parts, represented in Figure 4, each consisting of a flexible PCB with 72 piezo actuators (a), connected by a flat cable to a driver PCB with 8 audio-to-haptic amplifiers and routing electronics (b). In order to address the right actuators and synchronize their switching with the audio signals, a master controller (c) parses the control data generated at the host computer and routes them to the appropriate slave drivers.

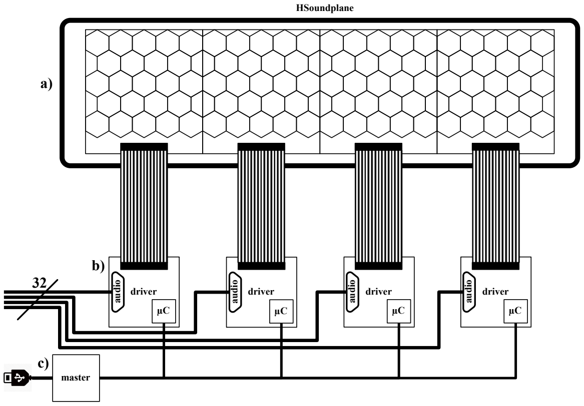

Figure 4: Overview of the complete actuators control electronics: a) piezo actuators on flexible PCBs (simplified view); b) slave PCBs with audio-to-haptic drivers and routing electronics; c) master controller.

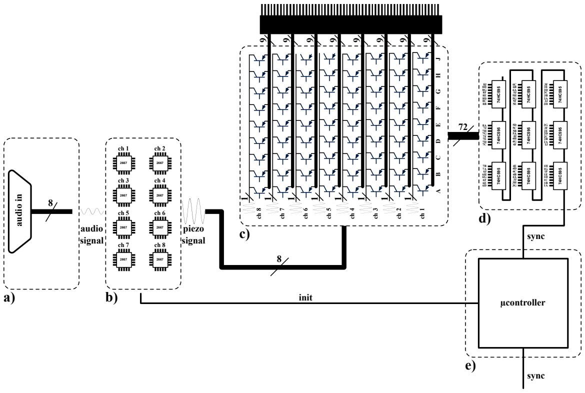

Figure 5: Overview of a slave driver board: a) 8-channel audio input; b) 8 piezo drivers; c) 72-point matrix of relays individually connected to each piezo actuator; d) relay control; e) microcontroller for initialization and synchronization.

2.3.2 *Driver board*

Figure 5 shows a slave driver board, which works as follows: Eight audio signals (a) are routed to the piezo drivers (b), where they are amplified to high-voltage and sent to a 8 × 9 relay matrix (c) which connects to each piezo actuator. This 72-point matrix is addressed by a chain of serial-to-parallel shift registers (d), commanded by a microcontroller (e).

At startup, the microcontroller initializes the piezo drivers, setting among other things their amplification level. When in running mode, the slave microcontroller receives routing information from the master, sets a corresponding 72-bit word and sends it to the shift registers, which individually open or close the relays of the matrix.

As shown in Figure 5, each amplified audio signal feeds a whole row of 9-points in the relay matrix. Therefore, each signal path is hard-coded to 9 addresses, which can be more appropriately defined as switching rather than multiplexing. Such fixed addressing is the main limitation of the current HSoundplane prototype: each column of 9 actuators can only be fed with a single vibrotactile signal.

2.4 Software

The original Soundplane comes with a client application for Mac OS, which receives multi-touch data sensed by the interface, and transmits them as Open Sound Control[6] messages according to an original format named "t3d" (for touch-3d). The t3d data represent touch information for each contacting finger, reporting absolute x and y coordinates, and force along the z axis.

In our prototype, these data are not only used to drive some audio engine, but also to activate the piezo actuators located at the corresponding x and y coordinates, and to drive them with vibrotactile signals.

2.4.1 *Control of signal switching*

In the current prototype, the synchronization between vibrotactile signals and the relay matrix happens at the host computer level. While vibrotactile signals are output by the audio interface, control messages are sent to the master controller via USB. The master controller parses the received messages and addresses the slave driver boards on a serial bus to set the state of relay matrices.

The choice of using a master controller, rather than addressing each driver board directly, was due to two reasons: first, properly interfacing several external controllers with a host computer can be complex; second, the perspective of developing a self-contained musical interface would require to get rid of a controlling computer and work in closed-loop. The presence of a main processing unit that receives touch data, processes them and generates vibrotactile information, is therefore a requirement in a mid-term perspective (see Section 4).

2.4.2 *Rendering of vibrotactile feedback*

The sense of touch is generally regarded as capable of perceiving vibrations in the 5–1000 Hz frequency range. Four mechanoreceptive channels have been identified in the skin, which mediate the mechanical aspects of touch [5]. The Pacinian channel is the most important for vibrotactile perception, as it determines sensitivity thresholds in the range 40–800 Hz (a U-shaped contour, with peak sensitivity between 200 and 300 Hz), and is sensitive to spatial and temporal summation.

In general, touch has been studied mostly as a receptive sense, by measuring the perception of vibrations in passive settings. However, the everyday experience of touch – including that arising from the performance on musical instruments – clearly shows that active touch (manipulation, exploration) is of primary importance. So far, only a few studies have investigated the perception of vibration in active touch and musical tasks (e.g. [6, 2, 9]). Aiming at overcoming the lack of knowledge in this field, recently some of the present authors reported novel results concerning the psychophysics of active touch for different pressing force conditions [27, 17].

Based on the current knowledge of vibration perception, and in order to optimize the output from the piezo actuators, vibration signals are first filtered with a bandpass filter (40–400 Hz). This also minimizes any sound spill, while maximizing vibrotactile perception. A low frequency boost is also available to compensate for the frequency response of the piezo actuators (see Section 3).

As it often happens with digital musical interfaces, the mapping possibilities between the users' gesture and audio output are manifold. Moreover, as opposed to common musical interfaces, the HSoundplane provides vibrotactile feedback to the user, and this requires to define an additional

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[6] `http://opensoundcontrol.org/`

mapping strategy. Since the actuators layer is part of the interface itself, we decided to provide the users with a couple of predefined vibrotactile feedback mapping strategies, while the sound mapping is left freely definable as in the original Soundplane. Two alternative mapping strategies are offered in the current prototype:

- One makes use of the sound output controlled by the HSoundplane: Audio signals are first filtered as mentioned above, and fed back to the actuators layer. This approach is straightforward and ensures coherence between the musical output and the tactile feedback, resembling what found in traditional musical instruments, where the source of vibration is also the acoustic source.

- A simpler mapping strategy relies on a pseudo-white noise signal, filtered as above, whose amplitude is set according to force data values. This approach has the advantage of maximizing the performance of the actuators and the perception of vibrations. Also, in a mid-term perspective, relying on the waveform memory provided by the piezo drivers, this mapping can be totally self-contained.

Currently we still have to evaluate the effectiveness of the implemented mappings. For instance, in the second one, being the produced vibrations independent from the sound synthesis, this may result in occasional perceptual mismatch between touch and audition.

3. MEASUREMENTS

Before the final implementation, the characteristics of different types of piezo actuators have been measured, and their performance evaluated, in this way guiding the choice of piezo elements to be used in the HSoundplane prototype.

Measurements were made with a Wilcoxon Research 736T piezoelectric accelerometer, connected to a Wilcoxon Research iT100M Intelligent Transmitter. The AC-coupled output of the transmitter was recorded as audio signals at 44.1 KHz with 24 bit resolution via a RME Fireface 800 interface.

The frequency responses of four different types of piezo elements were measured in the 10–2000 Hz range. For this purpose, we realized a scaled-down version of the HSoundplane layers, and placed the four actuators in correspondence of four pads of the top surface. The accelerometer was stuck to the surface with soft double-tape. Figure 6 shows a detail of the measured frequency responses in the 40–500 Hz range.

More measurements are still needed to assess the effective dynamic range of vibrations provided by different piezos, and their frequency response under finger-load condition.

In addition to such measurements, we informally evaluated the behavior of the different actuators by touch. Indeed the piezo elements having resonance at 4 KHz felt like the best of the group, both in terms of conveyed energy and low frequency response, thus confirming the measurement results.

Nevertheless, since each piezo driver has to feed 9 actuators in parallel, particular attention has to be paid to issues such as current consumption and heat dissipation. Among the analyzed actuators, the one resonating at 6.3 KHz has the smallest capacitance value, and therefore current needs, while the 4 KHz one has the highest. For this reason, as a starting point we chose to go for the piezo components resulting in less electrical issues, even though they are the least performing. However, in case their actual performance were not satisfying and new calculations showed that the piezo drivers can support a higher current load, they could be easily replaced.

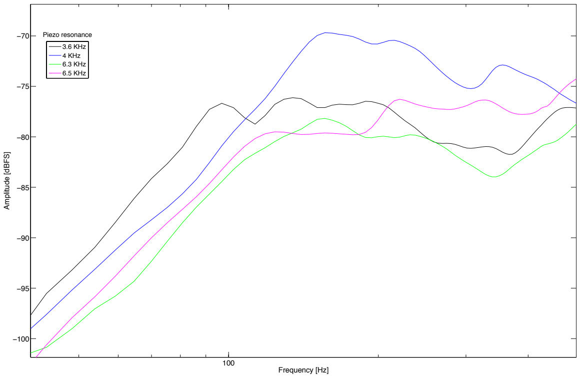

Figure 6: Vibration frequency response, measured at four different types of piezo actuators.

Vibrotactile cross-talk was informally evaluated by the authors during the development: Indeed we found that the HSoundplane is able to render localized vibrotactile feedback with unperceivable vibration spill at other locations, even when touching right next to the target feedback point. Quantitative characterization will be performed by measuring the vibration amplitude at non-feedback points.

Currently, time-domain measurements of the synchronization between audio signals and relay control are being carried out. The closed-loop latency from touch to the arise of vibrotactile feedback will be also evaluated.

4. PERSPECTIVES AND ISSUES

In a mid-term perspective we planned the development of an autonomous interface, able to generate vibrotactile feedback on-board while relying on an external computer for auditory feedback only. For this purpose, the touch information processed by the original Soundplane DSP chip could be directly sent to the master controller in our design, and used to route vibrotactile signals synthesized on-board or from pre-computed waveforms stored on the piezo drivers.

Currently, the development of new musical interfaces is mostly grounded on practice and intuition only, often leading to the production of one-of-a-kind prototypes. Conversely, we aim at a scientifically-grounded design of haptic musical interfaces. Parallel investigations on vibrotactile perception in musical tasks [27, 9, 17] are being carried out in our lab. Results from these ongoing studies will help optimizing the rendering of vibration and touch-to-vibration mappings in the HSoundplane and other haptic interfaces.

The designed solutions are currently being tested for isolating possible electronic and mechanical issues.

In addition, inspired by user experience studies in HCI, the HSoundplane will be tested in controlled experiments in musical practice context, aimed at evaluating the musician's playing experience. To this end, we will rely both on existing and new methodologies for the evaluation of musical interfaces (e.g. [23, 28]). We envision that rich vibrotactile feedback would make musical interfaces more accessible for hearing- or visually-impaired musicians, and therefore we will invite a pool of such subjects to the planned experiments.

5. CONCLUSIONS

We presented the HSoundplane, a prototype of musical interface based on the Madrona Labs Soundplane, which was augmented with multi-point vibrotactile feedback. Several constructive and electronic issues have been addressed in the current design to reach this goal. Nevertheless further optimization and evaluation are still needed.

The rendering of localized vibrotactile feedback is an open issue in current multi-touch interfaces, and we imagine it will become more and more relevant in the search for richer, more engaging interaction. We believe that at least some of the technological solutions described here can be of inspiration for the implementation of multi-point haptic feedback in future interfaces.

6. ACKNOWLEDGMENTS

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