Design and Implementation of a Whole-Body Haptic Suit for "Ilinx", a Multisensory Art Installation

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ABSTRACT

Ilinx is a multidisciplinary art/science research project focusing on the development of a multisensory art installation involving sound, visuals and haptics. In this paper we describe design choices and technical challenges behind the development of the haptic technology embedded into six augment garments. Starting from perceptual experiments, conducted to characterize the thirty vibrating actuators used in the garments, we describe hardware and software design, and the development of several haptic effects. The garments have successfully been used by over 300 people during the premiere of the installation in the *TodaysArt 2014* festival in The Hague.

1. INTRODUCTION

Since E. H. Weber's experiments on the sense of touch in the early 19th century (see e.g. [1]) various new fields of sensory research have been established, and principles of human haptic perception have been implemented in virtual scenes, electro-mechanical interfaces, as well as in robotic and bio-mechatronic systems. Nevertheless, prevailing studies remain mostly in engineering or psychology contexts where artists have little access to neither the research nor the tools developed. As a consequence many of these techniques that could have major artistic impacts are confined to technical academic conferences and papers exclusively, as they are not implemented in practical applications, and not incorporated into the vocabulary of artistic expression. The use of haptic technology in a new media art context is a promising area of artistic exploration that lies at the crossroads of engineering, info communications, neuroscience, and art.

The work described in this paper is a successful attempt at exploring this area. It is the result of a multidisciplinary

collaboration of haptic researchers, fashion designers and interactive artists, with the goal of creating a vibrotactile augmented garment to be used in "Ilinx", a multi-sensory art installation blending sound, visuals and whole-body vibrations. The design process and technical challenges behind the development of the haptic technology embedded in the garments will be described, together with the implementation of a vocabulary of haptic effects used during the installation.

The garments designed for "Ilinx" [1] illustrate a novel performance system that is able to convert exterior information and translate it into corporeal sensations. The mental manifestations and ideas that arise from the uncanny sensation of shifted proprioception can help to increase the personal awareness of the perceptual space that we occupy in our everyday life, and thus generate a sense of re-embodied presence, reminding us that not everybody feels the same in his or her own skin.

2. ACTUATOR CHARACTERIZATION

The initial phase of the project was dedicated to the choice and characterization of the vibrating actuators to be embedded in the garments. Several factors were clear since the early stages of the project: garments had to be wirelessly controlled (hence battery powered), light, robust and relatively inexpensive but capable at the same time of displaying interesting haptic effects.

We evaluated several different kinds of actuators for use in this project, including eccentric mass (ERM) rotating motors, linear resonant actuators, and tactile transducers. Our primary concerns for choosing an actuator were ease of implementation, price, and size. In particular we looked closely utilizing tactile transducers, which consist of a voice-coil driven by an audio signal (or any AC signal). In our experience the ability of this kind of actuator to respond to a broad spectrum of frequencies provides more flexible tactile stimuli. We chose to utilize ERM motors instead, however, for several key reasons. The first is that we knew in this project that we would be driving large arrays of actuators and we recognized the difficulty of working with a large number of audio signals. ERM motors have the

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[1] `http://phonemena.net/ilinx/`

benefits of being driven by DC (and hence able to be controlled by PWM signals), available in small form factors, and inexpensive due to their ubiquity.

2.1 Physical Characterization

In order to be able to proficiently design tactile effects to be displayed through the augmented garments, a full characterization of the actuators had initially to be performed, both from a physical and perceptual point of view. This characterization had been conducted in a previous work by some of the authors (Frid et al. [2]). The results are briefly summarized in the next sections.

We performed several measurements to provide an amplitude and frequency characterization of the motors. An Arduino Uno board connected to an IC unit was used to generate the PWM signal needed to drive the motor; a PCB 352C23 [2] 1-axis accelerometer was fixed on the top face of an accelerometer using petro-wax (Fig. 1). We recorded actuator vibrations at 192 *kHz* for 10 distinct duty cycle values of the PWM signal (ranging from 0.2 to 1.0). For each duty cycle step, we measured amplitude and average peak frequencey (Fig. 2) as well as ramp-up- and ramp-down time, i.e. the time need for the motor to go from a full-stop to target vibration amplitude and vice versa (Table 1).

As seen in Table 1, ramp-down times were measured to range from 400 to 610 ms, while ramp-up times were constantly below 15 ms for all PWM duty cycles. Fig. 2 shows a clear correlation of both amplitude and frequency to duty cycle value; as a result, these two parameters can not be separately controlled.
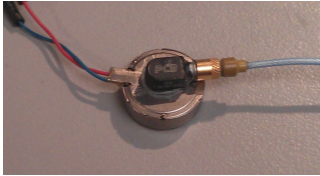

Figure 1: PCB 352C23 1-axis accelerometer fixed to the actuator.

Table 1: Ramp-down times for different duty cycles

Duty cycle	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
t (ms)	400	490	540	580	580	600	600	610	610

2.2 Perceptual Characterization

We conducted [2] two pilot experiments with a total of 8 participants (4 male & female, aged from 21 to 31 years old) for Experiment 1, and 10 participants (5 male & female, aged 21 to 31) for Experiment 2. In Experiment 1 we investigated vibrotactile absolute threshold for 5 discrete duty cycle steps (0.1 to 0.5). For this test, the actuators were placed on the back of the torso, symmetrically about the spine. An elastic Velcro® band was used to guarantee
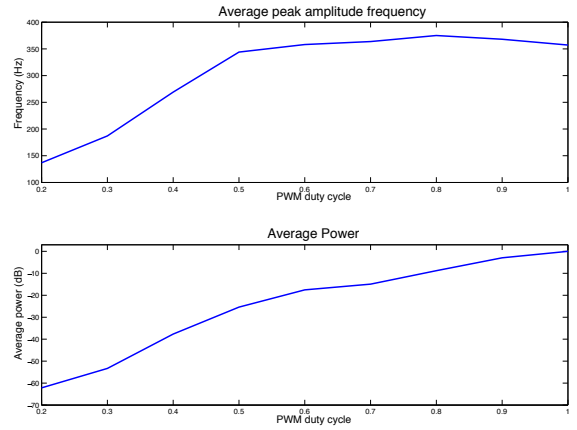
Figure 2: Average peak amplitude frequency (top) and RMS amplitude (bottom) at each discrete PWM duty cycle step from 0.2 to 1. Both these analyses were performed up to $1000\,Hz$ in the original spectrum, which is the upper limit for tactile perception. The average peak amplitude is a weighted average of the most significant frequency peaks found in the spectrum. The frequency range varies from 140 to $380\,Hz$. Average power is expressed in dB, with maximum amplitude used as reference power.

constant contact between actuators and skin. Participants had to wear headphones presenting pink noise, and were asked to report if they could perceive a 500 ms stimulus at a random duty cycle value.

In Experiment 2, we investigated the ability of participants to discriminate 500 ms long stimuli at different duty cycles, using a two-alternative forced-choice (2AFC) paradigm. With the same apparatus as in Experiment 1, participants were asked to perform "same" or "different" judgements on 81 stimuli pairs of various intensity levels presented in a randomized order.

Results from Experiment 1 indicated that stimuli with a duty cycle equal to or greater than 0.2 can be perceived more than 50 % of the times. Stimuli at 0.1 duty cycle were only perceived 4.2 % of the times. Table 2 summarizes the results from Experiment 2. The required difference in duty cycle for discrimination between two stimuli was found to be a function of the absolute value with reference to the duty cycle scale (0.2-1.0); a larger duty cycle difference is required for a stimulus in the upper duty cycle range than for a stimulus in the lower range. Overall, to ensure robust discrimination, only pairs with duty cycle differences greater than or equal to 0.3 should be used; as seen in 2, such pairs can be perceived as different above chance level.

Table 2: Correctness for different duty cycles. For duty cycle differences greater than 0.3, correctness is above chance.

Duty cycle difference	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Percentage	26	38	55	63	81	83	90	95

3. GARMENT DESIGN

3.1 Preliminary Tests

Early ideas of the wearable prototype were informed by previous work on vibrotactile augmented garment ([3], [4]) and by modular designs of vibrotactile systems developed by the authors and collaborators ([5], [6]). Moreover, a thorough review of literature on perceptual acuity and spatial resolution of the sense of touch at different loci (i.e. [7]–[11]) and of emergence of tactile illusions ([12], [13]) was carried on. This allowed us to have clearer picture of the physiological limitation inherent to the skin the body-parts we investigated during our tests, and at the same time to leverage tactile illusion in order to achieve a wider range of effects.
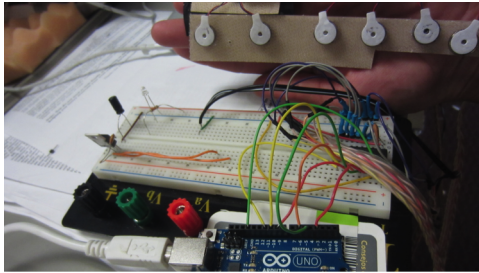

Figure 3: Early prototype using a Dual-Lock Velcro strip.

The first wearable prototype consisted of six pager motors mounted on a 3M Dual Lock velcro strip (Fig. 3). Prototyping with the velcro tape proved rather useful for defining salient distances betweeen individual actuators and receptive fields of the body, as the motors could be easily mounted and rearranged along the tape. During this early test phase, the critical distance between two actuators was evaluated by applying Weber's 2-point discrimination threshold technique: actuators were placed close together at first and then rearranged to increase the distance in-between them until two distinct vibrotactile sensations could be felt.
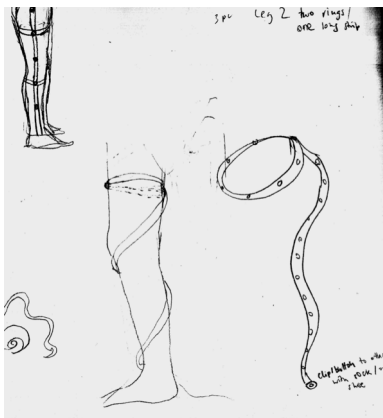

Figure 4: Sketches of possible actuator arrangement using detachable fabric strips.

In order to find the most appropriate receptive fields for stimulation, the actuator strip was applied to various different body parts, such as legs, stomach, back, inner and outer arms, neck and torso. The most salient sensations were found to be when the strip was either placed like a belt around the stomach, put along the outside of the leg, or twirled around the leg. These findings inspired the early sketching shown in Fig. 4.

Vibrations on the throat and neck felt very intense and almost uncomfortable, but spatial acuity was very high at these loci. By the means of these explorative studies, we have found that six actuators were enough to induce a continuously sensation that mimics movement along the arms and legs. Initially, sets of 2x4 actuators were believed to be necessary to convey specific activation patterns, however, the more economic solution of six actuators proved to be just as efficient. We believe that for certain receptive fields on the body as few as three actuators could induce the illusion of a continuous sensation along the skin.

3.2 Garment

Our preliminary tests led us to choose to place actuators in strips of six down the length of both arms and legs as well as in a circle around the torso. After several iterations garments were developed consisting of two chap-like leggings and a single garment with sleeves which are open down the length of the arm. Velcro straps were used to secure the sleeves to the arm in three locations and the leggings to the legs in four locations. In addition a wider velcro strap was used to secure the main body of the jacket to the torso. The open sleeves and leggings came with the advantage of being easy to put on and take off while holding actuators tightly to the body.

3.3 Hardware

The electronics for each garment consist of five circuit boards on each limb segment (two arms, two legs, and torso) and a single central processing unit. Each limb segment's circuit board contains power regulation, a 9DoF movement sensor consisting of 3-axis accelerometers, gyroscopes, and magnetometers, and a microcontroller for generating control signals for that segment's six motors. The central processing unit, as seen in figure 6, consists of a BeagleBone Black (BBB) microprocessor running an embedded distribution of Linux and a WiFi dongle. The BBB is responsible for transmitting and receiving messages over WiFi and routing incoming messages to the appropriate motor driver board.

As noted above the ERM motors have a prolonged ramp-down time. In order to compensate for this motor driver circuits were implemented that feature a 'braking' function which creates a short between the two motor terminals. This braking function is called for 100ms every time the PWM value of a motor's control signals transitions from a non-zero to zero value.

One key concern of the costume designers was that the motors be attached to the garments in such a way as to minimize the impact of the wiring on the garment's flexibility. The ethernet cables connecting the driver boards to the BBB had their external covers removed for this reason, and we chose to use conductive thread for connecting the motors to the motor driver boards on the limbs segments. It

Figure 5: The final version of the garment. The actuators are clearly visible on the two leg modules and on the jacket (sleeves and waist). The green labels show the name of the modules as they are referred to in Sec. 4.2.
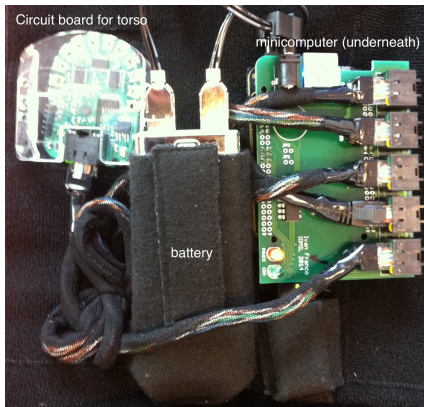

Figure 6: A driver board (left side) connected to the custom cape designed for the Beaglebone Black (BBB) central unit.

was also necessary to find a way to securely attach the motors to the garment which would also provide for a close fit between the motors and the body when the garment was worn. We created a 3D-printed housing for the motor (shown in figure 7) which contained three circular mounting points for sewing to the garment. The wires connecting to the motor were soldered to ring terminals which fit into cutouts in the housing, and then conductive thread was embroidered around both the holes in the housing and the ring terminal, fastening the housing to the garment and making an electrical connection at the same time.

Figure 7: 3D printed housing for connecting the motors to the garments.

4. CONTROL SYSTEM

4.1 System Architecture

The control of the system is relayed through a central processing unit based on the Beaglebone Black (BBB), a popular single-board computer with a 1GHz ARM Cortex-A8 processor. The BBB controls each of the individual driver boards through a custom PCB add-on, which implements a standard SPI bus. This SPI custom board is mounted directly on the BBB board and provides connectivity and power to each of the five driver boards through standard RJ45 connectors. Power is provided by a battery with two independent outputs, one plugged to the BBB and another to the SPI board (which also powers the driver boards), in order to share load and avoid possible power spikes in each of the subsystems.

The BBB is also connected to a local wireless network through a small WiFi USB dongle, so that each garment can be controlled by any other device on the same network via a messaging system based on the Open Sound Control protocol (OSC). In practice each garment can be understood as an individual OSC server, to which commands can be sent through an unique IP address. Additionally this self-contained system can be monitored and controlled through a *ssh* connection via standard Unix shell, through which it is possible to check execution results, manage running processes or audit the system's processing load.

4.2 Message Namespace

As shown in figure 8 the BBB is constantly running a python script that processes the incoming OSC messages and relays the respective command to each of the five driver boards through the SPI bus. The messaging system implements an abstraction layer through a namespace in which driver boards are associated to particular body segments according to the following convention (see Fig. 5):

- /ar: Right Arm
- /al: Left Arm
- /tf: Torso
- /ll: Left Leg
- /lr: Right Leg

Individual motors are addressed through a normalized value which represents the motor's location on the body segment, which can be discretized with an approximation to
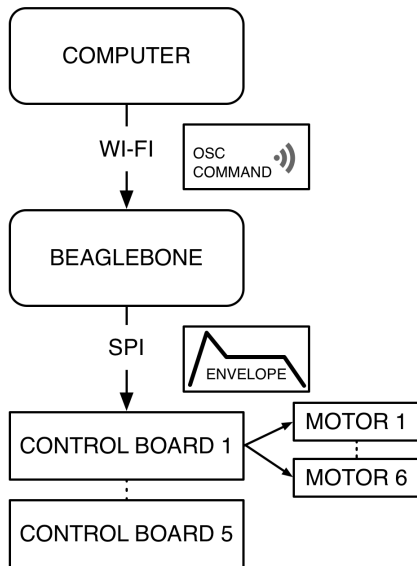
Figure 8: Signal flow of the system from the mainframe computer to the individual motors on each garment.

the nearest motor. This approach also allow for an arbitrary number of motors on each body segment, which might be scaled up or down according to specific application needs. The rest of the message is composed of an amplitude envelope with the intended response for the triggered event over time. A pseudo-message should contain the following data:

```
[limb, normalized motor position, attack
time, decay time, sustain level, release
time]
```

A practical example of sending an envelope to the middle motor of the left leg would be similar to:

```
/ll 0.5 250 500 0.7 250
```

This protocol allows for the generation of the control signals for the motor to be located on each driver board while the higher-level definition of haptic effects takes place on a remote computer. While it could have been possible to define and embed higher-level effects directly on the hardware system, this simple and effective control protocol permits users to design their own effects and control the system with many different types of software. In this project these effects were programmed in *Max/MSP*, a modular programming language oriented to music and media, and integrated into the performance control mainframe. This allowed for an easy and accurate synchronization between haptics and audiovisual events happening throughout the installation, which were also controlled though a Max-based software.

5. HAPTIC EFFECTS

We were interested in discovering and defining specific haptic effects to utilize during the composition process. We identified two main categories of effects to implement using this system: discrete and continuous. *Pokes*, *Buzzes*

and *Sparkles* fall into the first category. The first two effects are achieved through a simple activation of one or more spatially close motors. A *Poke* is implemented sending a sharper envelope message, while a *Buzz*-envelope has longer attack and decay times. The *Sparkles* effects consist of random actuation of actuator all over the body, or limited to one specified limb. The key differentiator of a discrete effect is that each instance of the effect is perceived as occurring at a single location on the body.

Continuous effects, on the other hand, use a combination of motors to create sensations that are perceived as moving on the body, and they rely on a precise pattern of actuation. The *Snake* effect requires the definition of a starting and ending point, duration, intensity and overlap factor (i.e. overlap between subsequent motor activations). An illustration of the effect is depicted in Fig. 9. Several other continuous effects were created. A wave effect reproduces the effect of a wave traveling horizontally or vertically across the body and effected by a sequential, overlapping activation of contiguous motors on a body segment. A variant of this is a spin effect in which the motors on the torso are activated in a continuous loop.
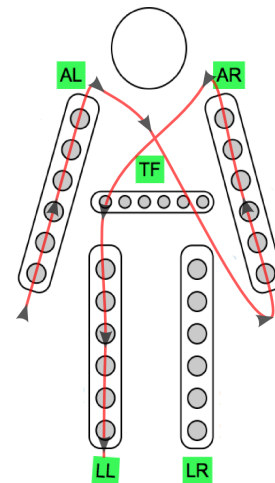

Figure 9: The representation of the garment in *Max*. The red path shows the actuation pattern of the *Snake* effect: a wave of vibrations traveling along the limbs, following a specified order.

6. PERFORMANCE

A brief description of the installation is provided in the following paragraphs, together with participants' feedback collected through short, informal interviews at the end of the installation.

More information regarding the garments' use in the installation as well as an overview of the installation itself will be provided in forthcoming publications.

Here we will instead focus on a few details pertaining to the perception of haptic effects.

The initial presentation of "Ilinx" was from September 25-28 at *TodaysArt 2014* festival in The Hague. Over four

days more than 300 visitors experienced the immersive environment while wearing the garments. The installation was divided into two sections. In the first section, participants enter the pitch-black room hosting the installation and are instructed to seat on the ground. The suits get activated and produce a vibration pulse effect, which is synchronized to a bell-like sound produced by quadraphonic speakers. The duration of this section is of roughly 10 minutes, and new sonic material is progressively introduced throughout the section. The second section starts with the appearance of faint lights, and at this point participants are free to stand and explore the room, while more visual and sonic effects appear. Vibration pattern matching sound and light effects in the room continue to be delivered through the suit.

Our experience using the system during the installation demonstrated vividly that the fit of the suit determined how effectively the actuators' vibrations were transferred to the body. In particular, getting the jacket tight enough around the waist for the vibrations to be as perceptible as they were on the limbs was difficult.

6.1 Participants' Feedback

Six informal interviews involving volunteer participants were conducted right after the installation. From the feedback we collected we could extrapolate the following main points about participants' perception of the suits and the haptic effects:

- Participants experienced different degrees of satisfaction concerning the tightness of the suit. Some of them found it too loose, while others judged the tightness to be good enough to guarantee constant actuator-skin contact.

- Even when the suit size perfectly matched participants' body-size, the actuators on the back were still too lose for participants to perceive them clearly;

- Participants consistently underestimated the number of actuators embedded in the suit (responses varied from 10 to 20). This might be due to the lower spatial resolution of the skin in targeted areas;

- Vibrations were felt more clearly in the first section of the piece. In the second section, when participants were standing and walking in an environment full of rich auditory and visual stimuli, the focus shifted from the tactile sense to the other senses.

Overall, participant enjoyed the installation, judging it surprising and engaging. They agreed that, in the body parts for which a sufficient level of tightness was reached, vibration effects could clearly be perceived. They perceived haptic effects such as the *Snake* as continuous vibrations travelling across the body. This suggests that the haptic effects we designed were accurately rendered through the suits.

Figure 10: One visitor at *TodaysArt 2014* wearing the final version of suit.

7. CONCLUSIONS

We presented the outcome of a collaborative project which resulted in the creation of a six tactile-enhanced garments to be used in "Ilinx", a multi sensory art installation. The creation of these garments was driven by a perceptual research-based methodology as well as by artistic and functional considerations.

In this paper, we focused on the haptic research which motivated the choice of actuator placement and effect design, and on development of custom hardware and software solution that were embedded in the suits. The technology we developed proved to be reliable and robust, and capable of allowing the creation of a variety of haptic effects. Given the time constraints, and the practical demands due to the needs of the artistic project, only a small fraction of the expressive potential of the suit could be explored. Several forthcoming projects based on the use of the suits will enable us to take full advantage of this potential and expand the vocabulary of available haptic effects.

Acknowledgment

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