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The Vibropixels: A Scalable Wireless Tactile Display System

Ian Hattwick[1,2] and Marcelo M. Wanderley[1,2]

[1] Input Devices and Music Interaction Lab,
McGill University, Montreal, Quebec, Canada,
ian.hattwick@mail.mcgill.ca, marcelo.wanderley@mcgill.ca
[2] Centre for Interdisciplinary Research in Music Media and Technology,
Montreal, Quebec, Canada

Abstract. The VibroPixels are wireless vibrotactile devices whose modular design allows them to be reconfigured for use in a wide variety of applications. Our wireless network implementation avoids both handshaking and packet acknowledgement in order to allow for reliable transmission of messages from a transmitter to large numbers of receivers, and utilizes a flexible two-part addressing scheme which reduces the number of wireless packets necessary to address arbitrary groupings of devices. Created within an interdisciplinary art-science research project, 145 Vibropixels were utilized in the premier of the artistic installation *Haptic Fields*. Recognizing that the artistic creation process often involves utilizing systems beyond their intended application, we designed our system to allow our collaborators to interact with and potentially modify the system on a hardware, firmware, or software level. Through interviews with our collaborators, we evaluated our system's ability to support the artistic creation process in light of Shniederman's principles for creativity support tools. While our collaborators mostly used and modified the highest level software tools provided to them, we argue that supporting lower level modifications may still be useful depending upon the time available to and knowledge of the user. . . .

Keywords: Tactile Display, Artistic Creation, Wireless Network, Vibrotactile

1 Introduction

The Vibropixels are a scalable, wireless tactile display system whose reconfigurable nature allows for use in a wide variety of applications. As the system was initially developed for use in professional artistic productions, we were concerned that it would support the artistic creation process as well as being suitable for use in professional public performances.

In this paper we describe the system as it was used in the artwork *Haptic Fields*, created by Chris Salter and Tez in collaboration with Ian Hattwick. *Haptic Fields* was premiered at the Chronus Art Center in Shanghai, China from July 9 - September 6, 2016. Based upon an earlier work by the artists, *Ilinx*, *Haptic Fields* is an immersive multisensory art installation with visual, sonic, and tactile elements [5]. In this work, visitors wear a garment with seven Vibropixels attached and navigate a large, dark space while experiencing a variety of tactile patterns.

1.1 Wearable Tactile Displays

Tactile displays systems have been created for a wide variety of applications, including navigational assistance [2], sensory substitution [1], and enhancing interaction with virtual environments [7]. Many tactile displays are either embedded in handheld devices [9] or in wearables limited to one segment of the body, such as a ring, glove, or belt [14]. Other displays are able provide stimuli over a large portion of the body, frequently taking the form of a jacket or vest [6]. However, it is difficult to create such a system that is both robust enough for use in public presentations and also inexpensive enough to scale easily.

Another challenge is that tactile display applications often have specific requirements for actuator locations. Lindeman presents a vest created to provide feedback to participant's interacting with a virtual environment [7]. One of their requirements was to provide feedback when an avatar collides with doorframes, necessitating actuators placed on those parts of the body most likely to contribute to such collisions.

The use of tactile displays in wearable form factors suggests the systems be embedded within a garment. Frequently, actuators will be distributed within the garment with wired connections to electronics which provide signals for driving the actuators as well as which allow for communication for a remote computer to control the display [13, Chapter 4, p. 11]. This architecture presents several problems for prolonged use. First, the wiring greatly impacts the garment's bulk, weight, and flexibility. Secondly, the wiring present potential points of failure as it often will be exposed to stress both when the garment is put on as well as in normal movements. Third, this construction can be time-consuming and expensive. Lastly, this architecture tends to locate the weight and bulk of the battery and wireless communications at a single point.

By switching to a system comprised of a monolithic, self-contained devices many of these problems are eliminated. However, the tradeoff is the increased size of the hardware at each actuator location. Therefore, ideal applications for the Vibropixels will be those which require a coarse distribution over the body rather than high spatial resolution.

1.2 Artistic Creation

In artistic contexts tactile displays have also been used in a variety of applications, including providing a tactile aspect to movies [6], providing performance instructions in music performance [4], and as an auxiliary voice in music compositions [3].

Creating systems for artistic performance

xisting interfaces

1.3 Artistic Production

The requirements which shaped the design of the Vibropixels grew out of our intended application of use in professional artistic productions.

One primary requirement was that the system be able to accommodate large numbers of actuators, allowing for the distribution of tactile stimuli across many simultaneous participants. The cost of developing and manufacturing the devices therefore became a priority. We also had an interest in supporting the social context of this kind of artistic experience. One way of doing so was the integration of LED lighting in order to allows participants to get a sense of the tactile stimuli being experience by other participants. Another was the integration of motion sensing which would allow future applications which transmit tactile information regarding other participant's movements.

Another primary concern in the systems design was both its robustness and ease of use. Artistic installations which last for weeks or months are often maintained day-to-day by untrained staff. The system should be not only robust enough to endure constant use throughout this timeframe, but also should not require any specialized knowledge to run, maintain, and repair in the case of failures.

Finally, we also had an interest in supporting the system's use over a wide variety of artistic works. Many applications for tactile displays may go unexplored due to the difficulty of creating such systems. Our intention was to create a system which would allow for easy reconfigurability, supporting a variety of applications both within artistic contexts as well as within the broader research community.

2 Technical Description

The Vibropixel system consists of four primary elements: the hardware implementation, the embedded firmware, the wireless communication implementation, and software tools for generating control messages. In this section we will discuss the first three elements; in section 3 we discuss the creation of software tools and user interfaces for use with the system.

2.1 Hardware Overview

The electronic hardware is built around an ATmega328PB microcontroller running at 8MHz, as shown in figure 1. For reasons described in section **??**, we also integrated four individually-controllable WS2812b RGB LEDs as well as a Freescale Semiconductor MMA8652 3-axis accelerometer. A Nordic Technologies nRF24L01+ 2.4GHz transceiver provides for wireless communication.

As the creation of vibrotactile stimuli was our primary concern, we examined a variety of tactile actuators in order to identify a solution that would be power-efficient, generate strong vibrations, allow for the creation of a variety of stimuli,

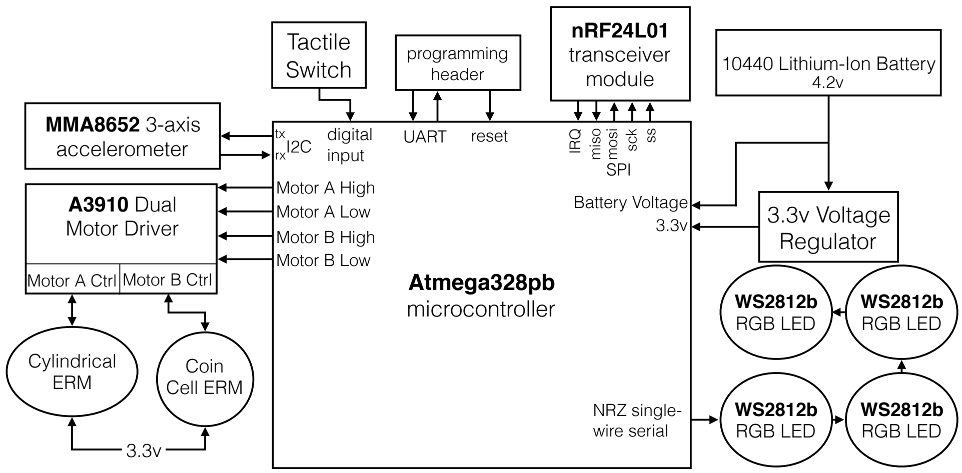

Fig. 1. A system overview showing the hardware configuration of a single Vibropixel.

and be cost-efficient. Our final design utilizes two different kinds of eccentric-rotating mass actuators which possess very different characteristics. The first is a pancake-type actuator that is highly-efficient in terms of power consumption and efficiency, and which creates a reasonable amplitude of vibration. We have found, however that this kind of actuator often responds very slowly, with a rise- and fall-time frequently exceeding 100ms.

In order to allow for the generation of stimuli which require faster response times, the Vibropixels also utilize a cylindrical-style ERM actuator. These actuators tend to be much less power-efficient, drawing three to four times as much current. However, they also respond much faster and are able to generate a higher peak amplitude of vibration.

The actuators are driven by an Allegro Microsystems A3910 Dual Half Bridge Motor Driver, which is controllable via PWM and also provides basic braking functionality by shorting both actuator terminals to 3.3v.

2.2 Firmware Overview

The embedded firmware on each Vibropixel consists of software modules for actuator control, LED control, power management, wireless communications (discussed in section 2.3), and system management. A module for use with the accelerometer is under development for future applications. The firmware was programmed in the Arduino IDE, which provides for an easy-to-install and easy-to-use hardware programming interface.

Signals for controlling the actuators are created onboard the Vibropixels using an actuator envelope generator with controls for attack time, sustain time, amplitude, and decay time. A secondary function we refer to as *oscillation generation* helps with minimizing wireless transmissions as well as providing for the

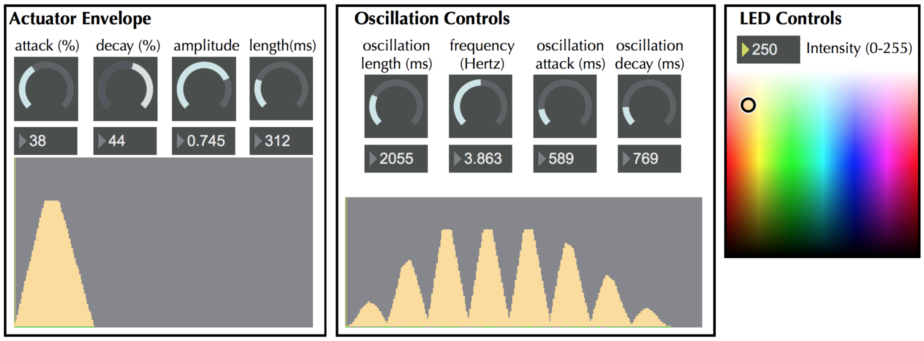

Fig. 2. A sample user interface which provides access to the control parameters used in *Haptic Fields*, as well as visual feedback regarding the current settings.

creation of more complex stimuli. The oscillation function allows for retriggering the actuator envelope generator at frequencies ranging from 0.01 to 30 Hz. Oscillation envelope controls allow for shaping the amplitude of the output from the actuator envelope generator, with controls for attack time, decay time, and over length of oscillation.

As the primary function of the LEDs is to provide a visual reference of the current amplitude of vibration, controls are provided for selecting the LED colour as well as for scaling the brightness of the LEDs relative to the vibration amplitude. Figure 2 shows a sample user interface which provides controls for the actuator envelope generator, the oscillation parameters, and the LED parameters. The interface also provides a simple visual feedback regarding the expected output of the current settings.

2.3 Wireless Communication Implementation

The design of our wireless network grew out of the requirements of creating a highly scalable system with no limit on the number of receivers. To accomplish this, our system consists of Vibropixels which act as passive receivers and transmitters which relay control messages from a central computer. One of our primary concerns was to minimize the number of wireless transmissions as our target applications could require many hundreds of receivers. To accomplish this, the system we created:

1. does not require hand-shaking between client and server devices in order to establish the network.
2. does not utilize packet acknowledgement capabilities which allow for confirmed packet transmission. Due to the fact that there is no guarantee that a particular control message will be received by its intended recipients, our implementation requires that each control message be entirely self-contained. All device settings and parameters are either set in firmware, permanently

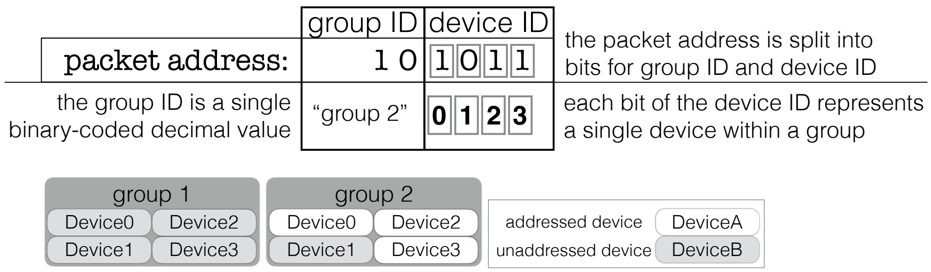

Fig. 3. A simplified depiction of the Vibropixel addressing scheme. In this example, the 6-bit address 101011 indicates the message is addressed to devices 0, 2, and 3 in group 2.

stored in non-volatile memory, or able to be contained within a single control message.

3. utilizes a two-stage device addressing scheme consisting of a group ID and a device ID. A control message can be addressed either a single group ID, or can also be broadcasted to all groups. Within each group, a message can be addressed to any combination of device IDs. This is accomplished by utilizing a device ID in which each bit represents a single device. If that bit is set high then the device it represents is being addressed; if the bit is set low, the device is not addressed. This scheme, as shown in figure 3, allows a single control message to be addressed to several devices.
4. allows for the creation of complex stimuli (as described in section 2.2) of durations up to 65 seconds with a single message.

3 Artistic Creation with the Vibropixels

Many considerations affect the ability of a hardware system to support the artistic creation process. In this section, we will discuss these considerations, the artistic creation process in *Haptic Fields*, and our ongoing work to facilitate the use of the Vibropixels in artistic contexts.

3.1 Artistic Creation with Digital Hardware Systems

One of the primary challenges of designing hardware systems for artistic applications is the definition of design requirements. In their overview of software engineering practices in the creation of interactive art, Trifonova et. al found that frequently "requirements are difficult to capture, vague at the beginning and frequently changeable" [12]. This is largely due to the exploratory nature of much of the artistic creation process, in which inspiration comes as much from the unanticipated consequences of a system's behaviour as from the intended results. One consequence of this, as Trifonova et. al found, is that artists are often interested in expanding their knowledge of software engineering in order to increase their ability to experiment with digital systems.

Considering that many artists will not possess the technical knowledge to program a system directly, Colin Machin argues that one way of facilitating artistic exploration is the creation of simple application-specific programming languages [8]. These can serve as a kind of middle-layer, providing the artist with the ability to change the system's parameters while shielding them from the underlying complexity. While Machin described these languages as potentially being structured like the BASIC programming language, in our experience developing application-specific tools in common new media programming languages such as Max/MSP or Processing can serve the same function of shielding the user from the system's complexity while also allowing them to control the system's parameters algorithmically.

However, the creation of these tools is a research area in itself. Ben Shneiderman argues that the proper design of software tools can facilitate the creative process, and proposed a set of design principles to assist in this, which include supporting exploratory search, providing rich history-keeping, and designing with low thresholds, high ceilings, and wide walls [11]. While Shneiderman's work is focused on the creation of software systems, these principles also suggest ways of structuring interactions with hardware tools. Supporting exploratory search, for example, might suggest the creation of multiple representations of system parameters, encouraging different perspectives on working with it. Providing rich history-keeping is particularly important for exploratory processes, giving the ability to locate and recall the results of earlier explorations.

Shneidreman's principle of designing with low thresholds, high ceiling, and wide walls corresponds most closely with the arguments of Machin and Trifonova et. al. This principle suggests that a system should provide an entry point for users with little technical skill, but also allow for access to lower-level parameters and functionality when appropriate. Wide walls refers to providing a range of functionality for solving application-specific challenges, minimizing the number of systems required to fulfill application requirements.

One example of the support of these principles in the music domain is *libmapper*, a software tool for creating relationships between sensor data from hardware control interfaces and music synthesis parameters [10]. A complete set of these relationships is often referred to as a *mapping*. In this software, available input and output parameters automatically populate the left and right sides of a GUI, respectively, and users are able to create arbitrary connections between them using click-and-drag techniques. While creating effective mappings is a challenging task, the software GUI allows for quickly and easily iterating through possible combinations of input and output parameters. In addition, once a connection has been made, an additional set of advanced parameters allow for mathematical and algorithmic transformations of the data between the input and output devices.

In the next sections, we will consider the ways in which the concepts described above manifest in how artists are able to interact with the Vibropixels.

3.2 The Creation of *Haptic Fields*

As our primary focus is not user interaction design but rather hardware system development, and our collaborators are fluent with new media software creation tools, we chose to focus on making the system easy to modify rather than attempting to create a fixed user interface. As described in section 2, the system utilized in the creation of *Haptic Fields* is comprised of four elements: the hardware architecture, the firmware, the communication protocol, and software tools for generating control messages. Many of the design decisions for each of these components were made explicitly to facilitating modification and programming of the system by our collaborators: the user interface was created in the popular multimedia programming language Max/MSP; the communications protocol was documented and communicated to our collaborators so that they could program alternative user interfaces for generating control messages; and the firmware was programmed in the Arduino IDE as many artists are familiar with working in that environment.

Following the initial public presentation of *Haptic Fields*, we interviewed our artistic collaborators in order to ascertain how they interacted with the system's components and the software tools we provided. In particular, we were interested in when components were used as-is, and when they were used as the basis for modifications. The components and tools we provided them and their use is as follows:

1. *Hardware implementation:* Various iterations of the Vibropixels throughout the prototyping and development stages.
   Use: The Vibropixel hardware was not presented to our collaborators as a development platform, but as a fixed hardware configuration, and in general was used as such in the creation of the work. However, for the final artwork 12 Vibropixels were utilized to create permanently installed ambient lighting. For this purpose, they were modified to accept power from a DC power supply, and hung from the ceiling of the installation space.
2. *Firmware:* Various iterations of the Vibropixel firmware developed in the Arduino IDE were provided.
   Use: While our collaborators did look at the firmware provided to them, they did not modify it or use it to increase their understanding of the system.
3. *Wireless communication protocol:* Written documentation of the wireless protocol and the control message structure.
   Use: The documentation was used to help in the creation of control messages independent from the GUI provided. However, the majority of the control messages were created with the software GUI with the modifications described below.
4. *Software Tool:* A software abstraction programmed in Max/MSP which accepted control messages and formatted them correctly for wireless transmission.
   Use: Used as intended, and not modified.
5. *Software Tool:* A simple software GUI programmed in Max/MSP for changing control parameters for the Vibropixels. Although the GUI shown in figure

2 was developed after the conclusion of *Haptic Fields*, the parameters are the same as those used in the earlier GUI.
Use: Used as the primary interface for exploring the functionality of the system as well as for creating control messages in the final composition. Various modifications were made during the creation process, including: adding support enabling a MIDI keyboard to send control messages to individual Vibropixels; adding algorithmic processes to transform device parameters over time; adding functionality for receiving control messages from external software controlling the progression of the composition.

6. *Software Tool:* A software GUI programmed in Max/MSP for generating device addresses in the format described in section 2.3.
Use: Used as-is to generate device addresses for both the creation of the work and in the final composition. Modifications were made to allow for algorithmic generation of device addresses, and for receiving control messages from external software controlling the progression of the composition.

From these responses we can see that our collaborators primarily interacted with the highest level software tools provided to them. While the documentation of the control message structure did allow for them to create some control messages, time pressure led them to revert to using the provided GUI. As one of our collaborators reported, "we did look at the documentation but I think at that point we were just trying to get things going and just wanted something as intuitive as possible." While part of our strategy for creating wide walls and high ceilings remains providing access to interacting with each of the system's components directly, it is clear that time pressures will often drive users to those tools which most closely match with their existing knowledge and preferences. However, the ability of a simple modification to the hardware to remove the need for a separate system to provide ambient lighting suggests that access to the the individual components remains valuable, but the ability to take advantage of this access is contingent upon time, knowledge, and the complexity of any necessary modifications.

A frequent comment in these interviews which indicates the need for lower thresholds was the desire for visualizations of system behaviour, such as that "it would be useful to have some way of understanding the correlations between the different envelope parameters", a problem we addressed in the creation of the GUI shown in figure 2. Another desire expressed was for a "visualization of groups . . . a top-down representation" of the current state of the system.

Comments such as these also made it clear that the lack of visual representations of the system's behaviour as well as the layout of the software tools negatively affected the users exploration of the system – "the tools at the software level could have been more intuitive in framing the paradigm . . . it was very difficult for us to get our head around having to trigger the envelopes all the time . . . some of the stuff could have remained under the hood . . . and the more generalizable parameters, amplitude, colour, intensity of the RGB channels, the oscillation features, those things could have been marked out more clearly to use them more creatively."

3.3 Facilitating Use of the System in Other Artistic Works

One of the goals was for the Vibropixels be suitable for use in a variety of artistic and research applications, and several such projects have been on-going since the initial public presentation of *Haptic Fields*. Development of the various components of the system is ongoing, and our goal is to build upon our prior experience to enhance the system's ability to support these projects. In this section we will discuss several development strategies and the ways in which they engage with Shneiderman's principles.

The creation of a new software GUI to lower the barrier to entry is one ongoing development. Figure 2 shows the current implementation, which takes into account our collaborators request for visual feedback of the interactions between actuator envelope and oscillation parameters, and also groups the controls in a way which makes their relationships clearer. While we remain focused on hardware development, we are also working with our collaborators on the creation of visualizations to provide feedback regarding the spatial distribution of multiple Vibropixels, and to provide a real-time visualization of vibration amplitude for the whole system.

Several aspects of the Vibropixel hardware are in development, including independent control of the two motors as well as the use of the accelerometer. While we are striving to use conceptually simple implementations for these aspects, their interaction with other aspects of the system can lead to complex behaviours. To assist in their use, we are planning on creating presets fixed in firmware which provide immediately useable settings. In addition, we are going to provide software tools providing access to each aspect's parameters as well as providing visual feedback regarding the current state of the system.

As we saw in *Haptic Fields*, simple hardware modifications can allow for implementing functionality outside of the Vibropixel's intended use, preventing users from needing to integrate additional systems into their application. To assist in this, we are planning on a hardware revision which provides access to unused microcontroller pins, providing additional analog inputs for reading external sensors and allowing for communicating with other digital modules using protocols such as I2C and UART. While most applications using these pins will need firmware revisions, we also plan on building into the standard Vibropixel firmware support for basic functionality, such as using analog sensor data to control actuator vibration.

4 Conclusion

In this paper we have presented a description of the Vibropixel system as used in the artwork *Haptic Fields*, and a discussion of the ways in which the system supports the artistic creation process. While our focus has been on artistic applications, much of the discussion is equally applicable to other research applications which could utilize a tactile display system. In particular, Shneiderman's principles which we have focused on arose out of work on creativity and innovation across disciplines including engineering, research, and media [11]. The observations we have made regarding our collaborator's use of our system, therefore, should be of interest to the designers of tactile display systems in other collaborative contexts.

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