The Creation of Hardware Systems for Professional Artistic Productions

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Abstract

This dissertation examines the challenges of creating digital musical instruments (DMIs) and other hardware and software systems that are intended for use in professional artistic productions. While the design of any DMI is not a trivial task, moving new instruments to the professional concert stage presents an additional set of challenges that encompass issues of technical design, use in artistic practice, manufacturing, and long-term usability. Although DMI designers often describe these challenges in accounts of their practice, existing overviews of the DMI design process primarily remain focused on issues of device functionality.

To address this gap, I present a framework consisting of seven design aspects: functionality, aesthetics, support for artistic creation, system architecture, manufacturing, robustness, and reusability. Each aspect presents a different perspective on the challenges of designing DMIs for professional artistic productions, and requires the establishment of a set design requirements to meet these challenges. In practice, the design requirements of different aspects will often conflict, and creating solutions to solve these conflicts is essential to the design's success.

The creation of this framework draws upon my experience in the creation of three hardware systems: The Prosthetic Instruments, the Ilinx garment, and the Vibropixels. For each system, a technical description and description of use will be presented, as well as a discussion highlighting the role of the design aspects in the system's development.

Finally, a set of design principles is presented that address individual design aspects. These principles reflect general design goals intended to assist in the creation of DMIs for use in professional artistic productions.

Sommaire

Cette thèse examine les défis de la création des instruments de musiques numériques (IMNs) et d'autres systèmes matériels et logiciels destinés à être utilisés dans des productions artistiques professionnelles. Bien que la conception de tout IMN ne soit pas une tâche banale, l'introduction de nouveaux instruments à la scène professionnelle présente un ensemble de défis supplémentaires qui englobe des questions de conception technique, de la fabrication et de l'utilisation dans la pratique artistique à long terme. Bien que les concepteurs d'IMN décrivent souvent ces défis dans les rapports de leur pratique, les aperçus existants du processus de conception d'IMNs restent principalement axés sur les problèmes de fonctionnalité du matériel.

Pour pallier cet écart, je présente un cadre de travail composé de sept aspects de la conception: la fonctionnalité, l'esthétique, le soutien à la création artistique, l'architecture du système, la fabrication, la robustesse, et la réutilisation. Chaque aspect présente une perspective différente sur les défis de la conception des IMNs pour les productions artistiques professionnelles, et nécessite l'établissement d'un ensemble de critères de conception pour relever ces défis. Dans la pratique, les exigences en matière de conception de différents aspects entrent souvent en conflit, et la création de solutions pour résoudre ces conflits est essentielle au succès de la conception.

La création de ce cadre s'appuie sur mon expérience dans la création de trois systèmes de matériels: les instruments prothétiques, le vêtement Ilinx, et les Vibropixels. Pour chaque système, une description technique et une description de l'utilisation seront présentées, ainsi qu'une discussion qui souligne le rôle des aspects de conception dans leur développement.

Finalement, un ensemble de principes de conception est présenté qui traite des aspects de conception individuels. Ces principes reflètent les objectifs généraux de conception destinés à aider à la création d'IMNs pour utilisation dans des productions artistiques professionnelles.

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List of Acronyms

CAD	Computer-assisted design
CHI	Conference on Human Factors in Computing Systems
DMI	Digital music instrument
EMF	Electromagnetic field
ERM	Eccentric rotating mass
LED	Light-emitting diode
HCI	Human-computer interaction
IDMIL	Input Devices and Music Interaction lab
MIDI	Musical instrument digital interface
NIME	New Interfaces for Musical Expression
OSC	Open sound control
PCB	Printed circuit board
PDS	Product design specification
SSSP	Structured Sound Synthesis Project
STEIM	Studio for Electro-Instrumental Music

Chapter 1

Introduction

While research into the use of digital technologies for musical performance dates back to the 1960s and 70s, the field has experienced considerable growth since 2001.[1] A growing area of research within this community has been the creation of *digital musical instruments* (DMIs), a research topic that has been facilitated by the establishment of a dedicated conference,[2] entitled 'New Interfaces for Musical Expression' (or NIME).[3]

Research into DMI design often involves the creation of new hardware computer interfaces, or gestural controllers, that translate musicians' performance gestures into digital signals which can be used to control the parameters of software sound synthesizers in real-time (Miranda and Wanderley, 2006, 4). One of the primary motivations for creating DMIs is to support the live performance of electronic and digital music (Tanaka, 2009), and it may be argued that the success of a DMI is best evaluated through its use in performance (Modhrain, 2011; Ferguson and Wanderley, 2010). However, the design of a novel DMI is a demanding task (Miranda and Wanderley, 2006, 1), especially when de-

[1]See Chadabe (1996) for an overview of the development of electronic and digital musical instruments.

[2]Which originated as a workshop at the 2001 Conference on Human Factors in Computing Systems (CHI).

[3]The abbreviation NIME is very commonly used to refer to the conference and research area in addition to being used as a noun synonymous with digital musical instrument.

signing for use by professional performers (Marshall, 2008, 214-222), and the challenges posed by this task remains under-explored.

This dissertation seeks to clarify these challenges through the presentation of a framework for DMI design which consists of seven *design aspects*, each of which present a different perspective on a DMI's design requirements. Collectively, the design aspects allow for a consideration of DMI design challenges which takes into account its the overall context. This includes the challenges presented during an instrument's initial conception, iterative prototyping stages, use in the artistic creation process, manufacturing, integration into professional production contexts, and use in performance, as well as considering potential support for future use and development.

1.1 Research focus

The research presented in this dissertation focuses on the creation of new hardware systems for professional artistic performance. As such, the research described herein addresses several related questions:

1. What are the challenges of designing hardware systems for professional artistic productions?
2. How can we successfully create these systems within collaborative academic research projects?
3. What principles can we draw from the DMI literature as well as our own practice to support creating successful hardware systems for this context?

Addressing the context of professional artistic productions: The use of DMIs in professional artistic performances makes possible investigation into many research questions, from the way new technologies shape artistic practice to the effectiveness of different approaches to the design of DMIs. However, this context also presents challenges to successful DMI design, many of which are not apparent at the beginning of the design process. The identification of these challenges at the beginning of the design process will assist in identifying their design requirements. Section 1.2.3 discusses the professional artistic context more fully.

Addressing the context of collaborative academic research projects: The development of the three hardware systems presented in Chapters 3-5, as well as the artistic works that provided the systems' initial uses, took place within three major collaborative academic research projects. While much of our discussion will focus on the challenges of designing for professional artistic contexts, the academic context also places a key role in hardware design decisions. One primary consideration is that our purpose in undertaking these collaborations is to further our own research, e.g. creating knowledge to assist in understanding DMI design challenges and processes. While we take seriously our obligation to help our collaborators successfully achieve their own research goals, our own research goals remain our primary concern, both in terms of our individual research careers as well as the advancement of the field as a whole.

Creating generalized principles of DMI design: While the description of knowledge gained through practice plays a valuable role in the field of DMI design, the articulation of generalized principles can help to provide an overview of the many different elements of an instrument's design. Our goal in this research has been to identify a perspective from which to create such a set of generalized principles and to organize these principles in ways which will be helpful to future designers.

1.2 Context of this research

In this section, I will address three elements which comprise the context within which this research was conducted: my motivations for addressing this research question; what I mean when I refer to 'hardware systems'; and what I mean by 'professional performance'.

1.2.1 Motivation for this work

My specific motivation for undertaking this research comes from my Masters work at the University of California, Irvine (Hattwick, 2011). In this work, I explored possibilities for designing digital systems for ensemble performance which privilege gestural interaction between the ensemble members. The system I used for this work consisted of commercial hardware interfaces (Nintendo Wii Remotes) and a software system I created in the multimedia programming language Max/MSP.

The use of commercially available hardware controllers grew out of both time and research constraints, as it was clear that it would be impossible to focus both on the creation of new DMIs as well as on the creation of the software system which enabled collaborative performance. However, I remained interested in exploring ways in which DMIs could be designed to facilitate ensemble interaction, and came to McGill with the intention of designing new DMIs for this purpose. It was clear, however, that this exploration would face several challenges, including the need to create multiple instruments to support ensemble use, as well as the need to support the system's use in performance.

Once I arrived at IDMIL I was given the opportunity to work on an existing research project, *Les Gestes*, which I discuss in chapter 3. I was interested in working on

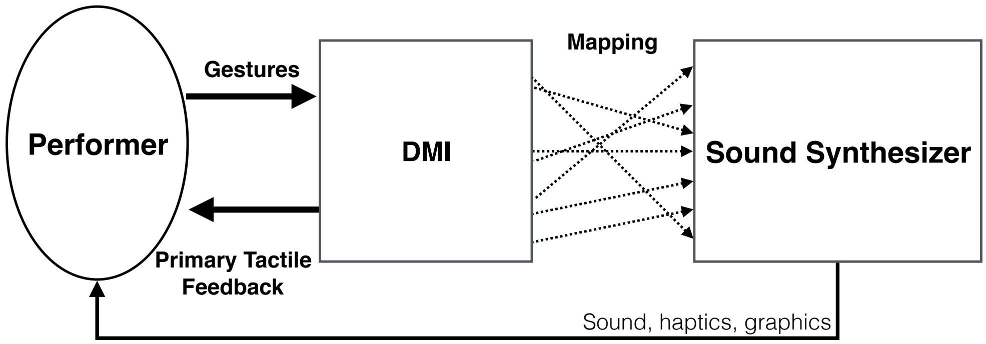

Fig. 1.1 A simplified model of a digital musical instrument, based on Bongers (2000, 45).

that project as would allow me to address my earlier concerns regarding manufacturing quantities of instruments as well as creating a system which would stand up to professional performances. Over the course of that project, however, it became clear that the challenges of designing for professional contexts were significantly more demanding than I expected. It also became clear that view of these challenges presented in the literature was both fragmented and also did not reflect changes in the capabilities of and access to hardware prototyping equipment, both in terms of digital manufacturing equipment as well as commercially available prototype manufacturing services. Understanding and clearly articulating these challenges became my primary research topic at that point.

1.2.2 Hardware systems

A digital musical instrument typically takes the form of a hardware computer interface connected to a sound synthesizer by some sort of mapping strategy (Miranda and Wanderley, 2006, 3). DMIs also generate different forms of *feedback*, i.e. information presented to the user as she performs (Bongers, 2000). This feedback can take several forms – as a sonic response to performer's gestures, as visual indications of the instrument, or as either passive (for example, the movement of buttons or knobs) or active (vibro-tactile or robotic movement) haptic feedback. Figure 1.1 shows a simple model of a DMI based on Bongers (2000).[4]

Multimodal interfaces: While there is no doubt that the musical context of DMI design presents unique challenges, the general model of a hardware device which produces both control signals and feedback is utilized in many applications of human-machine interaction – and, in fact, many music performance systems utilize commercial hardware systems which were not developed specifically for music, including my MFA work as described above. Other examples include the extensive use of gaming controllers, such as the Nintendo Power Glove in the 1990s (Mulder, 1994), the use of graphics tablets to control vocal synthesis (Perrotin and D'alessandro, 2016), and many examples of software synthesizers for phones and tablets (Kell et al., 2013).

This suggests that the boundary between the use of technology in musical performance and in other artistic disciplines is not fixed. Supporting this position is the work of many researchers who identify as DMI designers but who also participate in the creation of interactive, multimedia artworks, including Tanaka and Bonger's *Global String* (Tanaka and Bongers, 2002). Similarly, there have been many interactive artworks which aimed to allow visitors to experience musical interactions both with the system and with other visitors. For example, Golan Levin's *Scrapple* is a system in which "everyday objects placed on a table are interpreted as sound-producing marks in an 'active score' ",[5] and exists as both an installation as well as a performance instrument.

[4]Bongers actually describes his model as a generic human-machine interface, and also provides a variation on this model to describe the interaction between audience and art installation. Further developments of this model with a specific focus on DMIs are proposed in Marshall (2008), Wanderley (2001), and Birnbaum and Wanderley (2007).

[5]http://www.flong.com/projects/scrapple/, accessed May 21, 2017.

Several research streams in DMI design explicitly address the multimodal nature of musical interaction. The use of active visual feedback is common to assist in audience perception of musical performance (Berthaut et al., 2013) or to aid performer-instrument interaction (Berthaut et al., 2017). Tactile feedback has also been utilized to aid in the performer's interaction with their instrument (Birnbaum and Wanderley, 2007), or as a tool for communicating musical cues or instructions to an ensemble (Hayes and Michalakos, 2012). In addition, several systems have been created for translating audio signals into tactile signals, either to provide musical experiences for the hearing-impaired (Nanayakkara et al., 2009), or to provide an alternative or supplementary channel for musical composition (Gunther and O'Modhrain, 2003).

Hardware Terminology: Within this dissertation we will be discussing hardware systems both in the form of digital musical instruments (chapter 3) as well as in the form of tactile displays (chapters 4 & 5). While these hardware systems differ in terms of specific interaction modalities, they share many commonalities in their use in professional artistic productions, which is reflected in the framework presented in chapter 6. Although the background and context of this research remains within the NIME research community, when relevant to our discussion I will refer to more generalized descriptions such as 'hardware devices' and 'hardware systems'.

In addition, while the focus of this dissertation is the creation of hardware systems, in practice every digital hardware system is in fact a combination of both hardware and software components. The typical model for a DMI, for example, is a hardware interface with a variety of sensors, a software synthesis section with a variety of input parameters, and a software mapping layer which maps the output of the sensors to the input parameters of the synthesizer. While it might therefore make sense to think of the systems we discuss as being 'hardware/software systems', for simplicity and due to convention I will instead refer more simply to 'hardware systems', with the software element implied.

1.2.3 Professional performance contexts

I will frequently refer to 'professional performance' or 'professional artistic productions' in this dissertation. While the word 'professional' often refers to the degree to which the artists are paid for their work, in this context it also refers to the overall funding structure of the project and the role that the projects play in the participants' career paths. Each of the artistic works I participated in for this dissertation were funded both by Canadian grant agencies for the arts and humanities, including the Canada Arts Council and the Social Science and Humanities Research Council, as well as Canadian grant agencies for scientific and engineering research, such as the National Science and Engineering Research Council. The funding provided by these agencies supported my own work and the work of my scientific and artistic collaborators, as well as providing funding for materials and external contractors.

In addition, the artistic presentations of these projects were performed in venues attached to major cultural institutions, such as museums, concert halls, and festivals, most of which also contributed to the production of the artistic work. These contributions include both financial support as well as support in the form of paid and unpaid production staff, docents, and administrators. Each of the works has also been shown in multiple venues, each with their own support staff and infrastructure.

Finally, these artistic presentations were reviewed by professional reviewers as well as reviewers tied to funding agencies. The public reception of the works, as reflected in these reviews, were perceived by our collaborators as playing a major contribution to the development of their career opportunities, as well as to the impact of the work in terms of audience size, publicity, and marketing.

Designing systems for professional artists: Designing technology for artistic practices is always a challenging task. Bill Buxton asserts that designing to 'artist-spec' is more demanding than designing to 'standard-' or 'military-spec', arguing that artists who have spent years developing their craft deserve tools worthy of their investment (Buxton, 1997). However, the example Buxton uses, implementing a digital airbrush intended to emulate the experience of using a physical airbrush, is fundamentally different than the context of my work. My systems do not intend to replicate or augment existing systems, but instead are intended to afford new forms of interaction or sensory display. This allows more flexibility in the design of the system as users are not bringing fixed ideas regarding how it needs to work.

Nonetheless, there are several challenges our systems need to meet. First, it is essential to avoid technical faults that necessitate the interruption of a performance or that impact the artistic success of a performance. Second, the systems must perform consistently over time, allowing the artists to depend upon the systems' functionality. Third, the systems must be able to be set up, maintained, and run by the available support staff – who may or may not have significant technical training.

These challenges may be less significant for DMIs which are created as proof-of-concept lab demos, will only be used in concerts held in the controlled environments of academic or conference settings, or are developed as part of a personal artistic practice. But giving a DMI to an artist whose livelihood depends on their practice, and then expecting that artist to rely on your system for widely publicized artistic productions supported by major arts institutions, productions which can have a major impact on their future career – that is a level of responsibility in system design that is extremely demanding.

The three systems presented in this dissertation, the Prosthetic Instruments, the *Ilinx* garment, and the VibroPixels, were created within this context of these kinds of productions. Nonetheless, my role, and the role of the Input Devices and Music Interaction Lab (IDMIL) at McGill where I conducted my research, is not solely as the technical support for the artistic creations of our collaborators. At the same time as we are contending with the demands of professional productions, we are also conducting research into new forms of gestural performance, multimodal display systems, and user interaction design.

In particular, these systems were created within collaborative research projects, in which the technical and artistic development took place on parallel tracks. Throughout the discussions which follow we will see how the interaction between artists and technical developers influenced the systems' design, and the special considerations necessary for the support of artistic creation throughout these projects.

To summarize, the context of the research projects presented in this dissertation is the following:

1. They involve multiple collaborators from within and without academia, each with their own set of research goals and as well desired outcomes for the project. This includes artists, technology developers, scientists, and academic and cultural institutions.
2. They involve the creation of new hardware systems intended to be used in artistic performances.

3. They involve the parallel development of both hardware system and artistic works in which the systems will be used.
4. The artistic works are each presented multiple times at cultural institutions in different countries. The results of these productions will be reviewed by professional reviewers as well as reviewers from the funding institutions, and the success of the work as described in the reviews will affect the ability of the collaborators to fund their future projects.
5. The projects also result in prominent academic publications.

1.3 Contributions

Several contributions will be made by this dissertation, including a framework for designing DMIs for professional artistic productions, a set of design principles based upon this framework, and three examples of such systems.

A note on contributions: As the development of the systems described in chapters 3-5 occurred within highly collaborative projects, I will carefully explicate my role within these projects in three ways:

1. In the following sections I will briefly describe my role for each contribution.
2. Within chapters 3-5, each section of the technical and artistic descriptions will include a footnote detailing the contributions of each collaborator.
3. Appendixes A, C, and E list the role of all of the collaborators for each project.

1.3.1 A framework for the design of hardware systems for professional artistic productions

The first major contribution of this dissertation is an examination and elucidation of the challenges of designing hardware systems for professional artistic productions. With the maturing of the field of digital musical instrument design, it is increasingly common to participate in collaborative projects with ambitious research agendas. However, within the DMI literature there is little discussion of the challenges entailed in creating new technological systems in these contexts. To fill this gap, we propose a framework consisting of seven aspects of design of hardware systems in this research context, which includes design for:

1. *Functionality* – aspects of the design which relate to how the device is used. For a digital music instrument this would typically include the aspects of the interface which allow for gestural interaction, and is a primary concern of the DMI research community, as we will see in Chapter 2.
2. *Aesthetics* – aspects of the design that qualitatively affect the experience of the user or audience. While aesthetics often plays a key role in the artistic creation process, it also influences the ways in which users interact with technology, influencing the ways they feel about and interact with the system.
3. *Support for Artistic Creation* – one of the primary challenges in developing new technologies in collaboration with artists is supporting the system's use in the artistic creation process, a process which both begins at the initial conception of the research project but is also a continuation of the artist's professional practice.
4. *System Architecture* – aspects that support the interaction between different ele-

ments of the system. Examples include communication protocols, power management, and the creation of network topologies.

5. *Manufacturing* – elements of the design that facilitate its manufacturing. The selection of manufacturing processes will dictate much of this design aspect.
6. *Robustness* – aspects of the design that support the successful usage of the system in the performance context. This includes facilitating the management of the device by production staff who do not possess a technical background, as well as accommodating problems or device failure over the course of the device's use.
7. *Re-Use* – aspects of the design that enable use of the device in future productions or different contexts.

While the argument can be made that design for functionality should be the dominant goal for the creation of hardware systems in research contexts, we argue that a holistic approach which considers the needs of all of the system's stakeholders is essential to sustainable research. Creating systems which are difficult to use or unreliable compromises the success of the artworks created by our collaborators; creating systems which are uncomfortable, confusing, or aesthetically unappealing cannot help but impact the experience of the user and their willingness to invest effort and time in exploring the system; creating systems which are difficult or costly to manufacture, are difficult to repair or maintain, and which are not useable in other research contexts impacts the quality and amount of research the system can support. Considering the time, effort, and expense involved in creating hardware systems suitable for professional artistic use, as well as investment of time and faith contributed by our collaborators, creating systems which successfully meet all of these challenges is essential.

Publications: The design aspects were first presented in Hattwick and Wanderley (2017), which also includes a brief discussion of their role in the development of systems for professional artistic productions.

1.3.2 Principles for designing hardware systems for professional artistic productions

Building upon the framework described above, we will also present a set of design principles intended to aid in the creation of hardware systems for professional artistic productions. These principles are drawn from our personal experience in the creation of such systems, and represent general goals and specifications intended to meet the design requirements for each aspect. Figure 1.1 presents an overview of the design principles.

1.3.3 The Prosthetic Instruments

The Prosthetic Instruments are a family of digital musical instruments intended to be used by dancers in an interactive choreography-concert (Malloch, 2013, 107-134). The Prosthetic Instruments were created in collaboration with composers from McGill University and Isabelle Van Grimde and dancers from Van Grimde Corps Secrets, an independent dance company based in Montreal. The instruments were used in performances in Canada, France, Belgium, and the Netherlands in March-April 2013, as well as in a variety of additional contexts through July of 2015.

My contribution: While the project took place from 2010-2013, I began working on it in the Fall of 2011 upon the initiation of my doctoral studies at McGill. In addition, as a highly collaborative project the work I completed both drew upon and occurred in tan-

Principles of functionality	
Novel solutions are cool, but risky	
Re-use existing systems when possible, but be prepared to start from scratch	
It is more important that it work than how well it works	
Perform quantitative tests of the system when possible	
Principles of aesthetics	
Inspire confidence with the system's design	
Form and fit are important, and subjective	
Be conscious of ways in which the system's form may exclude users	
Don't harm the system's users	
Principles of support for artistic creation	
Create video documentation	
Allow the ability to program the system at multiple levels	
Design to allow for continuous use	
Pay attention to your collaborators' process, and be prepared to provide prototypes with the appropriate functionality	
Provide visual feedback regarding system status	
Principles of system architecture	
Every interface between modules is a potential point of failure	
Design to allow for continuous use	
Be aware of wireless details	
Consider the context of the system's use	
Principles of manufacturability	
Use appropriate manufacturing techniques	
Begin manufacturing early	
Identify opportunities to speed manufacturing	
Principles of robustness	
Repairability vs. replaceability	
Pay attention to material properties and points of failure	
Learn and use standard techniques for protecting electronics	
Principles of reusability	
Keep an eye towards future applications	
Keep documentation of the design process as well as the system	
Clarify the possibilities of system reuse from the beginning	

Table 1.1 Design principles based on the seven design aspects, categorized by aspect.

dem with work of other researchers, notably Joseph Malloch and Marlon Schumacher. I joined the project after the completion of the first workshop, in which non-functional conceptual prototypes made out of paper and foam were created, and my first contribution was the creation of functional prototypes of the instruments for the second workshop. These prototypes were guided by design decisions and previous tech development by Malloch, which included ideas about materials to use in the instruments' construction and the choice and implementation of sensing technology.

My primary contributions were the design and manufacturing of the Ribs and Visors, contributions to the design and manufacturing of the Spine, the creation of the mounting system for the instruments in collaboration with Malloch, the implementation of the lighting systems in the instruments, some software programming both in the firmware of the Ribs and Visors as well as the main Max/MSP program which processed the sensor data, and the preparation of the system for touring, in coordination with the technical support staff of the production.

Publications: Technical descriptions of the design and manufacturing of the Prosthetic Instruments as well as a discussion of manufacturing approaches were previously published in Hattwick et al. (2014). In addition, Joseph Malloch presents a general description of the Prosthetic Instruments in Malloch (2013, 104-137).

1.3.4 The *Ilinx* garment

The *Ilinx* garment is a full-body wearable tactile display embedded with 30 vibrotactile actuators. This garment was developed by researchers at the IDMIL in collaboration with artist and Concordia Professor Chris Salter and his artistic collaborator Maurizio Marinucci (also known as TeZ), and also with clothing designer Valerie LaMontagne and her wearable electronics atelier 3lectromode[6]. The garment was used in the immersive multisensory art installation *Ilinx*, presented first in the Hague in October 2014 and subsequently in Tokyo and Berlin in 2015.

My contribution: For this project, I lead a team of technology developers in the design and manufacturing of the electronic elements of the garment, coordinated with the garment designers in the incorporation of the electronics into the design of the garment, and oversaw the development of software communication protocols and user interfaces for use of the system.

Publications: Several publications detail different elements of the research. Lamontagne et al. (2015) presents an overview of the incorporation of tactile stimuli in media art, a description of the technical elements of the installation and the *Ilinx* garment, and details regarding the artwork's initial presentation. Giordano et al. (2015) describes the design and characterization of the tactile display system. Hattwick et al. (2015) describes software interfaces created for use in composing for the garment.

1.3.5 The VibroPixels

The VibroPixels are wirelessly controlled tactile actuators which collectively form a reconfigurable, wearable tactile display designed for distributed applications. Growing directly out of our experience with the *Ilinx* garment, the development of the VibroPixels sought to address several issues discovered in that project, as well as providing a platform for a wide variety of social tactile experiences. The first public work utilizing the VibroPixels was the premier of the immersive multisensory art installation *Haptic*

[6] `http://www.3lectromode.com/about`

Fields, shown in Shanghai, China from July-September of 2016.[7] In the summer of 2017, *Haptic Fields* was also shown at the Wiener Festwochen in Vienna,[8] and in an expanded form at the Berliner Festspiele.[9]

My contribution: The initial conception and specifications for the system were developed by myself and Ivan Franco, in collaboration with Chris Salter. I created the final specifications and design of the mechanical, electronic, and software components, and manufactured the system with the assistance of Julian Neri, Patrick Ignoto, and Alex Nieva.

Publications: Hattwick et al. (2017) presents an overview of the VibroPixels as well as a description of the use of software tools for the initial creation of *Haptic Fields*, and Ignoto et al. (2017) describes the use of the system for the creation of a tactile metronome for use by conductors of contemporary classical music ensembles.

1.4 Structure of the thesis

This thesis is structured as follows:

- **Chapter 2, "DMI Design Overviews and Frameworks"** presents an overview of existing overviews of the DMI design process and reviews knowledge regarding the design aspects drawn from the practice of DMI designers.

[7] `http://www.chronusartcenter.org/en/chris-salter-haptic-field/`, accessed May 23, 2017.

[8] `http://www.festwochen.at/programm/detail/haptic-field/`, accessed May 23, 2017.

[9] `https://www.berlinerfestspiele.de/en/aktuell/festivals/immersion/programm_immersion/immersion17_programm_gesamt/immersion17_veranstaltungsdetail_211095.php`, accessed May 23, 2017.

- **Chapter 3, "The Prosthetic Instruments"** presents a description of the Prosthetic Instruments and their development within the research project *Les Gestes*.
- **Chapter 4, "The *Ilinx* Garment"** presents a description of the *Ilinx* garment as well as its development.
- **Chapter 5, "The VibroPixels"** presents a description of the VibroPixel tactile display system as well as its development.
- **Chapter 6, "Design Aspects and Principles"** presents a discussion of the seven design aspects described above, as well as presenting a set of design principles drawn from our experience in the creation of the systems described in this thesis.
- **Chapter 7 "Future Work and Conclusions"** describes on-going and future work furthering the research described in this thesis, as well as suggesting ways in which the conclusions of the work may be useful to the wider artistic and research communities.

A note regarding the structure of the thesis: In the presentations of the three hardware systems in Chapters 3, 4, and 5, I will briefly mention the ways in which the systems relate to the various design aspects. However, a full explication of the framework will be delayed until Chapter 6, which will also include an in-depth discussion of the relationship between the framework and my experiences designing the three systems.

Chapter 2

DMI Design Overviews and Frameworks

In this chapter we will review the DMI literature to identify the current state of knowledge of the field of digital musical instrument design. Within this review we will focus on several different strands of research activities. The first is a review of proposed overviews and frameworks for the DMI design process. Since the beginning of the field of computer music research, and especially since the founding of the NIME conference, numerous researchers have proposed overviews of the process for designing DMIs and other hardware systems for musical applications. However, as we will see, these overviews typically remain focused on functional aspects of DMI design, and rarely touch on all of the design aspects necessary to create a DMI suitable for professional productions.

Secondly, we will take a look at the knowledge gained through practice-based research in DMI design. Within the NIME literature there are a great number of publications which report on specific interfaces or systems, and which include reflections on theoretical implications of the interface's design or on the design process itself (Gurevich, 2016). However, as these types of publications are numerous, we will focus on publications in which experienced researchers reflect on their practice over many years or decades. We will see that many of the design aspects in our proposed framework are touched upon by these researchers; however, this knowledge is typically not systematically organized, and is not presented within the context of an overview of the DMI design process.

Finally, we will briefly present perspectives on the long-term use of DMIs, and give an overview of the Digital Orchestra Project, an immediate precursor to the research presented in this dissertation.

Terminology: In order to clarify the terminology we will use below, we will draw upon definitions presented in Modhrain (2011):

principles General statements drawn from practical experience which represent design goals or qualities of a system, but do not provide specific guidance regarding how to achieve these goals.

frameworks A general overview of the elements which make up the design of a system, typically created in order to identify the overall design space and to help clarify the interaction between design elements.

A brief discussion of functionality: While the word ‘functionality’ may be used to broadly describe many aspects of a system’s design, within the context of this dissertation I will use it to refer to what a system does from a user’s perspective. Specifically, it refers to the affordances a system presents to a user in terms of physical interaction, as well as describing ways in which the system creates sensory outputs which may not be user-driven. From this perspective of interaction and active sensory display, functionality excludes aspects of the system that are static (e.g. visual appearance and physical characteristics) as well as excluding elements of the system which support interaction but do not materially shape it (e.g. the ways in which a system sends information to a computer or the ways a user may interact with or program the system outside the performance context). However, we should also clarify that the various design aspects are not necessarily mutually exclusive, and characteristics of a system may often contribute to multiple design aspects.

2.1 DMI design overviews

Digital musical instruments (DMIs) are systems which allow performers to control digitally synthesized sound using interfaces with embedded sensor technologies. While the creation of DMIs can be seen as a continuation of earlier practices in the creation of acoustic and electronic musical instruments (Tanaka, 2009; Gurevich, 2016), the move to the digital domain brings with it significant changes in the model of an instrument. One of the most prominent is the separation of the control interface and sound synthesizer, whose connection is not fixed but must be explicitly designed, a process referred to within the NIME literature as mapping (Miranda and Wanderley, 2006). The typical model of a DMI is presented in figure 2.1.

However, while this model is simple enough, the design of a DMI is not a trivial issue (Miranda and Wanderley, 2006, p. 1). With this in mind, there have been many attempts to provide overviews of the DMI design process. Miranda and Wanderley (2006) present one such overview, based on the model presented in figure 2.1:

1. Decide on the gestures that will be used to control the system.
2. Define gesture capture strategies that will best translate these movements into electrical signals.

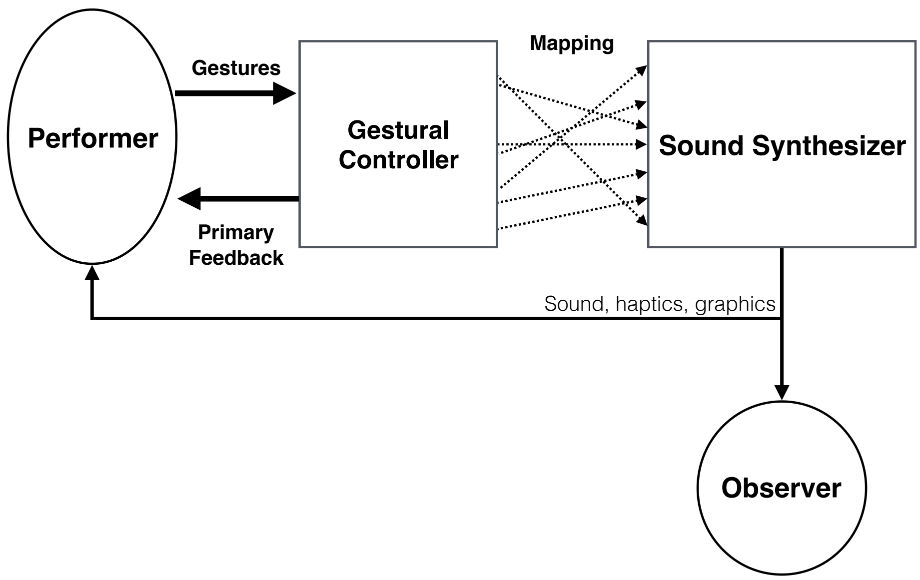

Fig. 2.1 A simplified model of typical DMI design, based on Bongers (2000, 45), Miranda and Wanderley (2006, 3), and Marshall (2008, 23).

3. Define sound synthesis algorithms that will create the sounds to be played; or, define the music software to be used for control of prerecorded musical processes.
4. Map the sensor outputs to the synthesis and music-controller inputs.
5. Decide on the feedback modalities available.

This approach focuses on first identifying and defining the functional requirements of a DMI, and then designing the technical specification of the system in order to meet these requirements. Marshall (2008) builds upon this approach, with the goal of "improving the performer-instrument interaction through the careful design of both sensor and feedback systems and the integration of these systems into complete digital musical instruments" (Marshall, 2008, 1-2). To achieve this, Marshall discusses the use of quantitative and user evaluations of the application of technologies to musical tasks, which he applies to the design of an interface's body, choice of sensors, and implementation of tactile feedback. As such, the results of these evaluations are explicitly intended to provide insight into the design of an interface's functionality. However, in a later section Marshall also relates his experiences in the collaborative development of DMIs within the context of the Digital Orchestra project, as we will discuss in section 2.3.

While the overviews presented in Miranda and Wanderley (2006) and Marshall (2008) focus on the technical design of a DMI based on an assessment of its functionality, other researchers have presented overviews which cover topics ranging from the challenges of designing computational systems for musical tasks to designing hardware systems to shape the experience of the users.

2.1.1 Early perspectives

Early research in the design of computer systems for musical applications, and computer hardware more specifically, included investigations into topics such as the identification of the challenges specific to musical applications of computers and the understanding the pertinent properties of hardware controllers.

Pennycook's "Computer-Music Interfaces": Pennycook (1985) presents an early survey of computer music interfaces, which begins by focusing on ways in which musical applications differ from general purpose computing applications. Pennycook makes four observations about "the nature of musical information as it applies to the design and implementation of user interfaces" (Pennycook, 1985, p. 268), which represent design challenges for any computer music interface:

1. Music cognition is a deep and complex process, of which relatively little is known.
2. The broad variety of musical tasks each present unique challenges which do not necessarily have equivalents within general purpose computer usage.

3. Music computer interfaces must accommodate the idiosyncratic preferences of individual musicians' artistic practices.
4. It is difficult to translate musical vocabulary and sound descriptions into digital representations which are accessible to and able to be manipulated by musicians.

Although not presented as such, these four observations form a rough framework which identifies challenges which inform musical HCI to this day. Following the presentations of these observations, Pennycook presents a survey of existing computational systems for musical tasks, covering a broad array of systems which focus on such diverse tasks as music manuscript preparation, computer composition systems, performance interfaces, and digital audio processing. In this survey, he reflects on ways in which selected systems address his earlier observations.

The majority of the paper focuses on issues of functionality, and particularly on the ways systems can be designed to accomplish musical tasks. However, several other design aspects are touched upon, especially in the analysis of the *Structured Sound Synthesis Project* (SSSP), a system created by Bill Buxton and researchers at the University of Toronto in 1978 (Pennycook, 1985, 273-276). Pennycook highlights ways in which the system supports the artistic creation process, including being presented to the user as "a 'software onion,' permitting the composer to access as many of the details of the processes as deemed suitable" (Pennycook, 1985, p. 276) as well as through a design which could be easily adapted to user preferences. Pennycook ties this latter point into his observation of the need to support idiosyncratic artistic practices, but this accommodation also facilitates the reusability of the system for different artistic practices.

Pressing's "Cybernetic issues in interactive performance systems": The creation of frameworks for the analysis and description of control interfaces was another early research topic. Pressing (1990) presents a framework for this purpose which is based on an analysis of the *cybernetics* of such systems, with cybernetics in this context meaning "the science of control and communication" (Pressing, 1990, p. 12). The framework consists of ten fundamental issues which Pressing argues must be addressed by anyone designing an interface for human interaction:

1. Physical variables carrying information
2. Dimensionality of control
3. Multiplicity of control
4. Control modality
5. Control monitoring
6. Control distance function
7. Literalness of control
8. Historical foundations
9. Design appropriateness
10. Psychological nature of control

In keeping with the focus on cybernetics, many of these issues attempt to assist in the description of functionality through a straight-forward analysis of the interface's channels of interaction. However, even for issues 7-10, which are singled out for special analysis, Pressing's analysis remains focused on the functional results of performative gestures.

2.1.2 DMI design frameworks

There have been several frameworks proposed for DMI design. These frameworks are primarily intended to assist in the specification of user interaction techniques in musical contexts.

Jorda's *Digital Lutherie*: The Ph.D. dissertation of Sergei Jordà presents a broad perspective of computer music systems with the goal of identifying the potentials and possibilities of DMIs (Jorda, 2005). In the dissertation's seventh chapter, Jorda presents a rough conceptual framework for DMI design, which includes such elements as:

1. **Efficiency**: the relationship between input complexity and output complexity (and also potentially modified by diversity).
2. **Learning Curve**: the way in which the relationship between input and output complexity change during the learning process.
3. **Diversity**: The ability of an instrument to create variable output, on different temporal scales. *Micro-diversity* refers to the ability of an instrument to allow for the creation of subtle nuances or gradations of structural variation in a piece. *Mid-diversity* refers to the ability to support flexible interpretations of musical compositions or improvisations. *Macro-diversity* refers to the ability to support stylistic flexibility.

While Jorda's discussions in this chapter encompass many other topics, including multi-threadedness, virtuosity, and expressiveness, it is clear that his focus is entirely on functionality design aspects throughout.

The second half presents descriptions of three computer music systems created over Jordà's career, primarily focusing on the conceptual background of each system and the ways in which the concepts are implemented technically. While these systems were used in professional artistic productions, Jordà's work remains focused on the conceptual and functional design of the systems rather than challenges of their performance context.

In addition, much of the technical implementation focuses on the creation of software algorithms, with only one of the systems possessing a significant hardware element.

The musical interface technology design space: Overholt (2009) presents a musical interface technology design space focusing on higher-level characteristics in order to examine "the gestures enabled by an interface and how they allow a performer to extend or enhance the playability of a musical interface" (Overholt, 2009, p. 217). This framework is comprised of seven evaluation measures:

1. How intuitive are the gestures?
2. How perceptible are the gestures?
3. How physical/powerful are the gestures?
4. How well-behaved is the controller and synthesis algorithm?
5. How unique is an instrument's identity?
6. How rich is the mapping methodology?
7. What is the widest range of expression?

Within the description of these measures Overholt proposes a variety of guidelines for the successful design of an interface. In these descriptions and guidelines, as well as in the discussion which follows, Overholt remains focused on functional design aspects. While a brief discussion of effort and ergonomics is presented, drawing on Ryan's earlier discussion of these topics (Ryan, 1991), Overholt remains focused on the ability of a instrument "to capture the inflections of a performer's physical articulations to impart a powerful and moving experience" (Overholt, 2009, p. 223).

Morreale and the *MINUET* framework: The MINUET (Musical INterfaces for User Experience Tracking) framework presented in Morreale (2015) consists of a two-stage process which is oriented around successfully creating the desired experience of the player. The first stage is an identification of the goals of the interface, and includes a consideration of who the interface is designed for, what the interaction activities will be, and where and when the interface will be utilized. The second stage consists of designing the interaction to successfully meet the goals identified in the first stage, specifically through a consideration of technological solutions. However, Morreale makes clear that his focus is "on the identification of interaction requirements rather than considering hardware and software implementations" (Morreale, 2015, p. 132).

2.1.3 Other design overviews

While not presented as generalized overviews of DMI design, there are several other pertinent publications which discuss the comprehensive design of DMIs.

Blaine and Fels' collaborative music systems: Blaine and Fels (2003) present an overview of characteristics of collaborative music systems, with an analysis both interactive artworks and musical instruments. Their overview focuses on functional descriptions of these systems, comprised characteristics such as focus, location, media, scale, player interaction, musical range, physical interface, directed interaction, learning curve, pathway to expert performance, level of physicality, and musical genre.

Armstrong's enactive approach: A more philosophical approach to DMI design is presented in Armstrong (2006), drawing upon theories of embodiment and enaction to discuss approaches to DMI design that enable "the possibility of continuously realizing new encounters and uses, and, in the process, of re-determining the relationship between technical objects and their human subjects" (Armstrong, 2006, p. 46).

Birnbaum et. al's dimension space: Birnbaum et al. (2005) present a dimension space for classifying and comparing musical devices. While the focus of the paper is on the utility of the visual representation of a dimension space, an example set of seven characteristics is presented, consisting of required expertise, musical control, feedback modalities, degrees of freedom, inter-actors, distribution of space, and the tole of sound. This set of characteristics draws upon several of the previously discussed publications, including Pressing (1990) and Blaine and Fels (2003).

2.2 Practice-based research

There is a strong tradition of practice-based research in DMI design (Gurevich, 2016). At the Studio for Electro Instrumental Music (STEIM) in Amsterdam, for example, researchers like Michel Waisvisz, Bert Bongers, and Joel Ryan have worked since the early 1980s to support artists interested in incorporating new technologies into their artistic practice (Ryan, 1991; Bongers, 2007).

Their publications blend practical observations and experiences in the design of DMIs with a consideration of theoretical and philosophical issues, such as the role of the performer in real-time performance of computer music and the importance of effort in musical performance. Many of their practical experiences are based on challenges in creating specific DMIs, such as creating robust wiring connections in Laetitia Sonami's Lady's Glove (Bongers, 2007, p. 13), as well as larger issues such as the ability of modular design to support the reusability of systems for future applications (Ryan, 1991, p. 13). However, we will see that these accounts remain rooted firmly in individual practice and do not attempt to present a coherent overview or framework of DMI design.

Joel Ryan and STEIM: The practical experience of researchers involved in creating digital systems often provides valuable insights into principles for instrument design. This can be seen in Ryan (1991), which argues for the utility of an empirical approach to computer music system design, drawing on work completed at the Studio for Electro Instrumental Music (STEIM) in Amsterdam. Rather than providing an organized framework, this paper draws upon Ryan's extensive experience to comment on multiple topics. One primary argument Ryan makes is that what he refers to as 'physical handles' can help to give definition to computer models of musical systems, as they allow for real-time accommodation of system limitations, rapid iteration of musical ideas, and enables the use of spatial and visual metaphors.

As an active system designer, Ryan also addresses aspects of the system architecture and reusability of computer music systems, noting that modular approaches to system creation allow for distributing processing load (a key concern at the time) as well as facilitating the creation of new systems. In particular, he describes the importance of what he calls the 'instrumentation' of a computer music system, which includes the mechanical and electronic elements, software interfaces, and higher level models applied to music.

While it lacks an explicit definition of specific principles, a liberal inclusion of case studies as well as generalized descriptions of system design at STEIM allows Ryan to touch on a wide variety of design aspects. While the focus of the paper is clearly on the musical functionality of system design, the importance of system architecture is repeatedly addressed, both in terms of how it impacts design functionality as well as how it allows for a variable approach to artistic creation and reuse of subsystems. In Ryan's discussion of interactive software development and the challenges of artistic and technological collaborations he argues for the use of tools which allow for rapid iteration and ease of use in the artistic creation process. Finally, Ryan also briefly describes aesthetic challenges in system design, both in terms of the ways in which his instrumentation approach can support the aesthetic goals of artistic collaborators as well as issues of ergonomics and performers' experiences of effort and musical expression.

Bert Bongers: Bert Bongers has made numerous contributions to the DMI research community, having worked on later versions of Michel Waisvisz's *Hands* (Waisvisz, 1985; Krefeld, 1990), Laetitia Sonami's *Lady's Glove* (Bongers, 2007), and many other similar projects. Bongers (2007) consists of a variety of reflections on his diverse experiences, and while much of his discussion is based around functionality, for example describing the evolution of the functionality of the Hands, he also describes moments where the design process was informed by other design aspects. In addition to the discussion of robustness in his experience with the Lady's Glove described above, he also mentions how aesthetics played a key role in choosing to leave the Glove's colored wires and heat-shrink uncovered. In addition, in his description of the design of the *Soundnet*, a 10m x 6m instrument consisting of shipping rope strung across an aluminum frame and which the members of Sensorband played by climbing on the wires, Bongers describes the choice of steel wires as being dictated not only by robustness but also by aesthetics, describing how the rope was chosen "for its feel and strength" (Bongers, 2007, p. 15).

The *Beatbugs*: The *Beatbugs* were developed by Gil Weinberg and Roberto Aimi as part of the Toy Symphony project, and were designed to be used by children in musical workshops and performances. From 1999-2006 several versions of the Beatbugs were created. The first, called the *Musical Firefly*, was an extremely simple controller with two buttons and an infrared communication port allowing two devices to communicate with each other. The second incorporated piezo sensors for identifying rhythmic taps on the interfaces body, as well as two flexible bend sensors, and utilized a wired connection to a central computer. The third was a development of the second and replaced the bend sensors with hall effect sensors, and added an accelerometer for additional input signals (Weinberg, 2008). An additional iteration which integrated wireless communication via Bluetooth was described in Aimi and Young (2004).

The development of the Beatbugs is described in several papers, and it is clear that the context of the device's use drove much of the system's development. For example, Aimi (2002) and Aimi and Young (2004) identify several ways in which "[t]he Toy Symphony project imposed strict design requirements for the [second] Beatbug system". Many of the requirements they describe correlate with the design aspects I presented in section 1.3.1 of this dissertation, and which are discussed more fully in Chapter 6. The requirements described by Aimi and Young are listed here, and labelled with the related design aspect:

1. The devices needed to be small enough for children to hold them – **Aesthetics**
2. Thought was given as to how to make the device appear more anthropomorphic – **Aesthetics**
3. The devices were made identical and spares were made in case they broke during use – **Robustness**
4. The need for the sound produced by the Beatbugs to be amplified for a large auditorium meant they needed large speakers located next to each device – **System architecture**
5. Concerns with battery life led them to use a wired connection for power – **System architecture**

6. Since they required a wire anyways, they were designed to also utilize other external hardware – **System architecture**
7. The implementation of wireless communication was delayed until they could be used in a “less hostile environment” (Aimi and Young, 2004, 25) – **System architecture**

The development of the final iteration of the Beatbugs was driven by many of the above factors, including a desire to simplify the system architecture as well as changes to improve the robustness of the device.

2.2.1 Perry Cook’s design principles

Ome way in which the knowledge gained from practice-based research can be crystallized is through assembling it into a set of design principles, which take the form of general statements and advice regarding the design process. The primary example of this within the NIME community are Perry Cook’s *Principles for Computer Music Controllers*, shown in Table 2.1. In 2001, Cook proposed 13 principles sorted into three groupings, “Human/Artistic Principles", “Technological Principles", and “Other Principles". In 2009, Cook expanded these principles to expand upon the previous groupings as well as proposing a new grouping covering “Controller (Re)Design".

Cook bases his principles on his own extensive experience as an interface designer and researcher, and describes them as being opinions more than universal recommendations. Coming from this perspective, his principles engage easily with such diverse issues as artistic motivation, technological implementation, and research methodology. As importantly, however, it reflects a longitudinal view of interface design in the context of research, especially the 2009 paper. Including observations from both his experience

Human/Artistic Principles	
Programmability is a curse	Functionality
Smart instruments are often not smart	Functionality
Copying an instrument is dumb, leveraging expert technique is smart	Functionality
Some players have spare bandwidth, some do not	Functionality
Make a piece, not an instrument or controller	Functionality
Redesign with backward compatibility	Reusability
Instant music, subtlety later	Functionality
Design (and pack) for post-9/11 travel	System Architecture
Some Technological Principles	
MIDI = Miracle, Industry Designed, (In)adequate	System Architecture
Batteries, Die (a command, not an observation)	System Architecture
Wires are not that bad (compared to wireless)	System Architecture
Some Other Principles	
New algorithms suggest new controllers	Functionality
New controllers suggest new algorithms	Functionality
Existing instruments suggest new controllers	Functionality
Everyday objects suggest amusing controllers	Functionality
Funny is often much better than serious	Functionality
Some New Principles	
More can be better! (but hard)	Manufacturing, System Architecture
Music+Science is a great teaching/marketing tool	N/A
The younger the student, the more fearless	N/A
Principles for Controller Redesign	
Build a (new) copy, don't trash the original	Reusability
Build two or more if you can afford it.	Robustness, Maintenance
Redesign with backward compatibility.	Reusability
Wire and document for future surgeries	Maintenance, Reusability
Build diagnostic features and displays	Maintenance
Construct controller proxies	Support for Artistic Creation

Table 2.1 Perry Cook's principles for designing computer music controllers, organized according to his categorization, with an indication of relevant design aspects for each principle.

with PLOrk as well as with the redesign of an accordion-inspired controller, Cook discusses issues which are not often seen within the NIME literature, including the maintenance, redesign, and evolution of an interface. As we might expect, his principles engage naturally with many of the design aspects as we present in Chapter 6.

2.3 Long-term use of DMIs and the Digital Orchestra Project

The importance of the use of DMIs in performance and their incorporation into long-term practice has often been recognized[1], and several research projects have explicitly engaged with this issue. In a discussion of the motivation behind the creation of the T-Stick, for example, Malloch argues that even the most robust DMIs "are often fragile compared to traditional acoustic instruments, and almost always the designer/creator must be present at all demos, practice sessions, and performances to instruct and trouble-shoot" (Malloch, 2008, p. 2). One of the explicit goals for the T-Stick was to create "a digital musical instrument that performers can take away with them, connect with no supervision, and then practice or perform for many hours a day without it wearing out or breaking" (ibid).

The Digital Orchestra Project: Following its initial creation, the T-Stick was further developed in the Digital Orchestra Project[2], a three-year research creation project supervised by Sean Ferguson and Marcelo Wanderley, and in which Joseph Malloch was a

[1]For example, the desire at STEIM for "our artists to build a practice around these instruments over a longer period of time and develop unique expressions and virtuosic skills" (Lippit and Andersen, 2012, p. 90).

[2]In addition to the T-Stick, three additional DMIs were created or further developed over the course of the project: the Fortier-Marshall Gloves, the T-Box, and the Rulers (Pestova et al., 2009).

research contributor Ferguson and Wanderley (2010). The goal of this project was to develop DMIs with the potential for long-term use, and which have "expressive musical potential comparable to that of existing acoustic musical instruments" (Ferguson and Wanderley, 2010, p. 17).

In order to achieve this, the project utilized a methodology in which interdisciplinary teams consisting of technologists, composers, and performers worked together to iterate through the design of DMIs over a three-year period. The overall structure of the project was: one year of technical development, with regular feedback from performers and composers; one year of workshops in which the team worked together to finalize the interface and develop software tools to assist in its use for composition; and a final year in which compositions using the interface were created, rehearsed, and performed. Based on the results of the project, Ferguson and Wanderley propose that an effective evaluation of a DMI may be its ability to reproduce specific compositions, including the ability to realize a piece based on a written score.

Several publications coming out of the Digital Orchestra Project highlight the challenges of designing DMIs within this context. In addition to Malloch's observations described above, Marshall (2008) also emphasizes the importance of instrument robustness, stating "[i]nstruments which are reliable enough to demonstrate, or even to practice with, may not be reliable enough to perform [sic]" (Marshall, 2008, p. 221). Marshall also mentions concerns with the visual aesthetics of DMIs, claiming that by "taking care to deal with the aesthetics of the instrument, making it more 'instrument-like' in its appearance, we can produce an instrument which encourages interaction and which attracts people to it" (Marshall, 2008, p. 230).

In addition, Pestova et al. (2009) note several challenges from the performer's perspective. One is dealing with *latency*, in this context referring to the time-gap between a performer's gesture and the audible result of this gesture. Latency typically results from the design of the system's architecture, often relating to the processing time of synthesis algorithms or digital to analog conversion. While Pestova et al. (2009) note several work-arounds they do not detail the source of latency in this instance. Another issue described is ergonomics, and particularly the need to modify the T-Box to utilize a smaller-sized glove in order to accommodate the hand-size of one of the performers.

Innovating reliability: Freed et al. (2013) present another perspective on the challenge of long-term use of DMIs, claiming that consistency in DMI design is required in order to allow performers to develop a mature performance practice. In particular, they argue that in order for an instrument to be long-lasting "a shift is required from innovation in the interface itself to innovations in the reliability and re-implementability of this interface" (Freed et al., 2013, p. 441). In other words, a focus on the functionality of an instrument at the expense of the system's robustness, aesthetics, and architecture will compromise the instrument's ability to support long-term use.

2.4 Summary

In this chapter, we have discussed existing overviews of DMI design, and found that there is a heavy focus on functionality in the literature, and a lack of comprehensive overviews of the challenges inherent in designing DMIs for professional performances. However, we have also seen that these challenges are discussed in the reports of experienced DMI designers, albeit not in a structured way. This suggests that one way to gain such a comprehensive overview might be through the experience gained through DMI design practice.

The next three chapters will present our experience in exactly this kind of practice, designing hardware systems for professional artistic productions. In addition to a technical description and description of use of these systems, we will also reflect on our experiences to understand the challenges presented by designing for these contexts.

We then draw upon these reflections and experience in the presentation of a design framework, presented in Chapter 6. Also in that chapter will be a discussion of design principles drawn from this practice.

Chapter 3

The Prosthetic Instruments

This chapter presents a family of digital musical instruments designed to be used in an interactive dance performance. These instruments grew out of earlier collaborations between the participants of the project, and were intended specifically to function as prosthetic devices worn by the dancers. In the context of the work described in this thesis, the development of the Prosthetic Instruments provided valuable information regarding the development of a hardware system from conception to use in professional performances.

In particular, over the course of the design of the Prosthetic Instruments specific challenges arose relating to the negotiating of conflicting design requirements, particularly in terms of aesthetics, manufacturing, and robustness, which is discussed in section 3.4.1. In addition, while robustness was seen as being a key concern from the initial conception of the Prosthetic Instruments, over the course of the project we found that the definition of successful robustness acquired more nuance than expected. For example, we found that one important consideration in the design of a robust system is considering the context of use and the expectations and training of the users, as discussed in section 3.4.5.

Our experience navigating the challenges that arose during the design process suggested that successfully designing a hardware system for this context requires a consideration of the system's design from multiple perspectives. A further exploration of these perspectives was part of our research into the design of the 'Ilinx' garment and the VibroPixels, as discussed in Chapters 4 and 5.

Structure of this chapter: The structure of this chapter is as follows:

- Section 3.1 presents an overview of the project, including a discussion of the collaborators, the project timeline, and the project outcomes.
- Section 3.2 provides a technical description of the Prosthetic Instruments.
- Section 3.3 describes the use of the instruments in their initial performance, as well as several subsequent uses.
- Section 3.4 presents a discussion of our experiences developing the instruments and their use in performance.
- Section 3.5 describes the ways in which our experiences developing the Prosthetic Instruments contributed to the overall research goals of this dissertation.

3.1 Context of the research project

The Prosthetic Instruments were developed as part of the project titled *Les Gestes: une nouvelle génération des instruments de musique numérique pour le contrôle de la synthèse et le traitement de la musique en performance par les musiciens et les danseurs*.[1] This collaborative research-creation project brought together our group — the Input devices and Music

[1] The title of the grant is presented here as it was in the grant proposal. The English translation is: "Gestures: a new generation of digital musical instruments for controlling synthesis and processing of live music by musicians and dancers."

Interaction Lab at McGill University — with the choreographer Isabelle Van Grimde, her dance troupe Corps Secrets, and composers Sean Ferguson, Marlon Schumacher, and Geof Holbrook. *Les Gestes* was funded by a grant from Le Fonds de recherche du Québec - Société et culture (FRQSC) for the period 2010-2013.

3.1.1 The participants

There were three groups of collaborators – ourselves in the Input Devices and Music Interaction Lab (IDMIL) doing the technological development, composers from the Digital Composition Studio (DCS), and Isabelle Van Grimde and members of her dance troupe Corps Secrets (VGCS). In addition there was a variety of support staff for the tour of the production, largely contracted by VGCS. While both IDMIL and DCS exist within the Schulich school of Music at McGill, Van Grimde's Corps Secrets is an independently-run arts organization. A complete list of the collaborators is available in Appendix A.

Within IDMIL, Marcelo M. Wanderley served as the director of technical development, the Prosthetic Instruments and their associated software were designed by Joseph Malloch and myself, and Malloch and Marlon Schumacher contributed additional software development related to mapping, synthesis, and compositional tasks. Anthony Piciacchia, an undergrad engineering student at McGill, served as an intern at IDMIL for one year and assisted with mechanical design, CAD modeling, and digital manufacturing. Aaron Krajeski, a Masters student in Music Technology, also assisted with the fabrication of early prototypes.

Previous collaborations: *Les Gestes* grew out of several prior collaborations. The first is the *Digital Orchestra Project*, previously discussed in section 2.3 (Ferguson and Wanderley, 2010). The methodology of the Digital Orchestra project was also adopted for

Les Gestes, particularly in the regular interaction between technology developers, composers, and performers.

In addition, *Les Gestes* also grew out of an earlier collaboration between Ferguson, Van Grimde, and Malloch in the creation of the performance piece *Duo pour un violoncelle et un danseur*.

3.1.2 The goals of the research project

Here we present an overview of the goals of the research project, as articulated in the initial grant proposal submitted in October 2009 by Sean Ferguson, Marcelo Wanderley, and Isabelle Van Grimde (Ferguson et al., 2009).

The primary goal was the creation of a number of new digital musical instruments for use by musicians and dancers. Six specific issues were mentioned in this context, three of which refer to technical development of the instruments – incorporation of wireless communications, incorporation of audio synthesis in the instruments as opposed to an external computer, and incorporation of vibrotactile feedback. Two of the issues relate specifically to the use of gestural controllers by dancers, including the exploration of form-factors appropriate for this context as well as the application of gestural control to dance. For the latter issue it is described that Van Grimde will determine the role that the controllers play, drawing upon her experience "experimenting with different levels of dialogue between dance and music, and dancers and musicians."[2] The final issue is described as being the creation of techniques for mapping gestural performance data to control parameters of digital signal processing algorithms, intended to allow the dancers' gestures to modify in real-time the sounds created by the musicians.

For the artistic goals, the proposal argues that most original aspect of the project is

[2] All quotations in this section are from the unpublished grant proposal (Ferguson et al., 2009).

the "integration of musical issues of performance practice and artistic expression with those of dance choreography, and their combination with advanced research in gestural control, digital signal processing and sound synthesis." The argument in this section is built on the observation that much use of technology in dance performance is intended to require limited modification of the processes of dance performance and choreography. Indeed, the assumption is that the technology will be built around existing practices in this area, augmenting the dance performance rather than demanding a mutual engagement of technology and dancer. In this section it is articulated that the kind of engagement envisioned would depend on an interdisciplinary approach from the beginning.

The initial grant proposes that the project take place in three separate year-long stages that mirror those of the Digital Orchestra Project[3]: development of working prototypes, refinement into final instruments, and composition and performances of artistic works. At the conclusion of each stage a public workshop would be held, and at the end of the third year there would be a series of larger presentations of the "artistic and technological results of the project". In addition, the proposal describes the intention for a thorough documentation of the work completed in the project, notably through the creation of a website hosting the information.

Overall, we can characterize the goals described in the project proposal as the following, listed in order of their emphasis in the proposal:

1. Creation of DMIs for use by dancers, focusing on physical form factors and integration into performance practice.
2. Clearly articulated implementations of existing technology into DMI use.
3. Exploration of the use of these DMIs by dancers, including issues of mapping and

[3]See section 2.3

examining ways in which dancers' performance practices adapt to accommodate the instruments.

4. Documentation and public presentation of research results.
5. Creation and presentation of artistic works for public exhibition.

From the point of view of this dissertation these goals are primarily concerned with technical functionality, aesthetics, and use in the artistic creation process. It is clear that the identification of form-factors for DMIs for dancers is a priority, including concepts for flexible or hinged instruments. However the ways in which these new form-factors will impact manufacturing and re-usability of the devices are not discussed. In particular, the mechanical challenges associated with designing instruments for dancers appears not to have been anticipated.

Many of the technical challenges articulated in the proposal are concerned with system architecture, with a particular emphasis on ways in which new instruments will fit neatly into the practice of dance rehearsals. The need for wireless devices, for example, was clearly articulated as required to avoid cables interfering with dance performance practice. In addition, the intention of creating instruments which incorporate both the gestural sensing as well as the audio synthesis would mean the instruments would not "require a separate computing device in order to function. This would be especially valuable for practical reasons, such as ease of rehearsal, since the instrument would be much more portable. Performers would be able to take the instruments with them easily on a tour, for example."

While manufacturing and re-usability concerns are omitted from the proposal, one sentence does hint at the challenges which the project would encounter: "The students in music technology will be able to have their own work tested under the concert conditions, in which a hardware failure or a software crash is disastrous. They will therefore learn to create extremely robust systems that are more highly polished and reliable than what is required for a demo at a conference, for example."

While concrete project outcomes are described in the proposal, including public workshops as well as publications, it is useful to note the lack of emphasis given to the artistic presentations at the conclusion of the project. They are described as being an extension of the workshop at the end of the third-year, and occurring within the context of the live@CIRMMT concert series held in the MultiMedia Room of the Schulich School of Music. No mention is made of a tour of the works or performances outside of Montreal. However, by the time I became affiliated with the project, concrete tour plans had been developed.

Design schedule: The progress of the project loosely followed the plan laid out in the grant proposal, the most important characteristic being the periodic workshops and the subsequent public presentations. As anticipated, these workshops provided concrete targets for the development efforts of the technology, as well as being occasions for an in-depth appraisal of the prototype instruments in a real-world context. Appendix B presents the overall schedule for the project.

At each workshop, the choreographer, composers, and instrument designers met for two weeks and work would be created drawing upon each of their contributions. As instrument designers, the workshops presented hard deadlines by which functional instruments had to be ready. They also presented an opportunity for iteration of prototypes within the span of each workshop, in order to address specific design problems.

3.1.3 The use of interactive technologies in dance performance

Most systems created to enable the interaction of dancers and electronic or digital systems utilize motion-sensing technology, either to sense the physical motion of the dancers or their location within the performance space. Perhaps the earliest such system was Léon Theremin's *Terpsitone*, a modified version of his Theremin electronic instrument (Mason, 1936). Both instruments use a system in which elements of the production of an electronic sound, such as pitch and amplitude, change in relationship to the changes of capacitance between a metal conductor and a performer's body. In the Terpsitone, the conductor is a large metal plate placed on the floor. Changes in the body posture of a dancer standing upon the plate vary the capacitance, allowing control of musical pitch. The Terpsitone is notable in that there is an expectation that dancers would create specific pitches, and even included a visual feedback device that used lights to indicate which musical pitch is being generated.

John Cage and Merce Cunningham's 1965 collaboration "Variations V" was another early dance piece to incorporate interactive technologies (Copeland, 2004, p. 140). The piece also used capacitive changes to enable the control of electronic sound, this time through interaction with 12 vertical metal antennae, as well as utilizing photoelectric cells which would trigger sounds when the dancers' shadows would fall upon them. In keeping with Cage and Cunningham's philosophy, in this system the dancers are not expected to control the system to generate specific musical results.

Contemporary interactive dance systems commonly utilize either computer vision, wearable motion sensors, or sensors which directly sense the bending of joints. Computer vision-based interactive systems have been used for some time, with David Rokeby's *Very Nervous System* being a very early example from the 1980s (Winkler, 1997), and *EyesWeb* (Camurri et al., 2000) and *EyeCon* (Wechsler et al., 2004) being developed in the 2000s. Wearable motion sensors typically incorporate some combination of accelerometers, gyroscopes, and magnetometers. The *Sensemble* system, for example, incorporates both a 3D accelerometer and 3D gyroscope (Aylward and Paradiso, 2006).

Several systems for measuring joint angles have been developed (Siegel and Jacobsen, 1998; Mulder, 1994), including a commercial offering by Yamaha, the *Miburi* suit (Vickery, 2002). These systems, like those described above, generally try not to restrict the dancer's movements. Their goal, as stated in Siegel and Jacobsen (1998), is that "if a dance interface is to be used by more than a handful of performers, then it must be capable of interpreting dance gestures without severely limiting the types of gestures that can be employed by the dancer or demanding that the dancer master difficult instrumental techniques."

The goal of the Prosthetic Instruments is to directly challenge this assumption, and to explore the incorporation of demanding, intrusive physical objects into dance performance. In this way, we are less interested in what gestures are possible despite the instruments and more interested in what gestures are possible because of the instruments, as well as how gestures can function as both choreographic material and as control gestures for digital musical instruments.

3.2 Technical description of the instruments

In this section we will present a technical description of the Prosthetic Instruments. There are currently three members of the family of Prosthetic Instruments: the Visor, the Ribs, and the Spine. While their physical forms and electronics implementation may differ, their visual aesthetics and conceptualization as hypothetical prosthetic additions

Fig. 3.1 Dancer Sophie Breton wearing non-functional prototypes of the Ribs in rehearsal. The different sizes of the small, medium, and large Ribs are visually apparent.

to the body help to unify them as a single family of instruments.

My contributions: The work presented in this section was highly collaborative, primarily between myself and Joseph Malloch but also with contributions by Anthony Piciacchia. To clarify, each section will describe the role of each member.

3.2.1 The Ribs and Visors

The Visor and Ribs are curved, translucent forms that feature touch sensitivity along their length and embedded motion sensing.[4] The original design conception was for a

[4] I was the primary designer and manufacturer for the Ribs and Visors, although the design was based on sketches and mockups made by Joseph Malloch during the first workshop. The firmware was based upon earlier code provided by Joseph Malloch. Anthony Piciacchia assisted with the CAD[5] models for

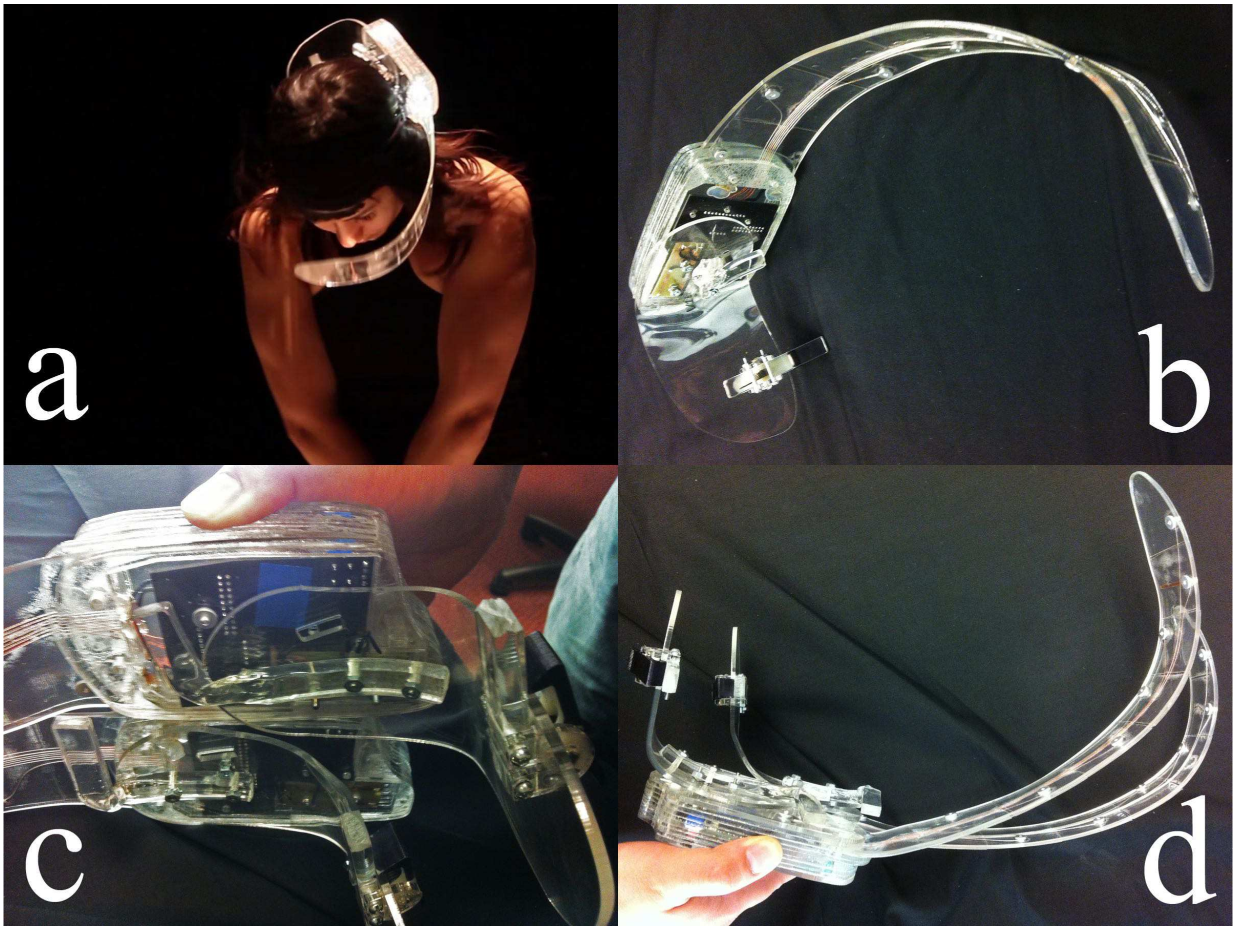

Fig. 3.2 Clockwise from top left: Soula Tragoukos wearing the Visor; a view of the Visor in which them mounting panel is clearly visible; the different shapes of the Visor formed for each dancers; and a closer look at the different shape of the Visors' and their mounting panels.

single form that could be attached to various points on the body, serving as a rib, visor, tusk, etc. However, during the course of development the evolution of their physical forms and their configuration on the body diverged and they assumed independent identities. Five final forms of Ribs and Visors were constructed - three Ribs of various sizes, which were worn as sets of three as seen in figure 3.1, and two Visors which were shaped to individually fit the two dancers' heads, shown in figure 3.2. Nonetheless,

the 3D-printed components.

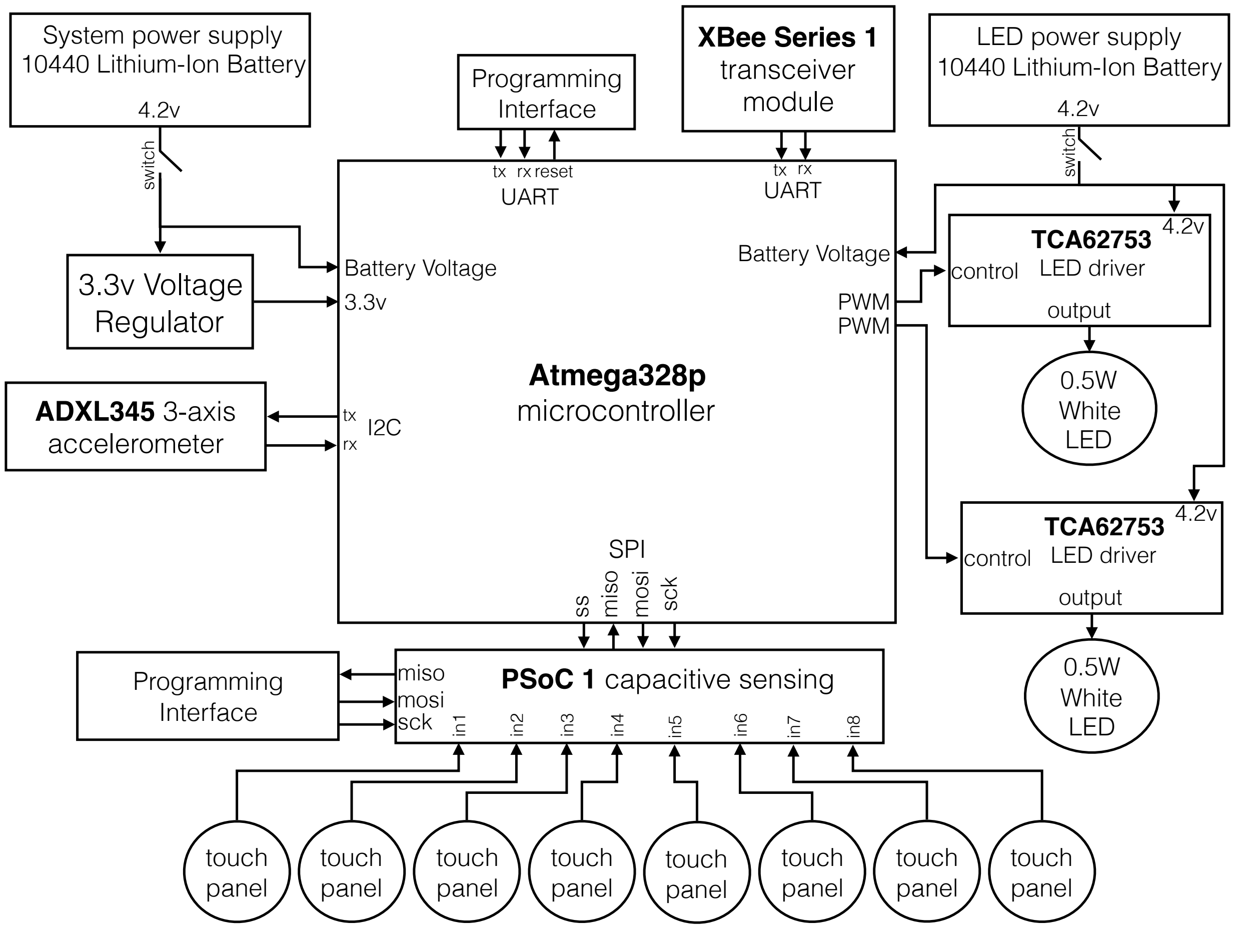

Fig. 3.3 A block diagram of the electronics for the Rib and Visor.

the electronics implementation on the Ribs and Visors is identical, and their physical construction very similar.

Electronics: The electronics in the Ribs and Visors consist of capacitive touch sensing, motion sensing, controllable lighting, wireless communications, and power management. The touch sensing is implemented via eight touch-sensing panels along the instruments' length, as seen in figure 3.4. The touch panels consist of a polyester film which is silver/indium sputter coated and has a nominal resistance of 27 ohms/square

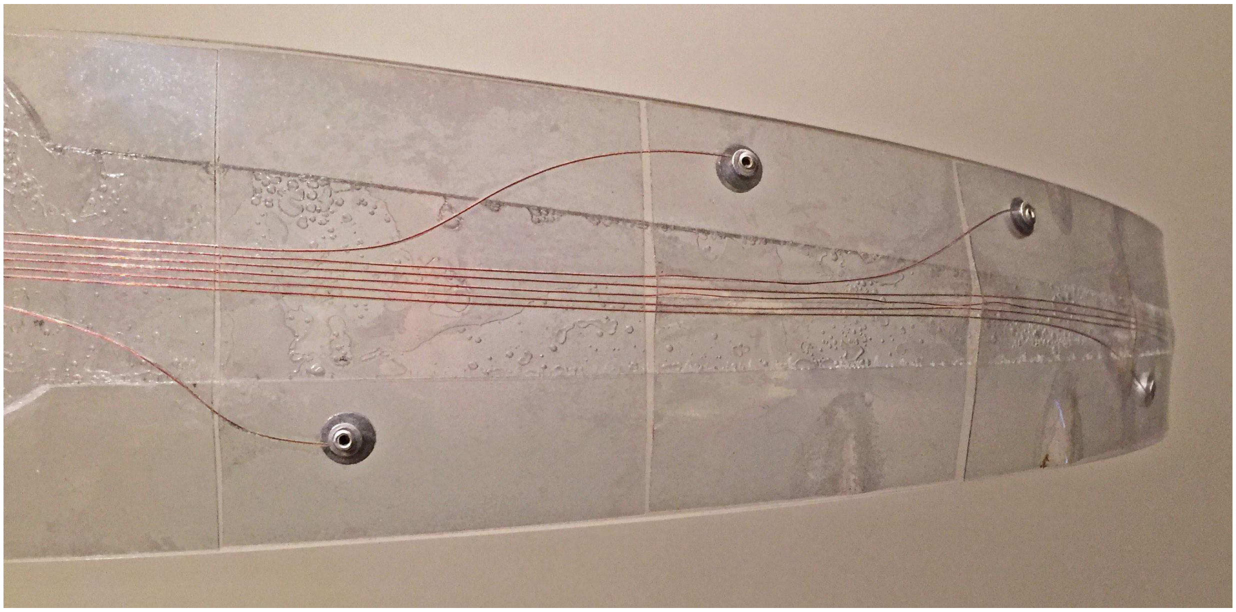

Fig. 3.4 A closeup of a Rib, showing four touch panels, the magnet wires, and rivets.

inch. The film has an adhesive backing applied, and is laser cut into panels which match the curved shape of the instrument's acrylic forms. Each instrument has eight shallow channels etched into its top surface, which lead from the electronics enclosure to holes cut in both the instrument and the touch panels. 32 AWG magnet wire is placed into each groove and a touch panel is attached to the instrument's surface, holding the magnet wire in place. An aluminum rivet is then inserted into the hole to make an electrical connection between the wire and the touch panel; the other end of the wire is soldered to headers on the printed circuit board (PCB).

To facilitate development, the outcome of a previous research project, the Sense/Stage MiniBee, was used to provide wireless communication (Baalman et al., 2010). While the MiniBee system includes firmware and software components, for the Prosthetic Instruments we wrote custom firmware and software and only utilized the hardware components of the MiniBee. The MiniBee version we used, rev. D, contains an ATmega

328p microcontroller, ADXL345 3-axis accelerometer, 3.3v voltage regulator, and headers for mounting an XBee radio transceiver. We designed a second PCB which contained headers for mounting the MiniBee as well as components to support capacitive sensing, controllable lighting, and connections for the removable battery. Figure 3.7 shows the electronics as installed in the Rib and the Visor.

Mechanical Construction: The Visor and Ribs are constructed primarily out of laminated layers of 1/8" clear acrylic. The Ribs contain two layers of acrylic for their entire length, one layer consisting of their primary form and the other consisting of a narrower support layer, which is visible in figure 3.4. In addition, a set of acrylic panels were lasercut and solvent welded to form an electronics enclosure at the Ribs' base. A removable cover for this enclosure was also created out of lasercut acrylic, and utilized a series of acrylic posts and magnets to secure to the main enclosure. The CAD designs for each of the layers of acrylic used in the creation of the Ribs is shown in figure 3.5.

Two additional layers cut from polycarbonate were added to the design of the Ribs in order to provide additional robustness. Acrylic tends to be quite brittle, and is susceptible to cracking when bent. Polycarbonate, on the other hand, will deform rather than crack when bent, and has higher impact-resistance than acrylic. However, polycarbonate is less suitable for lasercutting, with the edges of the cuts assuming a brown, burnt finish, as seen in figure 3.6. The polycarbonate layers provide both an additional layer of stiffness to the Ribs' mounting post and electronics enclosure, as well as preventing the total failure of the Rib in the case of the acrylic layers cracking under stress. Polycarbonate was also used to support the clip attached to the Rib.

The Visor is constructed of two parts - the main body, which includes all of the electronics, and a second panel which contains the mounting posts and a clip. The two parts

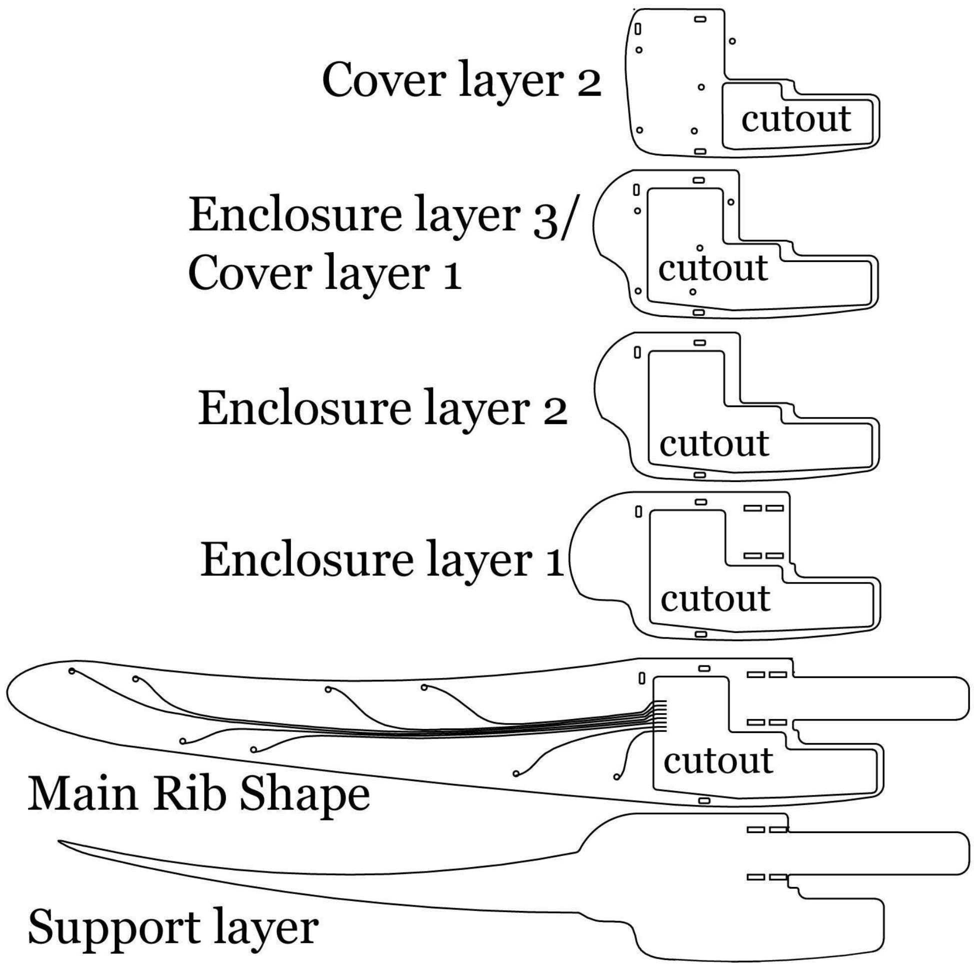

Fig. 3.5 The acrylic layers of a small Rib. Starting at the bottom, the support layer and the main Rib form are shown. On the main Rib form can be seen both the channels for the magnet wire as well as the holes for the rivets. The next three layers are solvent welded to the main Rib to form the electronics enclosure. The two cover layers are solvent welded together, and the cover is secured with magnets which fit into the circular holes of enclosure layer 3/ cover layer 1, and cover layer 2. The cutout which remains in cover layer 2 allows for the batteries to be replaced without opening the main electronics compartment.

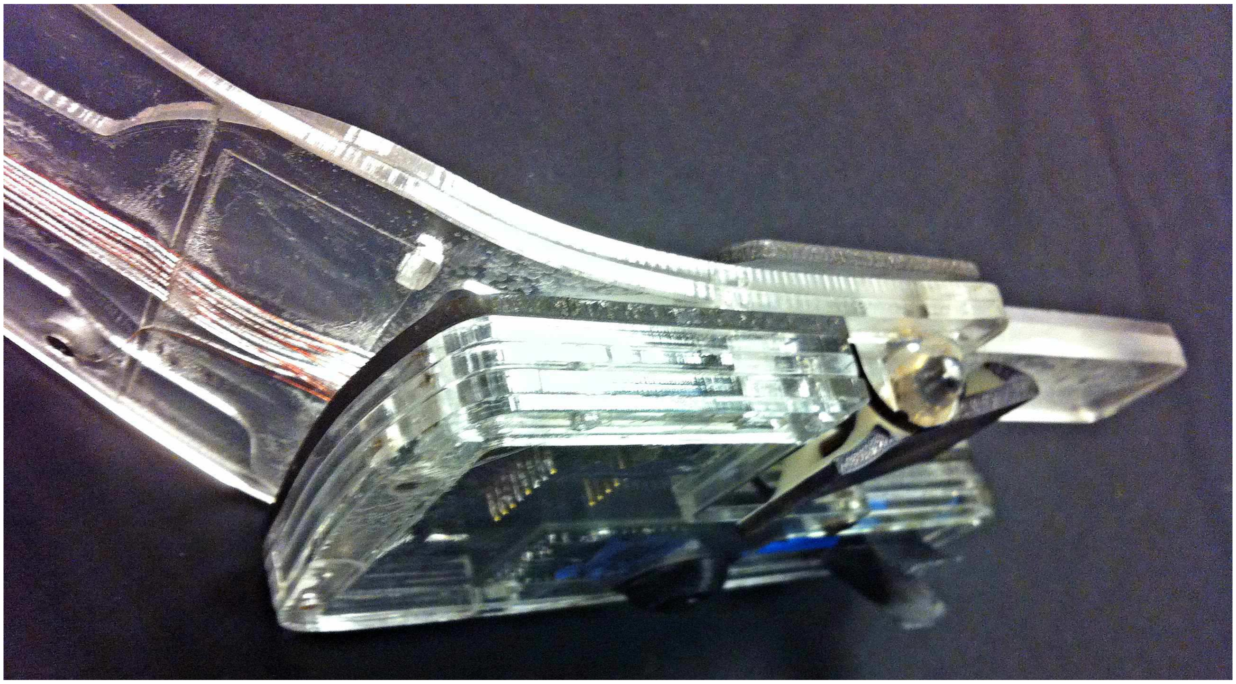

Fig. 3.6 Detail showing the laminate construction of the Ribs, with the protrusion and clip for mounting visible on the right. The polycarbonate layers are easily identified by their brown edges.

are shaped independently and fastened together at the last stage of construction. The main body of the Visors consists of a single layer of acrylic, with additional layers used to create an electronics enclosure as in the Ribs.

3.2.2 The Spine

The Spine consists of a long, flexible form which attaches to the rear of the head and the base of the Spine.[6] The electronics for the Spine are based on two commercially available 9DoF MARG (magnetic, angular rate, and gravity) boards, one located at head and one at the tail. Custom firmware written by Joseph Malloch handles communication, both

[6]The Spine was primarily designed and manufactured by Joseph Malloch. However, the lasercut and 3D-printed elements were collaboratively designed by Malloch, Piciacchia, and myself, and the lighting elements were designed by me.

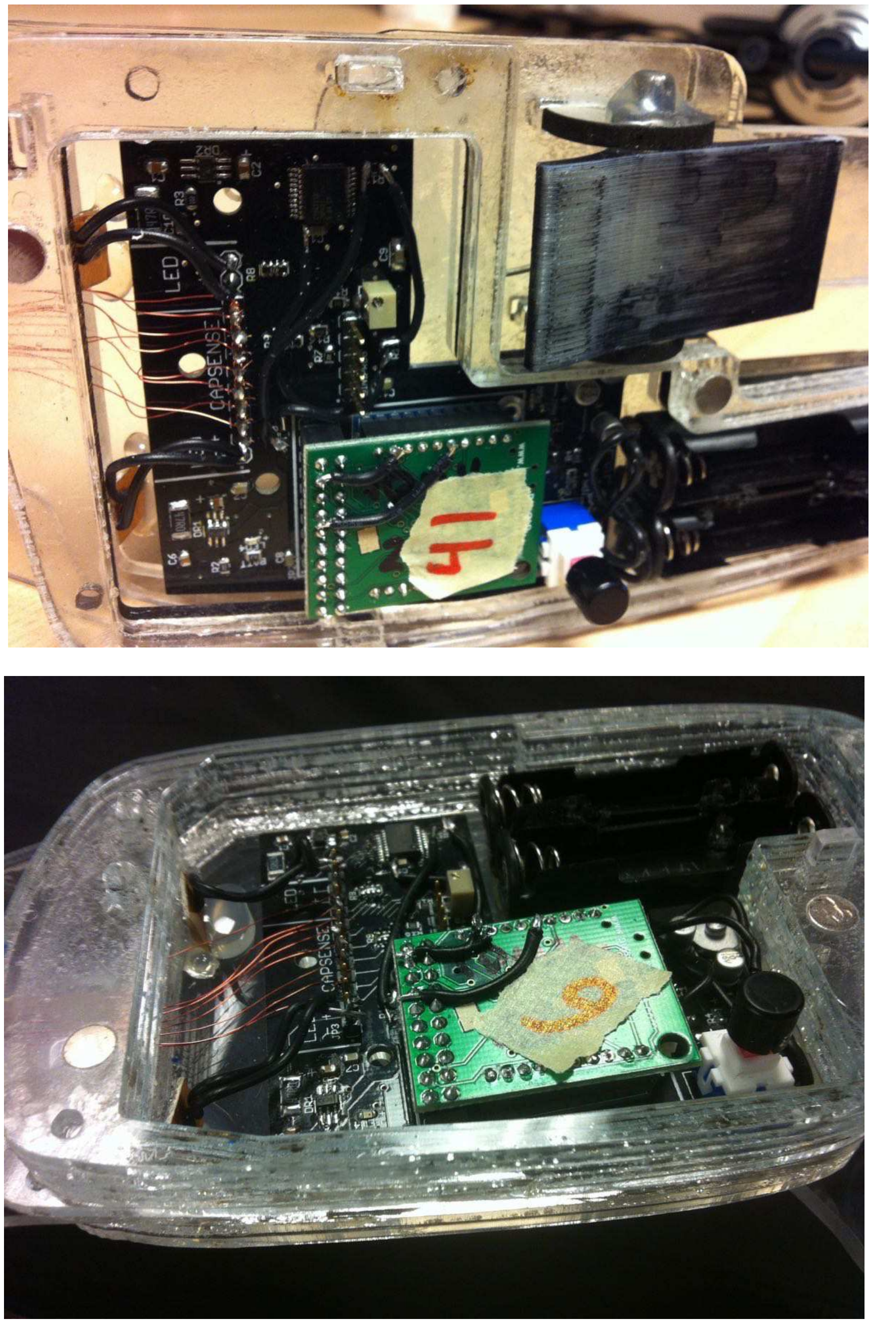

Fig. 3.7 The PCB and acrylic enclosure were designed at the same time in order to ensure a perfect fit. While most of the electronics were incorporated on the PCB, the LEDs and battery holders were mounted separately in order to allow for flexible position. (top) the electronics enclosure in the Rib, with the LEDs on the left positioned to shine down the length of the Rib. (bottom) the electronics enclosure in the Visor, showing the different location for the battery holder.

between the two MARG boards and between the board located at the tail and an XBee radio mounted on a breakout PCB. The firmware also implements sensor fusion of the MARG sensors in order to provide absolute orientation of the head and the tail, which then can be used to detect twisting and bending of the Spine.

Power for the sensing and wireless communication for the Spine is provided by a rectangular 3.7v lithium-polymer battery secured to a vertebrae using velcro, and which connects to one of the MARG sensor boards using a small JST connector. In order to provide lighting for the Spine, separate circuit boards containing MOSFET LED drivers and lithium-ion AAA batteries allow for the control of two LED flashlights mounted near the sensors.

Mechanical construction: The Spine is constructed of 1/4" thick acrylic vertebrae cut in a triangular pattern formed out of three extensions. At centre of each vertebrae is a hole through which the wiring connecting the two sensor boards passes, and additional holes for mounting the vertebrae are located at the end of each extension. Wide PVC tubing passes through two of the holes, providing a friction fit which secures the relative position of each vertebrae. A narrow, flexible PET-G rod passes freely through the hole on the third extension of the majority of the vertebrae, and is firmly attached to the bottom vertebrae and the second-from-the-top vertebrae via either a friction-fit mount made out of the PVC tubing or using a 3D-printed mount as seen in figure 3.8.

While the friction-fit of the PVC tubing preserves the relative location of the vertebrae, its pliability does not provide form to the instrument, which is instead provided by the stiffness of the PET-G rod. In addition, the fixed length of the rod forces the Spine into compound curves, where a curve formed at one end of the instrument creates an opposing curve at the other end.

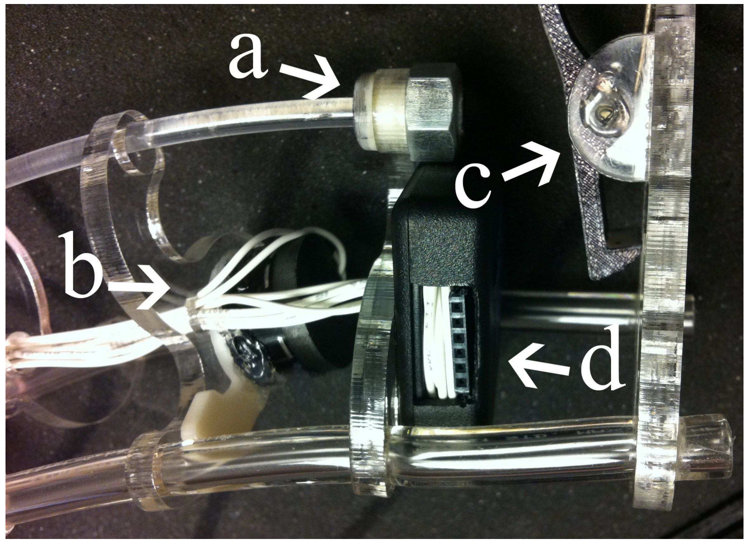

Fig. 3.8 The top of the Spine, showing various features: a) the Pet-G rod secured to the second-to-the-top vertebrae using a 3D-printed mount; b) the wiring for the sensor board coming through the central hole of a vertebrae; c) the mounting clip; and d) the sensor board in its plastic enclosure.

3.2.3 Common elements of the Prosthetic Instruments

The Prosthetic elements share several electronic and mechanical elements in common, including mounting hardware and wireless communication.[7]

Wireless implementation of the Prosthetic Instruments: The wireless communication in the Prosthetic Instruments is based on XBee series 1 radio transceivers, which are configured in a network consisting of a single coordinator and multiple end devices. The XBee functioning as the coordinator is connected to a central PC using a USB breakout PCB, and each individual instrument contains an XBee set up as an end device. Each instrument's firmware consists primarily of functions for gathering sensor data and trans-

[7]The SLIP encoding protocol and network configuration was defined by Joseph Malloch. The wireless details in the Ribs and Visors was implemented by myself. The sensor signal processing for the Spine was created by Joseph Malloch, and for the Ribs and Spines by myself and Joseph Malloch. The LibMapper and CLEF integration was by Joseph Malloch and Marlon Schumacher.

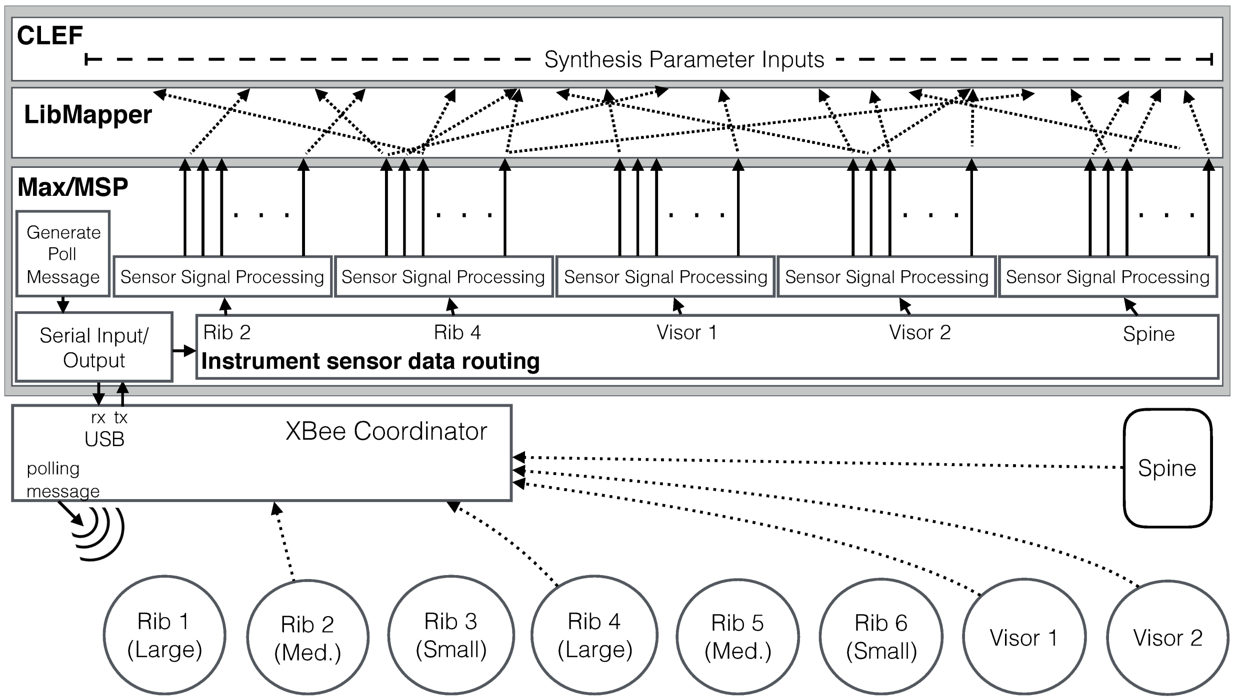

Fig. 3.9 The signal flow for the Prosthetic Instruments as used in *Les Gestes*. Blocks within the grey border are software environments located within PCs.

mitting to the XBee coordinator. A diagram of the signal flow for the system used in *Les Gestes* is shown in figure 3.9.

A wireless protocol based on single-ended Serial Line Internet Protocol (SLIP) encoding is used (Romkey, 1988). The data packet for each instrument is a fixed format, consisting of a single byte which serves as an instrument ID, and multiple bytes to accommodate the instrument's sensor data. Data flow for the system is controlled by a polling scheme, in which the coordinator broadcasts a single-byte polling message to all of the instruments. Upon receiving this polling message, each instrument transmits a packet consisting of the most recent sensor data to the coordinator.

Two Visors, one Spine, and three sets of Ribs were used in the performance of *Les Gestes*, each set of Ribs consisting of a small, medium, and large Rib. One challenge in wireless communication was managing transmission collisions from the various instruments. Each instrument transmits its sensor data simultaneously in response to the polling message, and we found an increase in dropped wireless packets when more than six or seven instruments were transmitting. Two strategies were adopted to address this problem. The first is that the Ribs and Visors were not always powered on, either being turned off as they were taken off-stage or being turned off as part of the choreography. Secondly, only one of each set of Ribs had sensor data transmission enabled. Within the context of the performance, this was seen as acceptable as the motion data for the individual Ribs tends to be similar, and the choreography took into account which Ribs transmitted sensor data to the computer.

When data from an instrument is received by the central PC, it is routed to software routines dedicated to that instrument, and then the processed sensor data is first passed to the LibMapper software (Malloch, 2008), which then maps the sensor data to sound synthesis parameters in the CIRMMT Live Electronics Framework (CLEF) software environment (Schumacher et al., 2013). The system as described in this paper consists of the instruments and the sensor signal processing software created in Max/MSP; the use of LibMapper and CLEF environment were the work of other researchers.

Mounting the instruments: The Prosthetic Instruments were created to be easily attachable and removable to costumes worn by the dancers.[8] This is accomplished by a system consisting of 3D-printed mounts and clips, and mounting posts which are integrated into the lasercut forms of the instruments. While our initial desire was to have a universal mounting system for all of the instruments, the final designs use two different

[8] The design and construction of the mounts was completed by myself with the assistance of Anthony Piciacchia. The corset and headband were designed and created by Pascale Bassani, and the wedges were designed and created by myself.

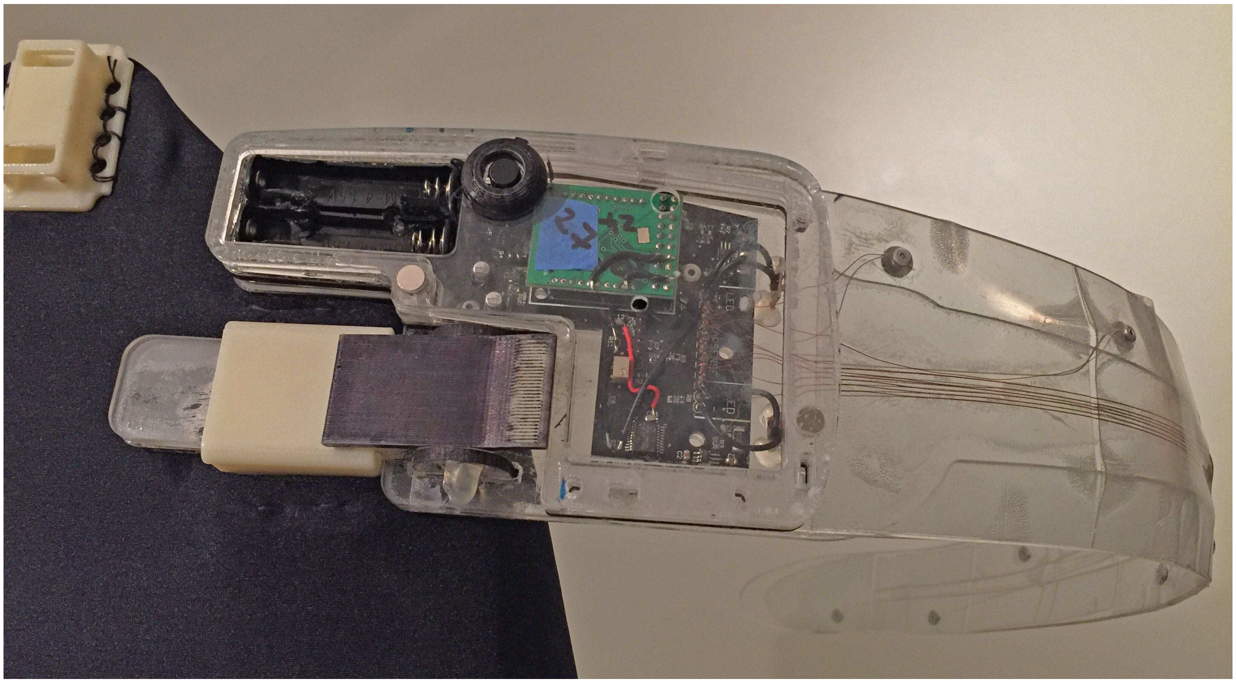

Fig. 3.10 The mounting system designed for the Prosthetic Instruments. On the top left is a 1/2" mount, with the holes provided for sewing to the garment and the slot for the clip easily visible. The mount for the Rib has fabric covering the sew holes.

widths to accommodate the needs of the different instruments. As the Ribs were quite long and heavy, a 1" mounting post was designed into the instrument body, as can be seen both in figure figure 3.6, 3.5, and 3.10. The mounts for the Spine and Visor, on the other hand, did not suffer the same kind of mechanical stress, but instead were mounted in places where a smaller mounting post is more appropriate, and so a 1/2" mounting post was suitable, which can be seen in figure 3.2.

The mounts contains three key elements: a slot which fits the mounting posts; a slot for the tooth of the clip; and holes for sewing the mount to custom-designed corsets and headbands, as seen in figure 3.10. The tooth of the clips as well as the matching slots were designed so as to allow for the instruments to be easily and securely attached to the garments. In particular, we found that a slightly long tooth with a rounded front

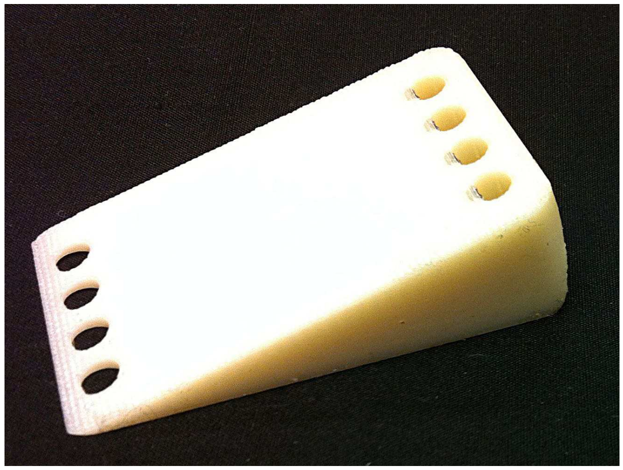

Fig. 3.11 A 3D-printed wedge which fits between a mount for the Ribs and the corset, changing the vertical angle of the instrument.

edge allowed the tooth to easily find and slip into the slot.

Several modifications to the garments and mounts were made in order to assure the stability and correct orientation of the instruments. The cantilevered weight of the Ribs required additional support in the corset. For this purpose, a 3/32" sheet of PET-G was embedded into the back of the garments whose resistance to sheer prevents the mounts from rotating under the weight of the instruments. The mounts were then sewn both into this support as well as the corset's fabric. In addition, plastic wedges were created to alter the vertical angle of the Ribs with respect to the dancers' torsos. These wedges, one of which is shown in figure 3.11, contain holes which match the sew-holes of the mounts, allowing them to fit between the mounts and the corset.

Similarly, a strip of 3/32" PET-G was sewn into the headbands to reinforce them. In addition, a clear plastic chin-strap was added to prevent the weight of the instruments from pulling the headband off during rapid movements.

3.2.4 Preparing the Prosthetic Instruments for touring

There were several considerations when preparing the Prosthetic Instruments to go on tour.[9] One of our primary concerns was that the touring staff would not include a dedicated technician for the instruments. Instead, the task of preparing and supporting the use of the instruments for each performance was taken care of by the production assistants and a technician whose primary responsibility was running the software used for the composition. Several training sessions were held which covered battery maintenance, an overview of the instruments in use, preparing the instruments for shipping, and preparation in case of instrument failure during a performance.

Battery management: In designing the power systems for the Prosthetic Instruments, we were aware that it would be common for rehearsals to take place immediately prior to a performance. For this reason, we ensured that the batteries were easily removable, and that enough batteries would be provided to allow for a full set to be charging while the instruments were in use.

Two different types of batteries were used, a rectangular lithium-ion polymer battery[10] and a cylindrical 10440 lithium-ion battery[11]. The rectangular battery used to power the Spine's primary electronics is of a type commonly used for permanent installation inside electronic devices, and attaches using a miniature JST connector. As only one Spine was used per performance, a single commercial battery charger was necessary, although two were purchased in order to have a backup. The cylindrical batteries fit inside standard 10440 (or AAA battery sized) battery holders which were mounted

[9] I was responsible for all of the work described in this section.
[10] https://www.sparkfun.com/products/339
[11] http://www.batteryjunction.com/10440.html

in the Ribs and Visors, as well as on the Spine to provide power for the lighting. Four commercial battery chargers with four charging ports each were purchased to be able to charge a full set of 16 cylindrical backup batteries simultaneously.

One of the primary duties of the stage technicians was battery management, meaning ensuring that all of the batteries remained charged and that fully-charged batteries were inserted into the instruments prior to rehearsals and performances.

Using the instruments in performance: In recognition of the non-technical background of the production staff, we minimized the amount of interaction necessary to prepare the instruments for performance. As there was a technician on tour to manage the software running the composition, we were concerned only that the instruments be able to be turned on and their data routed to the composition software, as seen in figure 3.9.

To accomplish this, all of the parameters for the instruments themselves, including their device IDs, were stored either directly in the instruments' firmware or in non-volatile EEPROM. Software was created to make it possible to wirelessly change the instruments' device IDs and to enable or disable wireless transmission from the Ribs and Visors, as discussed in section 3.2.3.

Within the software environments depicted in figure 3.9, all of the processing occurring within Max/MSP was designed to not require any manual interaction. The only UI aspects designed within this stage was simple feedback to indicate the reception of wireless messages from the different instruments, as shown in figure 3.12.

Backup instruments: During the evolution of the forms of the Ribs, discussed below in section 3.4.1, there were several problems with Ribs cracking under stress. Due to this fact, and also to ensure a full set of functioning instruments in case of problems, a set

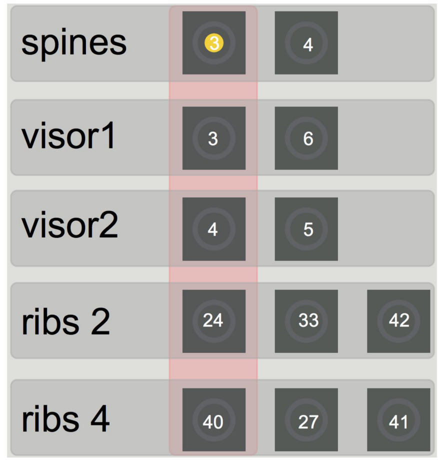

Fig. 3.12 When a message is received from an instrument, visual feedback is provided in which a button briefly lights up below a number indicating the instrument's device ID. Each row represents a single instrument used in the performance. The vertical columns represent the primary and backup instruments, with the red column indicating the primary instruments. Ribs 2 and 4 also utilize a third instrument, which is used in the opening section of the piece.

of backup instruments were created and shipped on tour. Sensor signals from both the primary and backup instruments were routed to the same sensor signal processing routines, and the production staff were trained that only one of the two should be powered up at a time.

The success of our preparations for instrument failure were never tested as there were no instrument mechanical or electronic failures in any of the performances.

Shipping the instruments: Since the instruments would be touring internationally, and would be shipped as part of a carnet, hard-shell cases for the Ribs and Spines were purchased. For the carnet, however, we decided to ship the Ribs and Visors within a larger shipping container along with other equipment. To protect them we purchased 22"x15"x4" polyurethane foam blocks,which we determined would be big enough to fit the larger Ribs. In addition we used Pelican pick'n'place foam which came with the hard

Fig. 3.13 The Ribs, Spines, and Visors encased in pink anti-dissipative plastic and placed in their protective foam enclosures, ready for shipping on tour.

case purchased for the Ribs. Each foam block then had cavities cut out for three of the Ribs or Visors. For the Spines we purchased a rifle case and cut cavities into the foam.

To protect the instruments against abrasion and electrical static build-up during transport, static-dissipative plastic tubing was purchased and cut into sections long enough to accommodate each individual instrument. Figure 3.13 shows the Prosthetic Instruments inside their protective plastic, and placed in the foam supports, ready for shipping.

3.3 The Prosthetic Instruments in performance

The first public performances of *Les Gestes* took place from March 13 - 16 at L'Agora de la Dance in Montreal. The production was installed from March 4 - 12, during which time the lighting was installed and programmed, the artistic work was finalized, and the pre- and post-performance process was decided upon. Following these initial performances, a short European tour took place in April 2013, which included performances in Paris, Bruges, and Arnhem.

The production team had considerable experience working with costumes and props, and they helped to create a backstage plan to facilitate the use of the instruments in performance. Two areas were created, the first for instruments which would not be in immediate use, and a second area for the instruments which the dancers would be attaching during the course of the production. In the first area locations for each instruments were defined, as well as for the battery chargers. Instruments would be stored in this area without batteries. Prior to and during the performance, batteries would be installed in those instruments which would be used, the Ribs would be placed in the corsets, and the production staff would place the prepared instruments in the performer staging area.

3.3.1 Additional uses of the instruments

Following the final performance of *Les Gestes*, I utilized the prosthetic instruments in several additional artistic projects. These projects are discussed here for the ways in which they utilized the instruments in different ways and illuminate aspects of the instruments' design.

Koumaria art residency: In October 2013 I was invited by McGill Professor of Philosophy Eric Lewis to participate in an arts residency program established by the art collective Medea Electronique[12], and for this trip I brought a full set of the prosthetic instruments to Greece with me, with the intention of using the instruments in a variety of contexts. Ultimately, they were used in four different projects during the residency: two live performances, an artistic installation, and a film project.

1. **Finding Maximum Grip**:[13] Dancer Alessandra Fabbri wore the Spine in this semi-improvised duet with bassist Dimitris Tigras. For this piece, I created an open musical score, as well as programming new synthesis and mapping algorithms. During the piece, audio from a pickup on the bass is continually recorded into a short audio buffer, and the Spine controls an FFT-based resynthesis using the buffered audio. A large part of the composition focusses on utilizing contrasting performance techiques for the two performers while they simultaneously utilize the same material (although time-shifted, as the Spine operates on the audio in the buffer).

2. **Herbario Fantastico**:[14] This piece was a collaborative creation between myself, dancers Hen Lovely Bird, Alessandra Fabbri, musicians Eric Lewis and Guido de Flaviis, projectionist Alessandra Leone, and projectionist/costume designer Jasa Baka. In this piece Bird utilized a set of Ribs and Fabbri wore the Spine, and the instruments' visual appearance were augmented by costuming created by Baka. For the first part of the piece the music is entirely created acoustically, while in the second part the sound is generated by the instruments, for which I created a new

[12]http://www.medeaelectronique.com
[13]https://vimeo.com/84896942, password: MUMT
[14]https://vimeo.com/84988534, password: MUMT

set of synthesis and mapping algorithms.

3. **Prosthetic Windchimes**: In collaboration with Eric Lewis, I created an installation in which the Ribs were suspended from trees in a public garden and functioned as 'wind chimes' which would both be activated by the wind but could also be activated by human actions. I utilized a peak detection algorithm which analyzed accelerometer data from the Ribs to identify sudden movements in the Rib. This algorithm was dynamic in order to adjust its threshold to sensitive to small movements based on environmental conditions while also being able to respond appropriately to human interaction.

4. **The Golden Owlive**: The instruments were used as props in this short film, created by Jasa Baka. During the film the instruments are worn by dancers Hen Lovely Bird and Stavros Apostolatos, visually augmented by costumes designed by Baka.

The hardware utilized for this residency was the same as that used for the performances of *Les Gestes*, except for resizable corsets created by costume designer Pascale Bassani. Although the primary users of the instruments during the dancers were women of comparable size to the dancers from Les Gestes, the instruments were also worn in rehearsals as well as in *The Golden Owlive* by dancer Stavros Apostolatos, a 6″2′ tall man. Although the curvature of the Ribs was found to be appropriate for Hen Bird, it was tight but wearable by Stavros. In addition, the length of the Spine was short enough that it constrained Stavros' movements.

The instruments were first presented during the residency as handheld controllers, and then the dancers were invited to try them on. Rapidly Hen and Alessandra were drawn toward different instruments, Hen towards the Ribs and Alessandra towards the

Fig. 3.14 A small corset created for Seth Woods by costume designer Pascale Bassani.

Spine. Both dancers seemed to find the physical affordances of the instruments, as well as their visual aesthetics, as primary considerations for choosing to work with them, rather than their interactive functionality.

***Almost Human*:** In 2013-2014 I collaborated with cellist/dancer Seth Woods on the composition *Almost Human*, for cello and Spine. Woods had attended a performance of *Les Gestes* in Paris, and contacted me interested in collaborating shortly thereafter. He travelled to Montreal in October 2013 and April 2014, during which time we explored the application of theories developed during his PhD research to performance with the Spine. His primary research was on using Laban notation techniques to annotate cello performance gestures, primarily for pedagogical purposes. Our concept for the piece was to identify specific cello performance gestures which were idiomatic to Seth's performance practice, analyze them for their gestural content, and then to use these analyses to create performance techniques which translate this content into performance gestures for the

Fig. 3.15 The mounts used in the quadcopter project. Clockwise from top left: a) A mount attached to an arm. b) A mount with a Rib inserted. c) Playing the Rib using the capacitive touchpads. d) Playing the Rib using motion data.

Spine.

For the piece I implemented new sensor signal processing, synthesis, and mapping algorithms. In addition we had Pascale Bassani create a mini-corset which omitted the mounts for the Ribs, shown in figure 3.14.

Performer-controlled quadcopter choreography: In 2014-15 I collaborated with students from Concordia University on a project to enable a performer to control quadcopter trajectory generation in real-time during a musical performance. My role in the project was to create trajectory creation algorithms and create and perform a composition using these algorithms. For this project, I used two Ribs as as interfaces for controlling both sound synthesis as well as quadcopter trajectories. As this project was focused on musical performance rather than dance, I created new mounts for the Ribs which allowed me to manipulate them with my hands more easily.

These mounts secure with velcro straps to the top of the forearms, shown in figure 3.15. With the Ribs inserted, one hand is able to to interact with the capacitive touchpads attached to the opposite arm. At the same time, the motion sensors in the Ribs allow for control data to be generated using arm gestures, movement, and orientation. One set of data I used extensively was the relative orientations and movements of the two Ribs.

These new mounts faced the same challenge as the mounts used in *Les Gestes*, that of creating a stable attachment between the body and the cantilevered weight of the instruments. The attachment created by the forearm mounts had the following properties:

- The velcro straps needed to be tightly secured, a difficult process to do by yourself.
- The attachment is compromised by clothing underneath the mount. In practice, I attempted to minimize the layers of clothing worn during the performance.
- When securely attached, the elongated form of the mount and the two velcro straps prevented the instrument from rotating along several axes.
- The biggest problem was a tendency for the instrument to rotate around the forearm, as that axis receives the least support from the mount's design.
- Another problem was instability along the length of the forearm, in which the Rib would rotate slightly. Given the elongated form of the Rib, even small movements due to compression of the muscles of the forearm would cause larger movements of the length of the Rib.
- One performance strategy I utilized was to press the back of my hand against the

Rib, providing another point to stabilization from the Rib. The variable nature of this point allowed me to change the force I applied to the Rib to suit the current performance conditions.

3.4 Discussion

The process of developing the Prosthetic Instruments made it very clear that the creation of a successful instrument in contexts such as *Les Gestes* involves the consideration of much more than meeting functional design requirements. In fact, the basic technical requirements and implementation, including the choice of sensor technologies and wireless implementations, had been decided upon before I joined the project. Perhaps the most interesting outcome of the project, as regards as the design process, was the way in which the requirements of the various design aspects interacted through the course of this project.

3.4.1 The evolution of the Ribs

Nowhere is this more evident than in the evolution of the Ribs, both in terms of their technical design, their aesthetics, and their manufacturing. During the course of development, the Ribs went through six major developmental stages:

1. An initial conceptual prototype made out of opaque, semi-rigid plastic.
2. The first functional prototypes, created out of translucent acrylic which matched the size and forms of the initial conceptual mockups, with touchpads and traces made out of copper tape to enable touch sensing.
3. Several prototypes exploring different materials for both touchpads and traces,

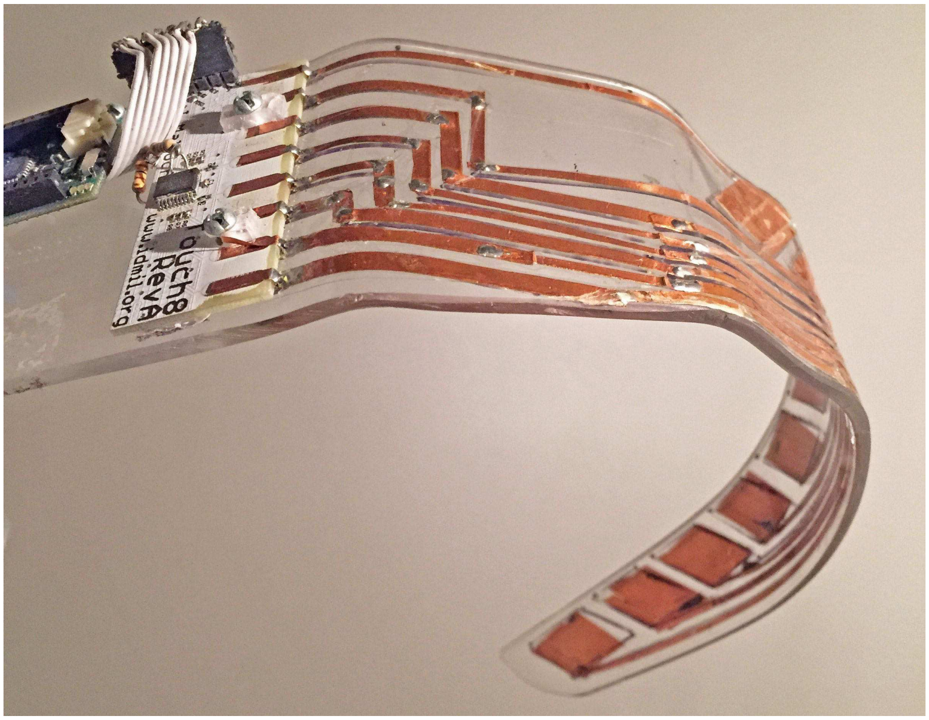

Fig. 3.16 One of the first functional Rib prototypes, with copper touchpads and traces.

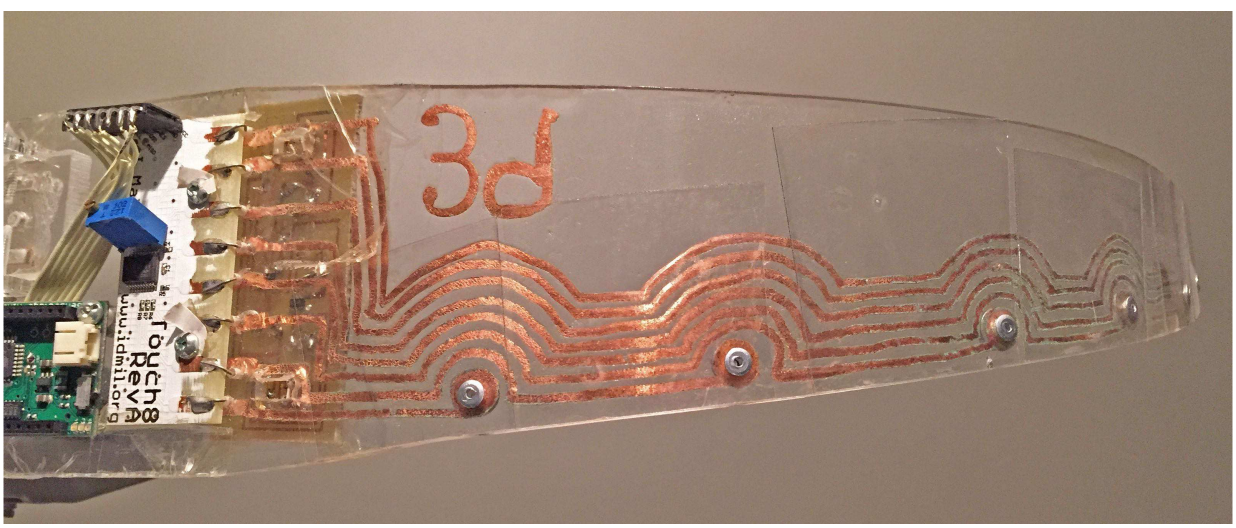

Fig. 3.17 A Rib prototype created with etched copper traces and transparent conductive plastic touchpads.

exploring both possible materials as well as manufacturing methods.

4. Initial prototypes using conductive plastic and magnet wire, created in similar sizes and shapes as the early prototypes, and conceptualized as being usable as both Rib and Visor.
5. A set of three Ribs in various sizes, manufactured using a laminate acrylic structure. This is the point at which the Visor assumed a form different than the Rib.
6. The final design of the Ribs incorporating the electronics enclosure and additional laminated layer of acrylic and polycarbonate.

Changes in each step were driven by the requirements of the various design aspects. The move from stage 1 to stage 2, for example, was driven by the need to implement the capacitive sensing, to explore manufacturing techniques for shaping and bending acrylic, and an exploration of the aesthetics of clear acrylic and copper traces.

The continuing exploration of materials for the touchpads and traces was largely driven by aesthetic concerns. While our intention in using copper pads and traces was to evoke the intricate network of electrical traces found on printed circuit boards, the prototypes in stage two were crudely made out of copper tape and soldered connections with a decidedly unrefined appearance, as seen in figure 3.16. In stage three we explored a variety of approaches to manufacturing more intricate copper shapes, leading to the prototypes shown in figure 3.17. While the results of these prototypes were clearly a step towards more intricate copper traces, the manufacturing process of creating them was prohibitively time-consuming and several technical challenges remained unsolved.

Finalizing the Ribs' technical design: The Ribs created in stage four incorporated several changes based on earlier designs. First, they used magnet wire to connect the plastic touchpads to the PCB, allowing both for a less intrusive and simpler visual appearance.

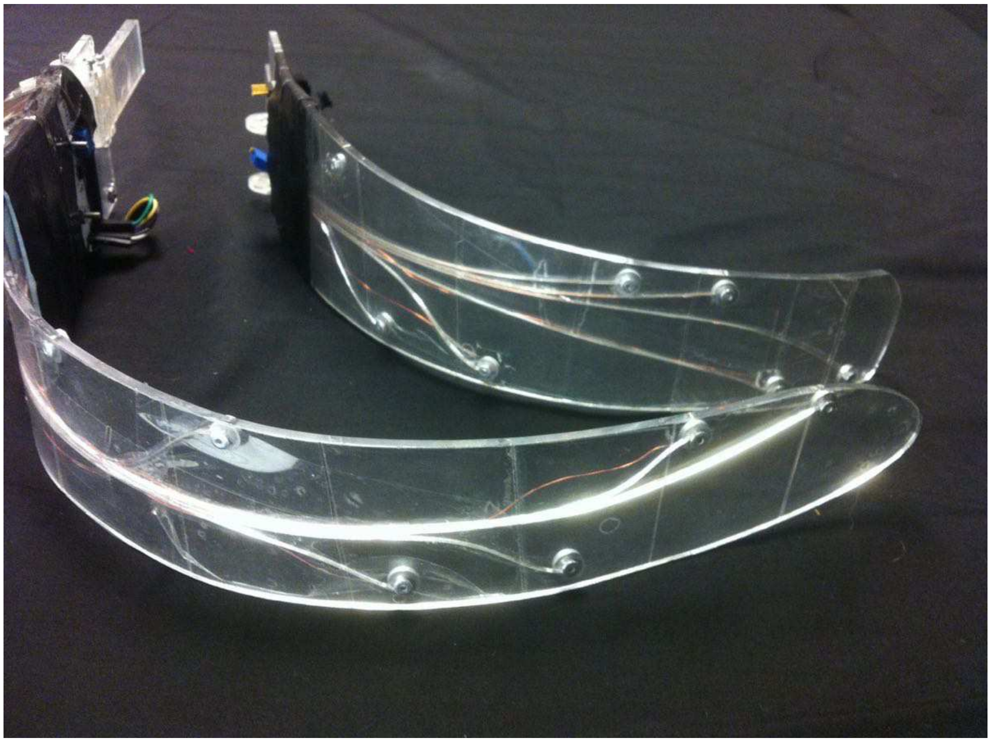

Fig. 3.18 The first two Ribs created using magnet wire. Notice the black gaffers tape attempting to compensate for cracks in the acrylic.

Second, they were sized slightly larger as the dancers had already indicated the rigid plastic forms needed to be larger than the semi-flexible conceptual prototypes.

The visual aesthetic of the transparent pads and magnet wire were immediately successful, and were maintained virtually unchanged through to the final prototype. However, the change of visual appearance led to several unintended consequences. First, the instruments had much less visual impact than the earlier versions with opaque copper pads, leading us to decide that forms of the Ribs must be much larger. The evolution of the Ribs' sizes is shown in Table 3.1.

The move to create larger size Ribs created several additional issues. First, the longer, single-ply forms were prone to flexing along their length during both dynamic movement and also under any pressure from the dancers' arms. Flexing in this way was aesthetically problematic, preventing the Rib from presenting as fixed part of the dancers' bodies, and also led to structural problems. In rehearsals, it contributed to both of the prototypes from stage four cracking at the base of the electronics mount, necessitating reinforcement with black gaffers tape as can be seen in figure 3.18.

Rib version	Date	Length
Stage 2	*February, 2012*	12
Stage 3	*April-June, 2012*	14
Stage 4, Small	*August 2012*	14
Stage 4, Large	*"*	18
Stage 5 & 6, Small	*October 2012*	18.5
Stage 5 & 6, Medium	*"*	24
Stage 5 & 6, Large	*"*	28

Table 3.1 Evolution of the Rib shapes showing their increased lengths. Lengths do not include mounting bars.

A laminated structure for the Ribs was created in order to create a stiffer form, as well as to provide an enclosure for the electronics. For the final design, the instruments' form and the final PCB were co-designed in order to ensure a perfect fit, as seen in figure 3.7. The final design also included additional polycarbonate layers to provide further resistance to cracking, as discussed in section 3.2.1.

After our problems with broken Ribs from stage 4, we experienced relatively few problems for the rest of the project. This was due largely to the more robust laminated construction of the final Rib design, but also due to the dancers gaining experience with with the Ribs, learning which movements were problematic and which were acceptable, and learning how the instruments fit into their proprioception. A single non-functional Rib broke during the dance rehearsals in November, and a final production Rib broke during the staging in early March. Interestingly, the dancer was apologetic about breaking that Rib, and the production team also placed the blame for the broken Rib on the dancer by jokingly placing it in her dressing room with the message 'I know what you did last rehearsal'. While the broken Ribs in August were clearly seen as an indication that the Ribs needed to be more robust in order to accommodate the movements of the dancer, by March it was perceived that the fault lay with the dancer for not accommodating her movements to the design of the Ribs.

3.4.2 Supporting the artistic workshops

A persistent challenge over the course of the project was making available prototypes of the instruments to our collaborators. Workshops posed hard deadlines for development, and unanticipated challenges immediately before workshops demanded urgent resolution. While the reality of having functional prototypes ready for the first workshop was the most challenging, each step of the schedule presented in Appendix B brought its own set of requirements, which only accelerated towards the end of the project. While a few simple functional prototypes were acceptable for workshops 2 and 3, for example, the choreographic rehearsals required a full set of non-functional prototypes, workshop 4 required a full set of functional prototypes, the final set of production instruments was required before the final rehearsals, and the full set of backup instruments were required before the initial performances.

3.4.3 Challenges with further uses of the instruments

After the conclusion of *Les Gestes*, our intention was to continue to use and develop the Prosthetic Instruments to continue research into the design of DMIs for dancers;

however, we ran into several challenges in this respect.

Sizing the instruments: The prevailing trend over the development of the Prosthetic Instruments was the increasing specificity of the physical forms. While this is true for the Spine, whose length was determined to fit the dancers' backs, this is especially true for the Ribs and Visors, which went from an initial conception of a single form which could be used in a variety of ways, to three specific shapes and sizes of Ribs. With the Visor, it was even necessary to shape each Visor to the dancer's heads individually.

In order to continue using the instruments with other dancers, we had a set of corsets and headbands created whose sizing was adjustable. However, the instruments themselves were not resizable, and this occasionally made it difficult for dancers with different sizes and shapes of body, as we found when using the instruments in Greece. While it would have been possible to design the instruments to be resizable through the use of removable mounts and possibly separating the main Rib shape from the electronics enclosure, that was not seen as the goal of this project and was therefore not a priority.

Disagreements over ownership: A larger problem arose in a dispute between the collaborators over the ownership of the instruments. While the specifics of this disagreement are beyond the scope of this dissertation, they made clear how important it is to establish future plans for the research outcomes at the beginning of the project, rather than waiting until the project's conclusion. In addition, we also learned the importance of consulting with legal staff before committing any agreements to paper. Unfortunately, the end result of the disagreement was the curtailment of the use of the instruments in August 2014.

3.4.4 Integrating the instruments into the production environment

The use of the instruments in a professional production setting was always one of our clear goals, and influenced many decisions big and small throughout the design process. However, as the production took shape there were several ways in which we chose to modify our designs in order to assist in a more successful production.

The most significant modification was the integration of lighting into all of the instruments. While lighting had been integrated into the Ribs in-between workshops 2 and 3, integrating lighting into the design of the Spine itself did not become a priority until our first meeting with the productions lighting designer, Bruno Rafi, during workshop 4. At this point, the lighting in the Ribs was very successful, and Bruno immediately began to conceive of the instruments' lighting as being an integral part of the show. To support this, I designed and installed lighting into the Spines before the final rehearsals. While some effort was put into making the lighting for all of the instruments controllable, time constraints prevented us from being able to successfully implement this before the final rehearsals, and therefore it was not included in the show.

3.4.5 Acceptance of the instruments by the performers

While most of this chapter is focused on the ways in which the instruments were designed to support the needs of our collaborators, we also note that by the final rehearsals it became necessary for the performers to accommodate themselves to the requirements of the instruments. For example, in section 3.4.1 we discussed how an instrument being broken came to be seen as the fault of the dancer. This was partly because the dancers became aware of the mechanical limitations of the Ribs over the course of the development process and rehearsals. At the same time, the modifications to make the instruments both stiffer and more robust helped build trust that the instruments would be able to withstand the rigours of performance. While the dancers certainly shaped their performance around the limits of the instrument, these limits were seen to be sufficient for the application.

Another example of this, as well as being an example of the difficulties of fully preparing for the performance environment, came on the opening night of the show. During the rehearsals for the performance we never had a problem with the wireless performance; however, on the opening night a significant communication dropout occurred. This happened at a point in the performance when the musicians moved behind the dancers and played the Ribs as they were attached to the dancers' bodies, therefore sandwiching the wireless transceivers on the Ribs in-between the musician's and dancer's torsos. The next day, we were able to reproduce the problem by having the musician stand very close to the dancer, and found that even slight modifications of the distance between the two performers helped to minimize the dropout. To resolve this problem, we first of all changed the transceiver attached to the main performance computer to a higher-power one with a larger external antenna. In addition, the musician learned to be aware of the problem and to keep a certain amount of space between her torso and the Rib in order to prevent a total occlusion of the transceiver.

3.4.6 Manufacturing

One of the biggest challenges in the development of the Prosthetic Instruments came to be the manufacturing process. Several factors made the manufacturing process difficult, including the need for the instruments to be crafted to complement the dancers' bodies, the need for specific mechanical properties for the instruments, the need for the instruments to be attached and detached from the costumes, and the use of custom-designed sensing. Over the course of the process we also came to be aware of the need to suit the manufacturing methods to the development stage, a conclusion we will discuss in depth in section 6.1.6.

3.5 Summary

This chapter presented a family of digital musical instruments designed to be used by dancers in professional artistic productions. The instruments contain a variety of novel characteristics, including their capacitive sensing, ability to be attached and removed from a custom corset, and their mechanical construction and manufacturing.

Over the course of the design process we encountered numerous design requirements, each of which reflected a different perspective on what would constitute a successful system. In particular, we were struck by the difficulty of creating solutions to satisfy conflicting design requirements, and also by how these solutions ended up being stronger for successfully meeting this challenge.

At the conclusion of this project, it became clear that it would be valuable to be able to consider the design of a hardware system from multiple perspectives. Further understanding what these perspectives might be was one of the research goals for our next project, the development of the *Ilinx* garment.

Chapter 4

The *Ilinx* Garment

This chapter presents the hardware/software system which comprises the *Ilinx* garment, created for the immersive multimodal art installation *Ilinx*. The *Ilinx* garment is a full-body tactile display worn by visitors as they explore a large space while experiencing a variety of visual, auditory, and tactile stimuli. The development of the garment involved a combination of technology developers, artists, garment designers, and scientific researchers over the course of a year of intensive development, leading to the installation's initial public presentation at the *TodaysArt 2014* festival in the Hague.

Our experience designing the *Ilinx* garment improved our understanding of design perspectives in several ways. The aesthetic design of the garment was heavily influenced by concepts drawn from the wearable electronics community, in particular the conviction that the system should maintain the look, fit, and feel like a garment, rather than being primarily perceived of as a hardware system. This led to a variety of challenges related to manufacturing, system architecture, and robustness. In addition, while the overall conception and structure of a digital musical instrument has been clearly articulated (in Miranda and Wanderley (2006), for example) and is generally understood by our artistic collaborators, the same is not as true for tactile displays. Due to this, we assumed more responsibility in the creation of software tools designed to support the use of the system during the artistic creation process.

Structure of the Chapter: The structure of this chapter is as follows:

- Section 4.1 presents an overview of the project, including a discussion of similar tactile display systems and the use of such systems in artistic productions.
- Section 4.2 provides a technical description of the *Ilinx* garment.
- Section 4.3 describes the uses of the *Ilinx* garment for artistic works, including a description of the initial presentation of the *Ilinx* artwork, subsequent public showings of *Ilinx*, and uses of portions of the system in other research projects.
- Section 4.4 presents a discussion of our experiences in the design of the garment.
- Section 4.5 describes the ways in which our experiences developing the *Ilinx* garment contributed to the overall research goals of this dissertation.

4.1 Context of the research project

The creation of the *Ilinx* garment grew out a research project called *Disequilibrium*, funded by the Canada Council for the Arts' GRAND NCE Media Artist and Scientist Collaboration scheme. The goal of this project was to leverage existing scientific knowledge of haptic perception in the creation and use of a wearable tactile display suitable for use in professional artistic productions, and to use this display to explore the compositional possibilities of a variety of tactile and cross-modal stimuli. The desired outcomes of the project included the creation of the tactile display, the public presentation of an artwork utilizing the system, and publications in both the artistic and scientific communities.

The participants in the project were from four different groups: IDMIL did the bulk of the technological development and haptic research; the lead artists were Chris Salter and Maurizio Martinucci (also known by his artist name, TeZ); and wearable electronics designer Valerie LaMontagne and her studio 3lectromode designed and manufactured the garments. The full list of participants is shown in Appendix C.

Design schedule: The project took place within one year, with the initial conceptual explorations occurring in the fall of 2013 and the initial public presentation of the artwork in the fall of 2014. Research into the technical design of the garment took place from January-June 2014, and the manufacturing of the final garments took place from July-September 2014. The overall schedule of the project is shown in Appendix D.

4.1.1 The conceptual framework behind the garment

The two major conceptual factors which underlay the design of the garment were leveraging contemporary research in tactile perception and the utilization of techniques drawn from the wearable electronics community.

Leveraging contemporary knowledge of haptic perception: One of the primary goals of the project was to explore the utilization of the haptic channel in artistic works, and the early stages of the project focused on this challenge. The tactile sensory channel is very different from the auditory or visual channel in that it is distributed all over our bodies, and in that tactile perception varies greatly depending upon the section of the body and type of skin involved.[1] While the distributed nature of tactile perception makes the creation of whole-body stimuli difficult, in empirical tests we determined that

[1] For a general overview of tactile perception see Hatzfeld and Kern (2009, 29-65) and Van Erp and Self (2008, chapter 2).

a display which includes elements on all four limbs as well as the torso provided a sense of tactile stimuli being experienced as being located 'all over the body.'

Several key characteristics of the tactile perception system influenced our design decisions. The most prominent of these is the limited spatial acuity of tactile perception, which makes it difficult to distinguish between two tactile stimuli in physically proximate locations. The characterization of spatial acuity is typically used to determine number and location of actuators in a tactile display (Lemmens et al., 2009). Spatial acuity also contributes to several tactile illusions, including apparent motion, sensory funneling, and sensory saltation (Lederman and Jones, 2011, 283-285). Apparent motion illusions are formed when sequential stimuli are provided to adjacent locations with an inter-onset interval less than the length of each stimulus. This creates the illusion of a single, continuously moving stimulus (Rahal et al., 2009, p. 87). The sensory funneling illusion occurs when two adjacent stimuli are generated at the same time, producing an illusion of a single stimulus at a midpoint between the actual stimuli. Sensory saltation, also known as the 'cutaneous rabbit', is a well-known tactile illusion in which sequential short pulses moving between multiple actuators can create the illusion of discrete stimuli whose location moves continuously between the actuators' locations (Geldard and Sherrick, 1972).

Based on these characteristics, as well as our early explorations, we quickly decided that the main goal of the garment would be to explore the spatial distribution and movement of tactile stimuli over the body. We experimented with several actuator arrangements which allow for generation of stimuli traveling up and down and around the limbs and torso, including placing actuators in different places on the torso, neck, and head. Ultimately, we decided that an arrangement which would allow for linear motion on the four limbs and a circular movement around the torso was most effective.

Wearable electronics: The garment designers in the project are experts in the field of *wearable electronics*, which integrates electronic circuitry into garments using materials and aesthetics drawn from clothing manufacturing and fashion design. One of the primary goals of this field is that wearable electronics systems should retain the fit and feel of traditional garments. One way this is achieved is through the use of 'soft computation,' whose goal is "is to achieve the seamless integration of technology into the tradition of textile and fashion design" (Berzowska, 2005). An example of this technique is the use of conductive thread and fabrics rather than wires, and the creation of electronic connections using sewing techniques rather than using rigid connectors.

The aesthetics of wearable electronics draw upon several traditional considerations from the fashion industry, including the idea that clothing should be stylish and comfortable, and a concern for the feel and fit of the garments (Lamontagne, 2013). While the reconciliation of these aesthetics with the goals of creating new hardware devices can be difficult to reconcile (Dunne, 2004, p. 16), during the design process for the *Ilinx* garment we worked continually to reconcile the need for an effective wearable tactile display with the techniques and aesthetics of the garment designers.

4.1.2 Use of the haptic channel in immersive art installations

Our collaborator Chris Salter has worked with vibrotactile stimuli in several previous artworks, including the works *Just Noticeable Difference* (Salter, 2012) and *Displace* (Salter, 2015, 167-238). In those works, vibrotactile stimuli were generated through the use of transducers attached to fixed platforms located within the exhibition space. The participants primarily experienced the stimuli when they rest upon these platforms.

4.1.3 Previous tactile-enhanced garments

Several previous examples of garments with embedded vibrotactile actuators have been created for research and industrial purposes. The majority of such garments are used as either navigational displays or for performance/entertainment. Gunther and O'Modhrain (2003) present a garment designed to make it possible to compose for the sense of touch. In their use-case, participants would wear the suit and then experience a precomposed audio, tactile, or audio/tactile composition. Their system was designed to allow for the creation of tactile stimuli by manipulating audio data within a traditional audio composition software environment, and the transducers were driven directly by audio signals. For this reason, their garment utilized relatively large actuators intended for tactile transduction of audio signals, and a wired connection was created between the garment and the audio amplifiers.

Lemmens et. al created a jacket intended to be worn while watching motion pictures, and which was intended to be used to create affective stimuli (Lemmens et al., 2009, 2010). 64 vibrotactile actuators of a similar type to those used in the *Ilinx* garment were sewn to this garment, and used for playing back precomposed tactile stimuli in tandem with video clips. Lemmens et. al make clear the distinction between using tactile stimuli as movie effects (e.g. creating stimuli to represent the tactile sensation of an explosion shown on-screen) and using them as affective effects (e.g. stimuli intended to convey an actor's anxiety or anger).

Many different wearables have been developed as navigational aids, but for this purpose displays tend to be created for a specific area of the body. For example, circular displays worn on the waist or ankle are often used to display cardinal directions (van Erp et al., 2005). Displays created for providing feedback in virtual environments are also often created to create stimuli in specific areas of the body. For example, Lindeman et al. (2004) present a vest with actuators located in the shoulders, which are intended to provide feedback for when an avatar's shoulders collide with doorframes or other obstacles in the virtual environment.

The *Ilinx* garment differs from the above garments in several key ways. First, it differs in terms of the type of effects it is intended to convey, being focused on creating the perception of continuously moving stimuli over the entire body. Second, it was designed specifically to be worn by the public in heavily-trafficked art festivals, rather than being designed for use in controlled lab settings. Lastly, it is intended to be worn as participants explore a physical space, necessitating both a fully-wireless implementation as well as a form and fit which permit the participants to explore comfortably.

4.2 Technical description of the *Ilinx* garment

The system created for use in the *Ilinx* garment consists of hardware installed in the garment, firmware and software running on that hardware, and a central PC running software which generates control messages for the system. This section will describe the first two aspects, and the next section will discuss software tools created to facilitate the creation of artistic works using the system.

The primary design requirements for the system were that it be:

1. Wireless in order to not restrict the movement of the participants.
2. Able to generate a wide range of continuous tactile effects over the whole body.
3. Able to be constructed in quantity as to allow for multiple simultaneous participants.
4. Robust enough to withstand sustained use at public art festivals.

5. Aesthetically appropriate for the intended artistic application.

My contributions: The work presented in this section was highly collaborative, primarily between myself, Ivan Franco, and Marcello Giordano. To clarify, each section will describe the role of each member.

4.2.1 Structure of the garment

The garment contains 30 vibrotactile actuators, divided into five sub-sections consisting of the four limbs and the torso.[2] Each section contains six actuators, position down the length of the outside of the four limbs and in a circular array around the torso, as shown in figure 4.1. Each section also has a dedicated actuator driver PCB which contains a microcontroller for generating control signals and ICs for driving the actuators. This board also houses a 9DoF MARG (magnetic, angular rotation, and gravity) sensor which was not utilized in *Ilinx*.

The garment is made up of a jacket and two leggings. Both the leggings as well as the jacket's arms are constructed in an open design, in the form of a single strip of fabric running down the length of each limb, and containing the actuators. Velcro straps are sewn to this strip and wrap around the limbs to secure the garment. Three such strips were used in the arms and four in the leggings. The main body of the jacket is secured around the torso using a single wide elastic strap with velcro connections. The open design of the garment allows for great flexibility of sizing, and aids in putting the garment on and off.

[2]The general structure of the garment was designed by all of the IDMIL researchers as well as Chris Salter. The garment itself was designed by Valerie LaMontagne and 3lectromode. I designed the actuator housing, actuator driver PCBs, and firmware for the actuator driver PCBS.

Fig. 4.1 A view of the *Ilinx* garment from the inside. The actuators are visible as silver circles running down the length of each limb and horizontally on the torso. The open design of the arms and leggings are also visible.

Fig. 4.2 A 3D-printed housing was designed for the actuator. This housing allows the actuators to be sewn to the garment, provides a connection point for conductive thread, and prevents stress on the wires connected to the motor. The wires from the actuator are soldered to metal ring terminals, and then conductive thread is embroidered around the ring. Three circular holes in the housing allow it to be sewn to the garment. The two which match the ring terminal are sewn to the garment during the embroidering process. The third, at the top of the picture, is sewn using normal thread in order to provide additional stability.

Actuator housing: The actuators we used for the garment are pancake style eccentric rotating mass (ERM) actuators.[3] While these actuators are fully enclosed and generally robust, they are designed for permanently attaching to a rigid surface, with an adhesive backing designed for that purpose. In order to provide a way to attach these actuators directly to a garment, we designed and manufactured a sewable actuator housing, shown in figure 4.2.

The housing also serves two additional functions. First, it provides protection for the most vulnerable part of the actuator, which is the point at which the wires are soldered to the actuator itself. Second, it incorporates two metal ring terminals to facilitate the use of conductive thread to connect the actuators to the driver board. The use of conductive thread is a common technique in the wearable electronics community. Impregnated with silver, this thread is more flexible and easier to incorporate into clothing than wires

[3]The Solarbotics VPM2, `https://solarbotics.com/product/vpm2/`, accessed March 28, 2017.

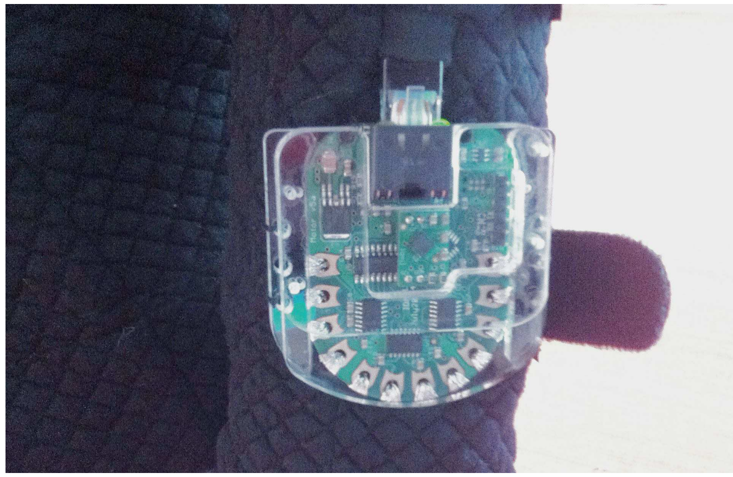

Fig. 4.3 The driver boards on the *Ilinx* garment incorporate circular terminals for embroidering conductive thread which connects to the actuators. At the top of the board is an RJ45 jack for the Cat5 cable which connects to the central control unit. Protecting the driver board is a laser-cut, solvent welded clear acrylic enclosure.

would be. Although conductive thread is more resistive than wires, with the wire we used having a resistance of around 0.5 ohm/meter, in our tests we found it did not noticeably impact the vibration amplitude of the actuators.

One of the primary challenges in implementing wearable electronics techniques is making the connection between the hard and soft components of the circuit, as e-textiles are not generally amenable to typical electronic manufacturing techniques such as soldering. One common way of making these connections is through embroidering, in which multiple strands of thread are tightly wrapped around a rigid conductor. To enable this technique circular attachment points are common, allowing many wraps of thread to be sewn around the conductor. This embroidery technique is facilitated by circular terminals incorporated into the driver board, as shown in figure 4.3, and metal ring terminals incorporated in the actuator housings, as shown in figure 4.2.

Central control unit: The central control unit is located in a pocket on the torso, and consists of a central minicomputer, a custom shield for the minicomputer which provides five RJ45 jacks for connecting to the driver boards, and a power supply.[4] The minicomputer we used is the BeagleBone Black (BBB), a commonly available single-board computer with a 1GHz ARM Cortex-A8 processor and running an embedded distribution of Linux. The power supply is a commercially available rechargeable USB battery, typically used to recharge USB devices. The battery we chose contained enough capacity to power the *Ilinx* system for up to 8 hours of continuous use, and contains two separate outputs. We used one output to power the BBB and the other to power the driver boards.

A small local WiFi network provides communication with the PC which runs the main installation software. In this network, each BBB has a unique IP address, allowing the central PC to send messages each garment individually. Messages can also be sent to all garments simultaneously via the use of broadcast messages.

Electronics enclosures: The central control unit is mounted in a pocket on the front right of the torso, as shown in figure 4.4.[5] Felt pockets were created for housing the battery and WiFi dongle, and the battery and BBB attach to the garment via velcro. Additionally, a fabric cover matching the main fabric of the garment secures over the central control unit via velcro along its edges.

The driver boards on the limbs are protected by a clear acrylic cover, consisting of two layers of 6mm thick clear acrylic solvent-welded together, as shown in figure 4.3. Holes embedded in the bottom layer allow the cover to be sewn on to the garment over

[4] Ivan Franco designed the shield for the BeagleBone Black, and the software running on the BeagleBone was written by Ivan Franco and Marcello Giordano.

[5] All of the actual garment design was by Valerie LaMontagne and 3lectromode. I designed the acrylic covers for the driver boards.

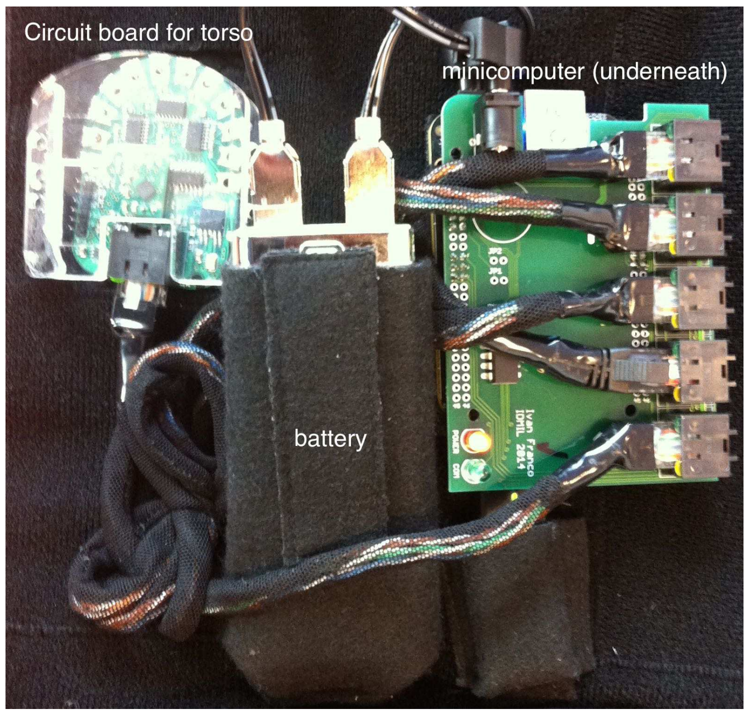

Fig. 4.4 The central control unit in the *Ilinx* garment, mounted in a pocket on the front right of the garment. The minicomputer, a BeagleBone Black, has a shield attached which contains five RJ45 jacks for the Cat5 cables connecting to the driver boards. The battery has two outputs, one used to provide power directly to the BBB and the other connected to the shield and providing a separate power supply to the driver boards via the Cat5 cables. Also located in the pocket is the driver board for the torso.

the driver board.

Control Signals: The system uses two types of control messages.[6] On the central PC, control messages are created in the Open Sound Control (OSC) format, and are transmitted via WiFi to the BeagleBone Black on each garment. The BBB continuously runs a python script which translates the OSC messages into a compact serial format for transmitting via SPI to the driver boards. An overview of the system configuration is shown in figure 4.5.

The OSC messages are in the following format, with all times indicated in milliseconds and position and amplitude normalized to values between 0 and 1:

`[garment section, normalized position, attack time, sustain time, normalized vibration amplitude, decay time]`

Within the OSC format, messages contain an address, always preceded by a forward-slash '/', followed by data to be received by that address (Wessel and Wright, 2002, 17-18). The five sections of the garment are addressed according to the following convention:

- right arm: /ra
- left arm: /la
- right leg: /rl
- left leg: /ll
- torso: /tf

The position of the intended stimulus is indicated using a normalized position parameter with a range of 0 to 1. On the limbs, a normalized position value of '0' indicates

[6] The system described in this section was designed by myself, Ivan Franco, and Marcello Giordano.

the extremity of the limb, while '1' indicates the position on the limb closest to the torso. On the torso, '0' indicates the front of the torso just to the right of the torso's midline. The position then wraps around the back, and '1' indicates the front of the torso just to the left of the midline.

The use of a normalized position parameter serves several functions. First of all, it allows for an undefined number of actuators. During development of the garment we were considering including additional actuators before settling on six.

Secondly, it conceptualizes each garment section as a single continuous display, rather than six individual displays. In practice, we found that it was rare for actuators to be perceived individually, but instead tactile stimuli was located in relation to the entire length of the limb or circumference of the torso. The use of a normalized position encourages thinking of the location in this way when programming stimuli as well.

Third, it allows for the interpolation of stimuli between actuator locations. As described above, it has been shown that a stimulus can be generated whose perceived location is proportional to the amplitude of two adjacent actuators (Lederman and Jones, 2011, p. 284). The use of a continuous position parameter allows for the creation of this effect by generating the appropriate control messages for two adjacent actuators.

The benefit of OSC messaging in our context is its human-readability and representation of parameters in conceptually appropriate ways. However, its primary drawback is a lack of optimization of message length, with all values being transmitted as ASCII-encoded values. Control messages within the garment, transmitted from the BBB to the driver boards, are sent via SPI with a low data rate of 125khz, chosen to minimize sensitivity to noise on the digital communication cables.

For this reason, the BBB converts control messages from OSC to simple SLIP-encoded serial packets (Romkey, 1988). The OSC address for each packet is used to determine

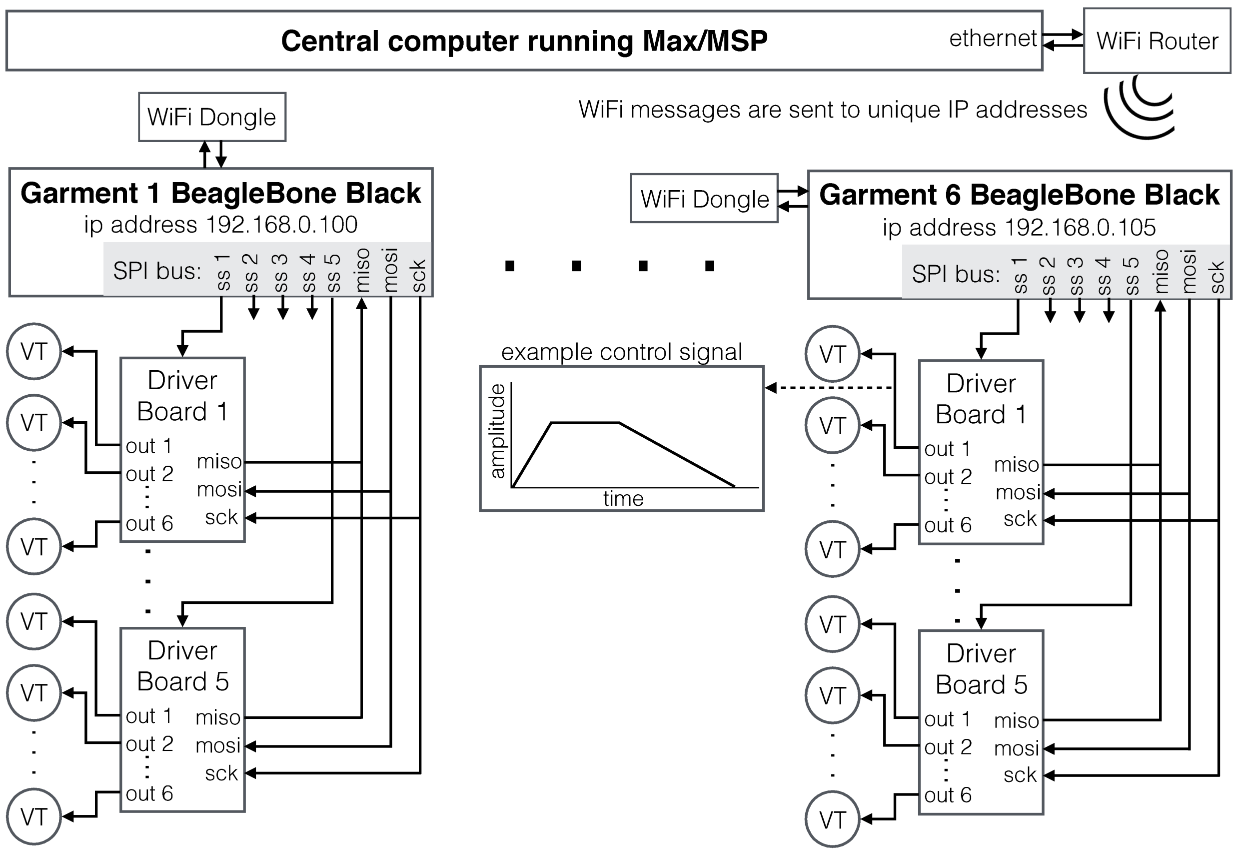

Fig. 4.5 A diagram of the network configuration for the *Ilinx* garment. Six garments were used in *Ilinx*, each consisting of five sections, each section with its own driver board and actuators. An example control signal is also shown, illustrating the attack-sustain-decay envelopes used for control of the actuators.

which driver board to send the packet to. Following this, the five control parameters are converted to eight-bit integers, SLIP-encoded, and transmitted via SPI to the appropriate driver board. The driver board uses the packet to set parameters for control envelopes for the indicated actuators, and then uses the envelopes to generate continuous control signals for the actuators.

4.2.2 Tools for creating tactile effects

One of the primary goals for the *Ilinx* garment is the creation of continuously-moving tactile effects over the whole body.[7] The 30 embedded actuators are not intended to function as solely as discrete sources of stimuli, but work together to create stimuli using the perceptual characteristics of the tactile perception system as discussed in section 4.1.1.

Over the course of development, several software tools were created to assist in generating control signals for the actuators. In this section, we will discuss these tools, the tactile effects able to be created by these, and the tactile composition of *Ilinx*.

Tactile effects: We defined several different tactile effects for use with the *Ilinx* garment. These effects fall into two categories: discrete and continuous. *Discrete* effects consist of one or many stimuli, each perceived as occurring at a fixed location on the body. *Continuous* effects, on the other hand, use a combination of motors to create the sensation of a single stimulus that moves along the body.

Three discrete effects we implemented are *pokes*, *buzzes*, and *sparkles*. The first two effects are achieved through the active of a single actuator or the simultaneous activation

[7] The definition of tactile effects presented here was created by the IDMIL team in collaboration with Chris Salter, and was based on work by Marcello Giordano, Deborah Egloff, and Emma Frid (Frid et al., 2014).

of adjacent actuators, and are differentiated by their amplitude envelopes, the *poke* effect utilizing short attack and decay times while a *buzz* utilizes longer attack and decay times. The *sparkle* effect consist of the random activation of actuators over the entire body, or over sub-sections of the body.

The primary continuous effect we implemented we refer to as a *snake*. This effect leverages the apparent motion illusion described in section 4.1.1, and consists of the carefully timed activation of 2 or more adjacent motors such that their envelopes overlap. While the illusion is most robust when occurring on a single garment segment, a similar effect also occurs as vibrations move between adjacent body segments.

Abstractions for generating tactile effects: The composition of the visual, auditory, and tactile elements of *Ilinx* took place within the software environment Max/MSP.[8] This software was chosen for its robust support for generating audio and visual signals, and as it is one of the primary programming tools for our artistic collaborators.

To facilitate the composition of tactile stimuli in Max, we created several software abstractions for generating the tactile effects described above. These abstractions allowed for the creation of variations on these effects through the use of a small number of higher-level parameters.

For example, for the *sparkle* effect, the input parameters are:

- *position*: select either a single body segment, or the whole garment. The appropriate actuator addresses are generated as a function of this parameter.
- *time*: the overall length of the effect, which consists of many individual events
- *intensity*: the peak amplitude of vibration for each event

[8]The abstractions described here were largely implemented by Marcello Giordano.

- *length*: determines several lower-level parameters, including the length of individual actuator envelopes, the attack and decay times for the actuator envelopes (in which the attack and decay are a fixed fraction of the total overall length), and the speed at which subsequent actuator envelopes are triggered.

Similarly, the *snake* effect is implemented with the following input parameters:

- *preset*: presets were created which consist of specific trajectories for the event. Example trajectories include: moving up one arm from the hand to the shoulder, and then down the following arm; moving continuously around the waist; and moving up one leg, across the waist, and then down the opposite arm. Each preset specifies a list of the addresses of the actuators involved in the trajectory.
- *speed*: the overall length of the effect, which determines the interval at which sequential envelopes are triggered.
- *length*: determines several lower-level parameters, including the length of individual actuator envelopes and the attack and decay times for the actuator envelopes (in which the attack and decay are a fixed fraction of the total overall length).

DrawOSC: A prototype iPad app was created in which the user is able to draw vibration trajectories directly on a visual outline of the body.[9] The app was designed so that the trajectory is begun when a finger is placed on a location on the body, the trajectory follows as the finger is dragged along the outline, and then ends when the finger is removed. An example trajectory is shown in figure 4.6. The speed of the trajectory is variable, following the actual speed at which the finger is dragged. The actuator inten-

[9] The DrawOSC app was created by Ian Arawjo.

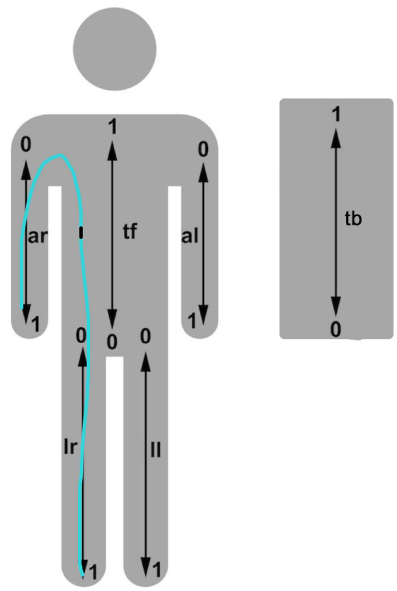

Fig. 4.6 An example of a trajectory drawn in DrawOSC. The indicated trajectory starts at the bottom of the right leg, moves up the leg through the right side of the torso, and then down the length of the right arm. Image courtesy of Ian Arawjo.

sity is determined by a slider placed next to the outline, and is able to be continuously varied over the course of the trajectory.

Trajectories are able to be saved and recalled, and multiple trajectories are able to be activated at once. The app implements control messages somewhat differently than the final system – while the basic control message structure is the same, the attack and decay times for the envelope are always set to 0, and the envelopes for each actuator are continuously varied using control messages specifying the currently desired amplitude for each actuator, necessitating a continuous stream of control messages to generate a changing stimulus. The app transmits these messages in the standard OSC message format over WiFi directly to the garments.

While a fully functional prototype of the app was implemented, it was not used for the creation of the artistic work, largely because it did not integrate into the Max/MSP environment.

The tactile composition of *Ilinx*: In the discussions which led to the creation of the tools described above, it was clear to us that restricting access to the system by mandating the use of predefined effects would place an arbitrary restriction upon artistic composition.[10] One approach we considered, for example, was to implement the abstractions described above directly on the BeagleBone Black. The user would then send the control parameters over WiFi, and all the subsequent control messages would be generated directly on the garment.

Ultimately, however, we decided that allowing access directly to the control messages within Max/MSP would allow compositional creation of tactile effects beyond those we made available. Ultimately, a variety of approaches to tactile composition were utilized in the premier production of *Ilinx*. These include the use of the abstractions described above in their intended manner, the creation of several new tactile effects, and also the specification of single actuator envelopes.

Two new effects were implemented directly by the artists. The first is the generation of a sequence through linear addition, in which a sequence is triggered multiple times, at at each repetition an additional actuator envelope is added to the end of the sequence. The second is a process of desynchronization, in which all of the actuators are triggered repeatedly at very slightly different rates. The first trigger for all of the actuators happens simultaneously, and following that the slight differences in rate cause the actuators to drift out of phase until they are entirely desynchronized.

[10] The tactile elements of *Ilinx* were composed by Chris Salter, TeZ, and myself.

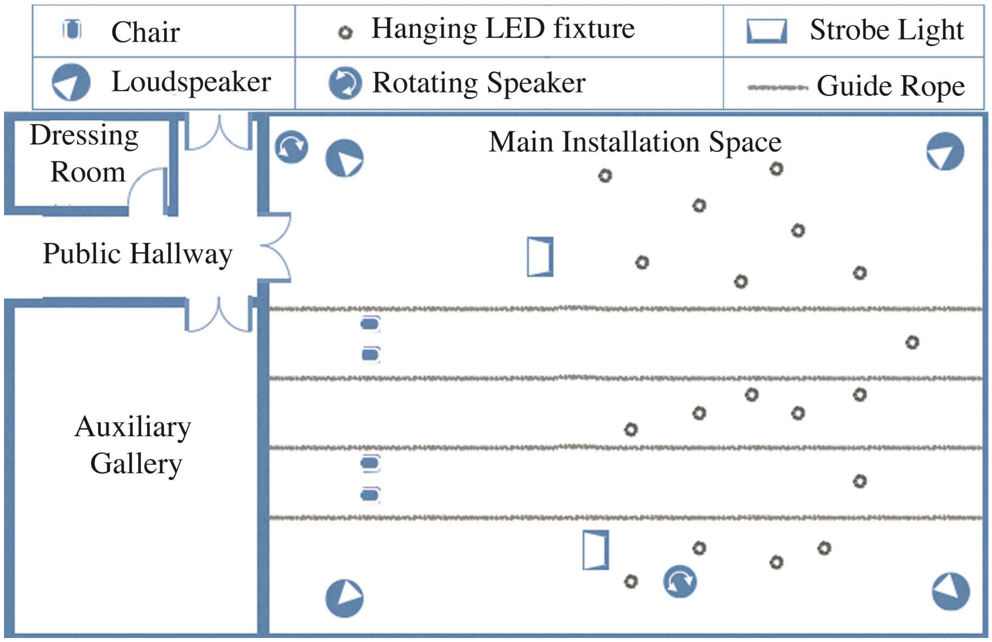

Fig. 4.7 A diagram of the performance space for the installation of *Ilinx* at TodaysArt 2014 in the Hague.

4.3 The *Ilinx* garment in use

The initial public presentation of the *Ilinx* artwork was from September 25-28 at the TodaysArt 2014 festival in the Hague. Over the four days of the festival, the installation ran for more than 40 hours, and more than 300 participants wore the garments and experienced the installation. To assist participants in putting on and taking off the garment, shifts of volunteer guides were organized for the entire festival. Each shift consisted of four guides, who were responsible for helping participants get dressed and undressed, and who also helped to guide the participants as they entered and exited the installation space.

4.3.1 Description of the *Ilinx* artwork

Ilinx is an immersive multisensory artwork in which visitors explore a large, dark space while experiencing a variety of visual, auditory, and tactile stimuli. For the installation, the visitors wear the *Ilinx* garment as well as a visor constructed with a frosted faceplate which causes any light sources to be heavily diffused.

After putting the garment and visor on, they are led into the main installation space, which is entirely dark, and guided to a chair located at one end of the space. The beginning of the piece consists of the visitors sitting in the chair and experiencing a variety of simple tactile and auditory patterns, which may or may not be synchronized. A loud bell and the appearance of faint lights at the other end of the installation space signals the beginning of the second section. In this section, visitors are encouraged to stand and explore the installation space at their own speed. A set of ropes were hung in the space to assist the participants in navigating, as their vision is heavily obscured. Towards the end of the piece, strobe lights begin an irregular pulsing that gradually crescendos until the piece is concluded. At this point, guides assists the visitors back to the dressing room to undress. A diagram of the performance space is shown in figure 4.7.

4.3.2 The dressing room ritual

Six *Ilinx* garments were manufactured and used in this production, in three different sizes, and typically four participants at a time were allowed to visit the installation. In order to accommodate as many visitors as possible while minimizing wait times, an appointment system was used in which visitors signed up via an online calendar for 30-minute slots.

Four guides were present at all times, and each guide would typically assist one participant in getting dressed and leading them into the performance space. Guides were discouraged from discussing the installation with the visitors during the dressing ritual, and instead mainly discussed dressing details, including making sure the garment and visor were fit securely and comfortably.

All six garments were kept turned on for as long as the installation was running, typically 10-12 hours a day, except for one half-hour break during which the batteries in the garments would be changed and the garment's system rebooted. The only interaction the guides had with the technical system came after helping the visitors get dressed, at which time the guides would plug cables leading from the jacket into the driver boards located on the leggings. At this point, they were asked to monitor two lights located on the driver boards, one of which indicated that the driver boards on the legs were receiving power, and the other that the system was receiving messages over WiFi. If either of these lights were not lit then guides were asked to either use a different garment or find a member of the *Ilinx* production team for troubleshooting.

4.3.3 Additional uses of the system

Following the initial presentation at TodaysArt 2014, *Ilinx* was also shown at CTM/ Transmediale 2015 in Berlin and at TodaysArt.JP 2015 in Tokyo. The technical system for these productions was identical to that described above, although the staging and composition of the work was altered slightly.

The driver boards for the system were also used by Marcello Giordano and Marlon Schumacher for the creation of a tactile metronome system for use in ensemble synchronization (Giordano, 2016, 138-148). 3D-printed enclosures for the boards were manufactured with a 2.5mm jack for plugging a cable leading to an actuator, and a wired

USB connection connected the driver board to a computer. The system was used for the composition "champ magnétique" by Fredrik Gran, and premiered by the Quasar saxophone quartet in 2015.

The entire hardware system is also currently being used for prototyping new garments for a project entitled "Musicking the Body Electric", a collaboration between IDMIL and Sandeep Baghwati at Concordia University. Ultimately, that project intends to make a new hardware system to accommodate different numbers and arrangements of actuators.

4.4 Discussion

The development of the *Ilinx* garment drew upon our prior experience with the Prosthetic Instruments in numerous ways, including making the system able to be run and maintained by non-technical staff, using a variety of manufacturing techniques for different applications, and focusing on issues of form and fit. In addition, several new challenges arose during the design process. In this section we will discuss some of these challenges, including supporting the artistic creation process, working with collaborators, and making a system that has a life beyond the initial production.

4.4.1 Supporting the artistic creation process

Much of the work in designing the system was hiding the complexity between specifying a tactile stimuli in the composition and generating that stimuli on the garment. The conceptual framework of the tactile effects discussed in section 4.2.2 was established early in the project, and guided many of our design decisions.

However, as we mentioned earlier, we made a conscious decision not to limit access to direct control of the actuators. There were three levels of possible control that were available to the artists: using abstractions for generating tactile stimuli as described in section 4.2.2, directly specifying actuator envelopes, or generating a continuous stream of amplitude messages as used in DrawOSC. Ultimately, the composition used the abstractions we provided as well as the new abstractions created by the artists in Max/MSP. While DrawOSC enabled a way of creating stimuli that would have enabled a more flexible approach to generating continuous stimuli, it was not used in the artistic creation process due to the fact that it did not integrate into the artists' preferred software environment.

4.4.2 Working with collaborators

This project differed from the development of the Prosthetic Instruments in that we shared the design and manufacturing process with Valerie LaMontagne and her atelier 3lectromode. This meant that we were only responsible for the electronics components, and were able to leverage existing commercial electronics manufacturing services to do the bulk of the manufacturing for us. The driver boards, for example, were assembled by PlaceDroid, a small PCB assembly company in British Columbia. The only direct manufacturing we undertook in the lab was the assembly of the BeagleBone Black shield and the placement of the actuators in their 3D-printed housing.

The ability to leverage the knowledge of our collaborators regarding the construction of a wearable electronics system was also highly important. The ability of the driver boards and actuator housings to support the use of conductive thread, for example, depended highly upon advice from our collaborators. Several other key design decisions regarding the electronics were also impacted by our collaborators' work. We had originally intended to design a hard enclosure for the central control unit, for example, rather than the soft enclosure designed by our collaborators.

Another interesting design decision made by our collaborators was in regards to the cables connecting the central control unit to the driver boards. We chose that these cables would be standard Cat5 cables, both so that they would be robust and also in an effort to avoid manufacturing cables ourselves. From our perspective, this was a reasonable compromise between manufacturing time, cost, and reliability. However, our collaborators found that the cables were overly stiff, and in order to remedy this they manually removed the stiff outer coverings of the cables (which provide electrical shielding to the cables) and replaced it with flexible mesh coverings, which can be seen connecting to the driver board in figure 4.4.

Perhaps the biggest persistent challenge for the *Ilinx* garment, however, was designing a robust coupling between the actuators and the body. In order for actuators sewn to a garment to be effective, they must be held firmly next to the skin, or else their vibrations are only felt through the vibration's diffusion in the garment. However, the use of velcro and elastic to secure the garments to the body was made relatively late, as our collaborators preferred to try other methods of securing the garments which would be more related to traditional garment manufacturing, such as using buttons or snaps. Their late inclusion meant their design was finalized quickly, and were less than ideal from the perspective of securing the actuators to the body. The biggest problem was that the straps were not consistently located at the same locations as the actuators on the arms and legs, meaning it was possible for an actuator which was not directly in line with a strap to be caught in a fold of fabric, and thus held away from the body. This was a particular issue in the torso, as the fabric of the jacket had a tendency to bunch up.

4.4.3 Building systems to be reused

As we found in the Prosthetic Instruments, wearable electronics systems tend to require designs specific to their application. In the *Ilinx* garment, we found this to limit the use of the garments in several specific scenarios.

First, the location of the actuators in the *Ilinx* garment was determined by our specific conceptions of creating moving tactile sensations. As the location of actuators in a tactile display tends to be highly application specific, this caused the garments themselves to be unsuitable for other applications, such as the "Musicking the Body Electric" project described above. With the creation of tactile displays being a recurrent theme in our lab, we resolved to create a new system which would be reconfigurable and modular.

Secondly, while the *Ilinx* garments were designed to be able to be worn by a variety of people, and were created in several sizes for this reason, we did not take into account special considerations due to physical disabilities or cultural contexts. The biggest problem this created was in the use of the system at TodaysArt.JP in Tokyo. While for our earlier productions in the EU we found that both men and women predominantly wore shorts or pants, in Tokyo most of the women wore skirts, and thus were unable to wear the leggings of the suit. We can imagine other scenarios where a visitor's dress or a physical disability would also cause them to be unable to utilize the suit as designed. While it is not always feasible to design a system to be able to accommodate every body type and culture, we resolved to at least attempt to consider this issue during the creation of future systems.

In particular, we want to note that these limitations of the use of the system in terms of failing to accommodate cultural or physical differences relate both to the robustness and the reusability of the system. From a reusability standpoint, it places obvious limitations on the ability of the system to accommodate artistic and research questions which depend upon the use of the system by specific communities. In cases like *Ilinx*, however, where the system is designed for a general audience, it represents degradations of the system caused by its inability to accommodate reasonable variations in the needs of the participants. This demonstrates the ways in which robustness reflects the interplay between the system's design and its context.

4.5 Conclusion

In this chapter, we presented the design and use of the *Ilinx* garment, a vibrotactile enhanced garment used in a multisensory immersive artistic installation. This system was used in the artwork *Ilinx*, which was shown in three international art festivals in 2014 and 2015, and experienced by more than 1000 visitors.

While the system was successful in the context of the *Ilinx* artwork, we were left with several areas we wanted to improve upon. The most important was to design a system that is more scalable, robust, and reusable for additional artistic and research projects. The creation of only six *Ilinx* garments limited the number of simultaneous participants, and increased the potential impact of a technical problem with one of the garments. In addition, the fixed architecture of the tactile actuators limited the potential future applications of the system, as we saw in section 4.4.3. The next project we will discuss, the VibroPixels, was our attempt to address these issues.

Chapter 5

The Vibropixels

This chapter presents the VibroPixels, a wireless tactile display system created for distributed applications. The development of this system drew upon our experience in the creation of both the Prosthetic Instruments and the *Ilinx* garment, and was specifically created to address concerns regarding the design of the *Ilinx* garment as described in section 5.1.3. These include the scalability of the system in terms of manufacturing larger quantities, the robustness of the system in terms of being able to easily replace or repair faulty actuators, and the support for easily reusing the system for other artistic and research projects.

One solution to these issues was to create a system consisting of individual actuator devices. Separating all of the electronic functionality from the garment itself makes it easy to replace a faulty actuator, whereas with a design like the *Ilinx* garment fixing such a problem would either replacing the entire garment or investing a significant amount of time and labor in replacing a single actuator. Replacing an actuator in this case would require a significant level of technical expertise, and would not be practical while the system is in use.

The consolidation of all of the electronic functionality into small monolithic devices provides several other benefits. First, it simplifies the manufacturing process considerably, enabling a larger quantity of devices to be manufactured. Second, the physical independence of each module allows for a reconfiguration of the physical layout of the actuators, making it easy to use in applications which require different actuator locations.

However, the reconfigurability of the system, as well as the addition of oscillation functionality as described in section 5.3.4, increased the complexity of the system from the user's perspective. The increasing number and complexity of software systems to support this functionality required more consideration for ways in which the system is designed to support the artistic creation process, which we discuss at length in section 5.5.

Challenges of tactile display systems: Tactile display systems utilize sensations such as vibration and pressure as a modality for computer-human communication. While most tactile displays consist of single-actuator notification systems embedded within wearable or handheld devices, systems containing multiple actuators have been developed for navigation (Rupert, 2000; Van Erp and Self, 2008), sensory substitution (Bach-y Rita, 1967), and entertainment (Lemmens et al., 2009) applications. The recent proliferation of virtual and augmented reality systems, as well as the expanding market for wearable computing devices, has also driven increased interest in such systems (Lindeman et al., 2004). However, wearable whole-body tactile display systems, which incorporate actuators on all four limbs as well as the torso, are still relatively rare.

While there are numerous applications for wearable tactile displays, designing and manufacturing robust systems for practical use remains a challenge. While reconfigurable systems are suitable for prototyping and perceptual experiments, they are not generally designed to be robust enough for prolonged use. On the other hand, a fixed configuration of actuators limits the potential usage of a tactile display, as actuator layout is heavily dependent upon application requirements.

The system we present is a reconfigurable, scalable tactile display which addresses these challenges. This system uses an easily scalable network of modular, wirelessly addressable actuators which we call VibroPixels. We provide a description of the VibroPixel system and describe our approaches to managing the challenges of minimizing wireless bandwidth and generating efficient control messages. We also present the results of system tests conducted in order to characterize the performance of our wireless protocol.

The system is well suited to a variety of challenging tactile display applications, including use of whole body displays in social environments, immersive artworks with actuators either worn or embedded in the environment, and use in virtual and augmented reality environments in which the physical configuration of the tactile display is dependent upon the VR application. Three such applications are presented: the immersive multisensory art installation *Haptic Field*, premiered in Shanghai, China from July 9 - September 6, 2016; a tactile metronome system for use by conductors of contemporary music ensembles; and the creation of social games focused on tactile perception.

Structure of the Chapter: The structure of this chapter is as follows:

- Section 5.1 presents an overview of the project, including a discussion of the configuration of tactile displays and our experiences with the *Ilinx* garment.
- Section 5.2 provides a technical description of the VibroPixels.
- Section 5.3 provides a discussion of the implementation and performance of the VibroPixel's wireless network.

- Section 5.4 describes the uses of the VibroPixels in the artwork *Haptic Field* and in other additional applications.
- Section 5.5 presents a discussion of our experiences in the design of the VibroPixels, particularly in terms of both support for artistic creation as well as the manufacturing of the system.
- Section 5.6 describes the ways in which the design of the VibroPixels was influenced by our consideration of the various design aspects, and also discusses ongoing and future uses of the system.

5.1 Context

Tactile displays have been created in a variety of form-factors. While our focus has been on designing wearable systems, displays have also been embedded in car-seats to provide navigational instructions (de Vries et al., 2009), in the backs of chairs to function as a sensory-substitution system (Baijal et al., 2012), and in hand-held electronics or devices attached to the body in other ways (MacLean, 2008). Whether a system is wearable, embedded in a device, or embedded in the environment, the physical layout of the actuators is dependent upon a variety of factors, including the information intended to be displayed, the characteristics of tactile perception on the portion of the body where the display will be located, and the environment in which the display will be utilized.

5.1.1 Considerations for the physical configuration of distributed tactile displays

Tactile displays generally fall into the categories of information delivery/notification systems, translation systems, and tactile synthesis systems (Giordano and Wanderley, 2013). Information delivery systems can generate tactile stimuli in several forms, including semantic, in which the user is expected to learn the meaning of specific tactile icons[1], environmental, in which the tactile signals are intended to be representative of the user's relationship or interaction with either a real or virtual environment (Choi and Kuchenbecker, 2013), or affective, in which tactile signals are generated to replace forms of touch encountered in social contexts (Huisman, 2017). Tactile translation systems generally attempt to compensate for auditory or visual sensory loss by "[relaying] the information from artificial sensors to the human sensory interface" (Bach-y Rita and Kercel, 2003).

Tactile synthesis systems attempt to create compositional languages utilizing the sense of touch. Frequently this is conceptualized via analogy to sound composition (Gunther and O'Modhrain, 2003; Baijal et al., 2012), but it can also take the form of tactile elements within interactive art installations (Salter, 2012; Lamontagne et al., 2015).

Actuator placement as a function of application: The placement of actuators will be heavily dependent upon the application. The use of tactile displays to communicate environmental information demands the use of tactile displays with specific actuator locations. For example, Lindeman et al. (2004) presents a system in which the actuators are located at positions on the body corresponding to places where an avatar might bump

[1] Often referred to as tactons (Brewster and Brown, 2004).

into features of a virtual environment, such as doorframes. Another common example is a display worn around the waist which is intended to display navigational assistance, in which case the location of the display is less important than its implementation in an arrangement which is able to display cardinal directions (van Erp et al., 2005).

Sensory substitution systems often utilize arrays of actuators which are placed on a part of the body with a large area of skin with relatively consistent tactile perception characteristics. An example of such a system is the Tongue Display Unit, which consists of a small electrotactile array located on the tongue and which translate an image generate by a video camera to a two-dimensional tactile pattern (Bach-y Rita et al., 1998). The back is another common location for sensory substitution systems, such as the Emoti-Chair, which utilizes a two-dimensional grid mounted in a chair back, and which translates audio signals to tactile signals (Karam et al., 2010). In this case, the physical design was driven by conceptual models which relate musical features to a two-dimensional tactile grid; for example, pitch range or frequency content is often mapped to vertical position on the display.

Sensory synthesis systems tend to be more flexible regarding their configuration, but will still locate actuators based on the intention to synthesize specific signals. One example, as we discuss below, is the *Ilinx* garment, which was designed to facilitate the creation of tactile stimuli which move continuously along the limbs and torso (Lamontagne et al., 2015).

Actuator placement as a function of tactile perception and environment: Another factor which influences a tactile display's physical layout is the heterogenous, multidimensional nature of the tactile perception system. Not only is the tactile perception system sensitive to different types of stimuli, but the sensitivity to different stimuli varies continuously over the body, which suggests that there may not be a single 'best way' to create a multi-purpose tactile display (Van Erp and Self, 2008, Chapter 2).

The application environment also plays a role, with a common requirement that systems be designed so as not to conflict with dexterity required for other tasks (Cholewiak and Collins, 2000). In addition, systems occasionally need to integrate with clothing or equipment supporting other aspects of the application, such as flight suits (Raj et al., 2000) or musical instruments (Linden et al., 2011).

5.1.2 Reconfigurable tactile displays

It is common to utilize systems with reconfigurable actuators in order to determine actuator choice and placement during the development of fixed actuator systems (Jones et al., 2004; Giordano et al., 2015). For applications which remain in controlled situations, such as perceptual experiments, tape and velcro straps may be sufficient (Rahal et al., 2009; van Erp, 2005). However, reconfigurable systems such as these are not generally designed to be robust enough for use outside of controlled environments. For example, the actuator placement may not remain consistent when the wearer moves about, or the wiring connecting actuators and electronics may be exposed to stress. One possible exception to this is the use of reconfigurable systems in artistic performance (Hayes and Michalakos, 2012; Schumacher et al., 2013), situations which involve experienced performers who may be willing to accommodate the bespoke nature of such systems.

Another common form of limited reconfigurability is in wearable systems which need to accommodate differently-sized persons. The use of velcro elements to allow for resizing wearable tactile systems is common (Lindeman et al., 2004), as is the use of stretchable materials (Lemmens et al., 2009). However, these systems are generally designed to preserve consistent actuator locations over bodies of various sizes, rather than serving as a way of varying actuator locations in relation to the body.

5.1.3 The *Ilinx* garment

The application and design of the VibroPixels draws heavily upon our earlier experience creating the *Ilinx* garment (Lamontagne et al., 2015), as described in Chapter 4 of this thesis. While the *Ilinx* garment successfully met the needs of its application, there were several aspects which we wanted to improve upon. The first is overall system robustness. While no significant problems developed during their use, we remained concerned over the long-term durability of the garment.

Our concern over durability was particularly focused on the wiring. The garment consists of a central minicomputer, five actuator driver PCBs, and 30 ERM actuators. Two kinds of wiring were utilized – Cat5 cable connecting the central minicomputer to the actuator drivers, and conductive thread sewn into the garment to connect the driver PCB to the actuators. Each type of cable and mechanical connection presents potential points of failure.

In addition to these concerns, the *Ilinx* garments were expensive to manufacture, largely due to the amount of labour involved. This fact limited the number of garments that were manufactured, as well as making it difficult to make additional garments with modifications to allow for other applications. Increasingly, we became interested in creating a system which was more robust, less expensive, and easier to employ in a variety of applications.

5.2 Technical description

This section presents an overview of the VibroPixels, comprised of a discussion of the design requirements and a technical description of the hardware and wireless subsystems.

My contributions: The work presented in this section was collaborative, although I was primarily responsible for it. However, in keeping with earlier chapters each section will describe the contributions of the collaborators.

5.2.1 Design requirements

Our intention in designing the VibroPixels was for them to be used in artistic installations which utilize wearable tactile actuators, and the assessment of our requirements of these applications drew upon our experience in the design and use of the *Ilinx* garment as described in section 5.1.3.[2] This application poses a large number of challenges, some generally applicable to the design of wearable tactile systems and some driven by the specific nature of the application. In assessing the design requirements, we considered three general areas – implementing the intended functionality, supporting the devices' use in context, and the devices' mechanical construction and manufacturability.

Functional requirements: The functional requirements for the VibroPixels include the generation of vibrotactile stimuli and lighting effects controlled by a central computer. We were interested in exploring three main dimensions for supporting the creation of tactile effects.

[2]The conceptual design of the VibroPixels grew out of conversations between myself, Ivan Franco, and Chris Salter.

The first is creating a variety of tactile effects using a single actuator. The central considerations for this are the maximum amplitude of vibration as well as the quality of vibration which arises due to actuator frequency, rise time, and decay time.

The second dimension is creating tactile effects consisting of multiple tactile stimuli on the body. This necessitates the ability to address any combination of actuators in a garment at the same time. In addition, sequences of actuators should be able to be activated with reasonable reliability and transmission rate jitter. The results of our tests to determine these characteristics are presented in section 5.3.6.

The third dimension is the ability to generate tactile stimuli for multiple participants. Specific goals were the creation of identical simultaneous stimuli across garments and generation of stimuli which moves between garments. This necessitates the ability to address garments both individually and in groups.

The incorporation of lighting into the VibroPixels was intended to aid in the perception of tactile stimuli moving from garment to garment. In order to accomplish this, the lighting was designed to be able to indicate the current amplitude of the actuators on a VibroPixel. In addition, the lighting is also able to be controlled independently of the actuators in order to facilitate the creation of independent visual elements.

The VibroPixels are intended for use in real-time applications in which the parameters and timing of tactile stimuli are algorithmically generated in tandem with the creation of other kinds of stimuli (e.g. audio signals). This suggests the use of a central computer which generates parameters for various stimuli and then transmits them to the appropriate systems. As our system was designed to be able to control hundreds of independently addressed devices, it is necessary to minimize the number of wireless transmissions from the central computer. To accomplish this, we decided that the central computer would generate messages specifying the behaviour of tactile events

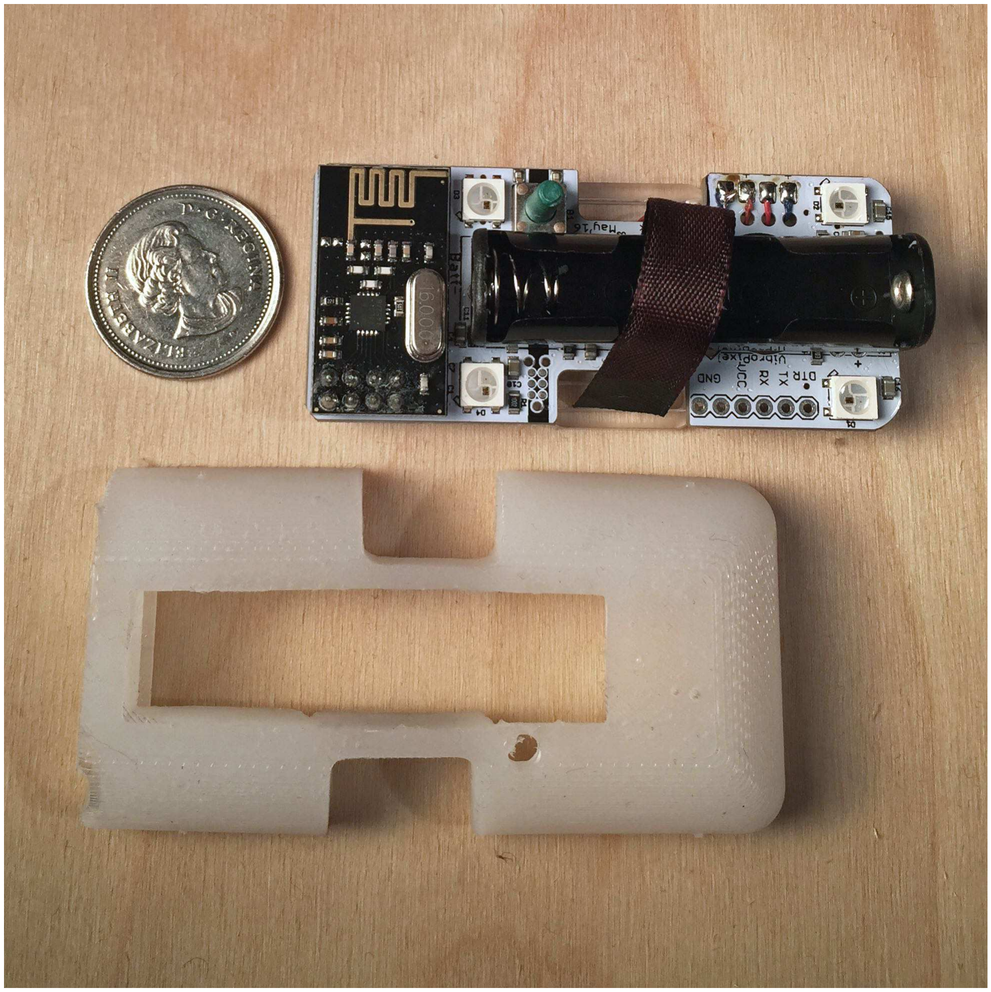

Fig. 5.1 A top view of a VibroPixel and its silicone cover.

lasting from 0.1 to 60 seconds. These messages would be wirelessly transmitted and all timing-dependent processes would be carried out independently on each device. This both minimizes the total number of wireless transmissions as well as prevents lost packets or transmission rate jitter from affecting the quality of the tactile events.

Supporting the devices in context: The artistic context of our intended use suggested a variety of design requirements. First and foremost is ease of use and reliability. The system should require no special skill or knowledge to turn on and begin running the installation. In case of software problems, resetting the devices should be easy or automatic. In the event that a device malfunctions or breaks it is essential that it is easily repaired or replaced. In practice, with unskilled staff, the easiest approach is to supply replacements to replace broken devices.

For professional artistic contexts we rely upon removable rechargeable batteries as being able to easily swap out batteries allows for the devices to be continuously used. In such a system, it is necessary to have two batteries and one battery charger for each device, allowing for the replacement of batteries in the complete set of devices at once. Both batteries and chargers should be readily available, inexpensive, and able to be easily used.

An additional requirement is that the system should be easy to program, both in terms of creating software to send control messages as well as in terms of modifying the firmware on the devices. For this reason the control system software was created in the multimedia programming environment Max/MSP and the firmware was developed using the Arduino programming environment.

5.2.2 Mechanical construction and manufacturing

The primary considerations for the devices' mechanical construction was for them to be lightweight, small, inexpensive at our desired quantities, simple to manufacture using commonly available digital manufacturing techniques, and robust.[3] Our initial goal was to create from 100-400 VibroPixels. In order to achieve this goal it was necessary to focus both on simplifying manufacturing techniques, outsourcing manufacturing when possible, and minimizing component costs.

[3] I did all of the electronic, mechanical, and software design for the VibroPixels, except for the CAD modeling for the silicone covers, which was designed by myself and Louis Fournier.

Table 5.1 A Comparative Analysis of a Selection of ERM Actuators evaluated for use in the VibroPixels, part 1.

Number	Form Factor	Size (mm)	Current (mA)	Amplitude (g)
1	Coin	10x2.7	60	0.56
2	Coin	12x3.4	60	1.0
3	Coin	12x3.4	70	0.36
4	Coin	12x2.7	50	1.0
5	Coin	12x3.4	60	0.6
6	Coin	12x3.4	70	0.93
7	Coin	14x3.4	30	0.56
8	Cylindrical	4x8	270	2.5
9	Cylindrical	4x14	290	3.8

Several additional mechanical requirements included preventing audible rattles due to vibration, the creation of effective diffusion for the LEDs, and providing an effective enclosure in order to protect the electronics from damage due to moisture, abrasion, or impacts.

Actuator choice: The VibroPixels are built around a pair of eccentric rotating mass (ERM) tactile actuators. While a variety of actuators for generating tactile stimulus are commercially available, ERM actuators remain our preferred choice due to their low cost, ease of implementation, and strength of stimulation relative to their size.[4] Our prior wearable tactile systems mostly use a single 12mm coin-cell ERM actuator, but a desire to increase the maximum vibration intensity led us to compare nine commercially available ERM actuators, with results shown in Tables 5.1 and 5.2.[5]

[4]For an overview of the characteristics of available types of tactile actuators, see (Van Erp and Self, 2008, Chapter 4) and (Choi and Kuchenbecker, 2013).

[5]All actuators were purchased in bulk from `http://www.aliexpress.com`, except for actuator 2 in Tables 5.1 and 5.2, which was purchased from `http://www.solarbotics.ca`.

For measurement, the actuators were mounted on unpopulated circuit boards from an early version of the VibroPixel. A spring based clamp secured an analog accelerometer on the opposite side of the circuit board, which was then used to measure acceleration orthogonal to the circuit board. The actuators were driven at a constant 3.3v with the exception of the measurement for rise time, in which case the actuators were driven with 100 millisecond long pulses. As ERM actuators can be quite audible a measurement of the sound produced by the test configuration was made using a smartphone-based sound level meter. The base level of the testing environment was 49.2dB.

The actuators we evaluated came in two different form factors, with significant performance differences. Those in a flat, circular form factor are commonly referred to as 'pancake' style or 'coin' style actuators, and tend to be more efficient, with the models we tested being able to provide a vibration intensity of up to 1g at current draws of less than 80mA. While the cylindrical style ERM actuators provided a greater amplitude of vibration, their current draw was disproportionately higher, approaching 300mA in the models we tested. However, the cylindrical actuators also have far superior response times, and are able to reach peak amplitude from 2-3x faster than the coin type actuators.

Due to their different characteristics, we incorporated two actuators in the VibroPixel. These consist of a coin-type (number 6 in Tables 5.1 and 5.2) and a cylindrical-type ERM actuator (number 9 in Tables 5.1 and 5.2). In our current implementation, a single vibration amplitude parameter is mapped to control values for both actuators in order to generate the widest range of vibration intensity. By using both types of actuators we are able to balance lower current draw by using the coin cell actuator for low to medium amplitude vibrations, while adding the cylindrical actuator for moments of higher amplitude vibration.

Table 5.2 A Comparative Analysis of a Selection of ERM Actuators evaluated for use in the VibroPixels, part 2.

Number	Type	Frequency (hertz)	Rise (mS)	Volume (dB)
1	Coin	260	100	52.7
2	Coin	195	100	55.3
3	Coin	130	90	56.3
4	Coin	230	80	65.7
5	Coin	180	80	54.8
6	Coin	168	100	54.8
7	Coin	125	80	52.2
8	Cylindrical	200	40	51.8
9	Cylindrical	220	30	53.9

The actuators are mounted on a lasercut acrylic base and are driven by an Allegro MicroSystems A3910 dual half bridge actuator driver, which provides two output channels with a combined maximum of 500mA current. The A3910 is configured as a low-side driver, and is able to provide a simple braking functionality by connecting the low-side of the actuator to 3.3v, effectively creating a short circuit across the actuator terminals.

Power and battery design: The VibroPixel's design utilizes a replaceable battery in order to accommodate the need for the VibroPixels to be able to run continuously over 6-12 hour timespans. We chose to utilize a lithium-ion battery in the 10440, or AAA, size. This form factor is easy for untrained personnel to quickly replace, is available in rated capacities of 500 mAh or greater, and is generally able to provide 1*C* of discharge current which accommodates the VibroPixels' peak current draw of around 500mAh (with both actuators and all four LEDs at maximum amplitude).[6]

[6]Charging and discharging current typically is described using the unit *C*, in which 1*C* is equal to the rated current capacity of the battery.

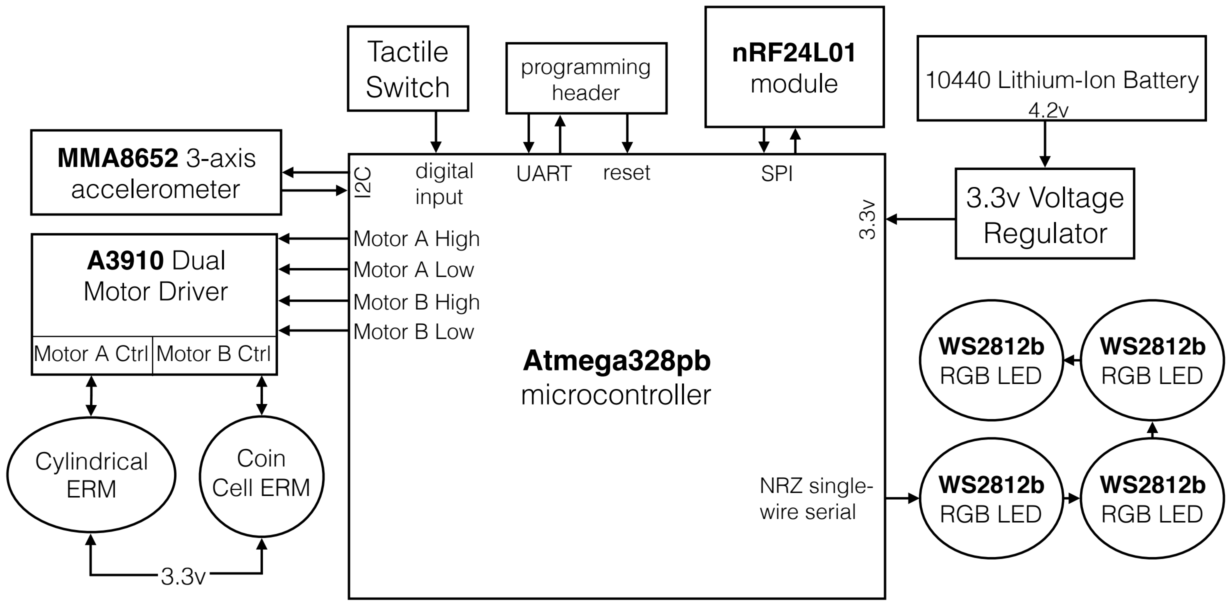

Fig. 5.2 A system overview showing the hardware configuration of a single VibroPixel.

While a variety of ready-to-use lithium-ion battery chargers are commercially available, we found that they were quite expensive considering we required one battery charger per VibroPixel. In addition, the commercial chargers we have used in the past have been configured for charging higher-capacity batteries. This causes their charging current to exceed the recommended charging current for a 10440 cell.[7] Ultimately we decided it was easier as well as cheaper to build our own battery chargers using lithium-ion battery charger modules. The modules we used consist of a single populated PCB which is based on a generic 4056e lithium-ion charging IC, and has an on-board mini-USB jack for power input as well as holes for soldering wires to attach a battery or battery holder. These modules also were configured for charging higher-capacity batteries, with a charging current of 750mA. However, replacing a single resistor allowed

[7] The recommended and maximum charging currents for lithium-ion batteries is generally in the range of 0.2-1C (Qian, 2010).

us to change the charging current to 200mA.

Lighting and sensing: The integrated lighting is a key element to the VibroPixels. One of the challenges of working with tactile stimuli is its personal nature. In a social context, it is very difficult to be aware of the tactile sensations experienced by other people. The integrated lighting allows for the linking of visual and tactile stimuli, allowing for the design of stimuli which is expressly intended to explore social distribution of tactile sensation. Four WS2812b individually-addressable RGB LEDs are located near the four corners of the PCB, as seen in figure 5.1, which allow for a variety of lighting effects. To aid in the diffusion of the LEDs, as well as to provide protection to the circuit board, a translucent cast silicone shell wraps around the battery holder and PCB.

A Freescale Semiconductor MMA8652 3-axis accelerometer allows for interactive stimuli to be created. However, this functionality is disabled in the applications described here.

A single tactile button is provided on the VibroPixels. In prototyping, we utilized this button to directly set device IDs, with each subsequent button press incrementing the device ID by one. However, for public use we chose to disable use of the button and to provide each VibroPixel with a fixed ID. The process of setting this fixed ID is described in section 5.2.4.

Choice of wireless transceiver: The Nordic Technologies nRF24L01 is a widely used 2.4GHz transceiver module. This transceiver is well-suited to our application as it is inexpensive, low-power, and is able to implement a network topology which can accommodate large numbers of transceivers. For the VibroPixels themselves, we utilize commercially available modules which incorporate the radio transceiver IC, all supporting circuitry, and a PCB trace antenna. In order to transmit messages from a computer, we also designed a transmitter device which includes a USB port, microcontroller, and nRF24L01 transceiver. The transceiver used for the transmitter is a commercially available radio module with an external SMA antenna and an additional RF amplification stage which provides a stated +20dB boost to transmission power.

5.2.3 Mechanical construction

The mechanical design for the VibroPixels consists of four vertical layers.[8] The bottom layer is a 1/8″ thick acrylic base to which the actuators are attached. A shallow outline was laser-etched on the acrylic to provide guidance for the correct placement of the actuators during manufacturing. This bottom layer also contains cutouts for attaching a strap to the VibroPixel. The next layer consists of several strips of 3M VHB (very high bond) double-sided mounting tape, which is designed to provide an alternative to rivets and screws for permanent installations. The tape we used consists of a foam substrate with acrylic adhesive on both sides, which provides a layer of mechanical isolation between the acrylic base and PCB. The printed circuit board with the remaining electronic components forms the next layer. Mounted on this board are the radio transceiver and the battery holder. Finally, a cast silicone shell with a cutout for the battery slips over the PCB.

5.2.4 Device firmware

The firmware running on the VibroPixels contains functions for setup, controlling peripherals, and monitoring the state of the device. One of our prime considerations

[8] The mechanical construction was designed by myself.

in designing the firmware was to make the devices not require any configuration on powerup – in practice, the firmware contains a single state which is entered immediately upon applying power or resetting the microcontroller. All system parameters are stored in EEPROM and are not able to be changed under normal use. Functions monitor the current battery voltage, disabling all peripherals when the battery voltage falls below 3.3v and indicating low-battery status by lighting the LEDs a faint red. Additionally, a watchdog timer is used to reset the microcontroller in cases of firmware freezes or malfunctions.

The only system parameter which is able to be changed in the final application firmware is the device's address. To accomplish this, special messages for setting and indicating group and device IDs were created. To use these functions, the button on a VibroPixel must be held down. On receiving a set message consisting of parameters for group and device ID, the IDs are saved to EEPROM, and the VibroPixel lights up green to indicate the message was received successfully. To check the currently set IDs, a query message is sent, following which the devices blink the group ID in red and the device ID in orange.

5.3 Wireless networking specifications

While there has been extensive research into the design of wireless sensor node systems, most tactile displays utilize networks of wired connections with a central point of communication to the controlling computer.[9] The actuator drivers may be centrally located or located in multiple nodes with driver electronics, each with parallel connections running to individual actuators, as in the Philips' tactile jacket (Lemmens et al., 2009).

[9] The wireless network specifications grew out of discussions between myself and Ivan Franco, although the implementation and testing described here are my own work.

The increasing miniaturization of electronics has led to another paradigm in which the driver electronics for each actuator are located with the actuator itself, allowing a two- or three-bus wire communication protocol to connect all of the actuators in series (Van Erp and Self, 2008, Chapter 4, p. 11).

The shift from a wired to a wireless network topology has a number of implications. In terms of the hardware design, this will primarily affect durability, size, and power concerns. In terms of the wireless network, this will primarily affect system bandwidth and the network's size and physical configuration.

5.3.1 Hardware design for modular tactile actuator nodes

A fundamental requirement of tactile displays is that they be able to withstand the physical demands of their application. This is a particular challenge for wearable designs, which are subject to considerable stresses due to the necessary coupling with the wearer. A monolithic design for each actuator node, with no external wiring connections, removes a common point of failure and may make it easier to design a robust system.

The size of the actuator node will always be a major concern. The largest factor will often be the choice of a battery which is able to support the application in terms of length of use and peak current draw. The best approach is to design the system to minimize current draw. While a holistic approach to power efficiency is always a good idea, in practice the power consumption of an actuator node will always be dominated by the power consumption of the actuator itself. However, it is also necessary to weigh the power consumption benefits of more efficient actuators with their tendency towards higher prices, considering the price of both the actuator as well as the electronics to drive the actuator. For example, while piezo actuators commonly draw significantly less power than electromagnetic actuators, the cost of the actuators and driver circuitry are both at least an order of magnitude more than when using commonly available ERM actuators (Choi and Kuchenbecker, 2013).

5.3.2 Wireless network configuration

The utilization of a mass wireless network for the implementation of tactile displays has both benefits and drawbacks. Perhaps the most important benefits are that the system is highly scalable and reconfigurable. One caveat is that communication with large numbers of devices quickly eats up wireless bandwidth, especially in artistic applications which demand low latency data transmission (Aylward and Paradiso, 2006). Managing bandwidth was one of the core concerns in the design of our system.

Packet reception and transmission rate jitter are additional concerns. In section 5.3.6, we review the tests we performed to characterize these aspects of our system's performance. We consider packet loss to remain a primary concern, while transmission rate jitter is less of a factor for several reasons. One is the tolerance of our tactile perception to discrepancies in the perception of synchronous stimuli, with it being suggested that a 30ms interval between impulses on the limbs is unable to be distinguished (Hatzfeld and Kern, 2009, 443-444). In addition, systems which utilize ERM actuators have to contend with mechanical latency in the actuator which frequently exceeds 30 milliseconds. The end result is that achieving acceptable transmission rate jitter is relatively easy.

Requirements for a passive receiver network: Any single-band wireless communication protocol is inherently half-duplex, in which nodes will switch back and forth from receive and transmit modes of operation. In order to minimize our system's wireless bandwidth consumption, each tactile actuator node in our system is *passive*, in the sense that it remains constantly in receive mode. This requires that the wireless transceiver not require *hand-shaking*, in which the master node queries slave devices to identify their presence, and also that any auto-acknowledgement functionality is disabled.

Auto-acknowledgement functions are a common way of minimizing dropped packets, in which a receiver sends a brief acknowledgement message in response to an incoming message. If the transmitter does not receive an acknowledgement it will re-transmit the original message. In a wireless system with a large number of nodes, auto-acknowledge functions greatly increase the amount of radio traffic, and when multiple receivers are addressed may be a source of packet collisions. The down-side to disabling auto-acknowledgement functionality is that it is difficult to ensure that a packet has been transmitted successfully. While we consider it unlikely that the occasional dropped packets will be significantly affect the success of the system for our target application of multimodal artistic works, this will not be true for all applications. In section 5.3.6 we describe several tests conducted to investigate the reliability of communication using our network configuration.

5.3.3 Addressing and serial communication protocol

In our system, transceiver-layer addressing is disabled through the use of broadcast messages in order to allow for our custom addressing scheme. This scheme utilizes a combination of group and device IDs, which allows for minimizing the number of wireless messages used to address a large number of actuator nodes.

Addressing en masse using group IDs: The fundamental problem is that addressing large numbers of devices individually in real-time contexts would require an excessive

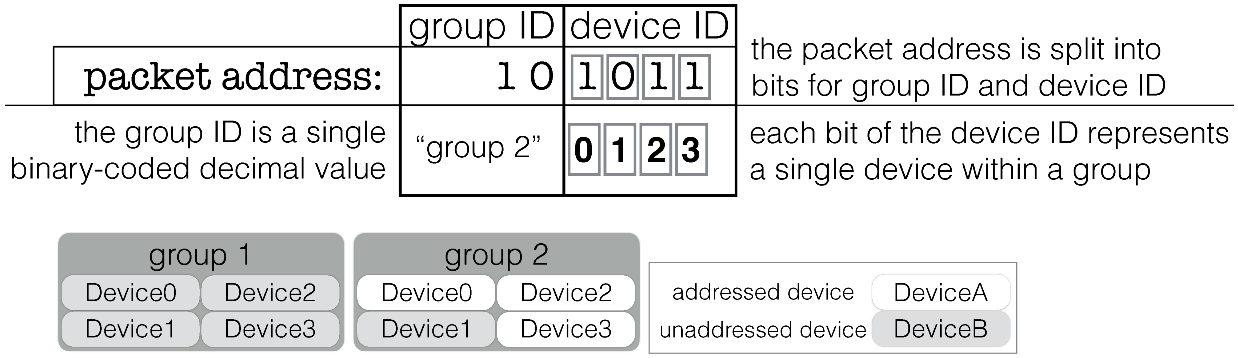

Fig. 5.3 Example of the VibroPixel addressing scheme using a 2-bit group ID and 4-bit device ID. In this example, the packet is addressed to devices 0, 2, and 3 in group 2.

amount of bandwidth. Our solution is to utilize a message address with two arbitrary groupings of N and D bits. The first N bits are used to set a group ID, with a total number of possible values of 2^N. Within each group, the address of each device is represented by one of the bits in the D grouping, in which a value of 1 indicates that the incoming message is addressed to that device. This allows for a single message to address any number of arbitrary devices within a group, as shown in figure 5.3.

A special case arises in which the group ID is equal to 0, which is considered a broadcast message to all groups. Another special case is when none of the device ID bits are set, in which case the message is addressed to the transmitter and ignored by the receivers. Considering these exceptions, in a system consisting of N groups of D devices the total available number of device addresses is equal to $((2^N)-1)*D$. The implementation we used for *Haptic Field* utilized a 7-bit group ID and a 9-bit device ID, allowing for the individual control of up to 1,143 devices.

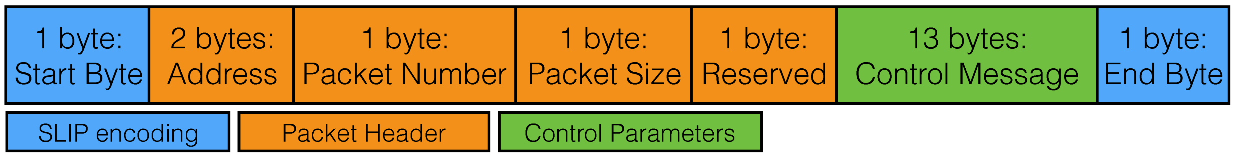

Fig. 5.4 Overview of a complete VibroPixel wireless packet.

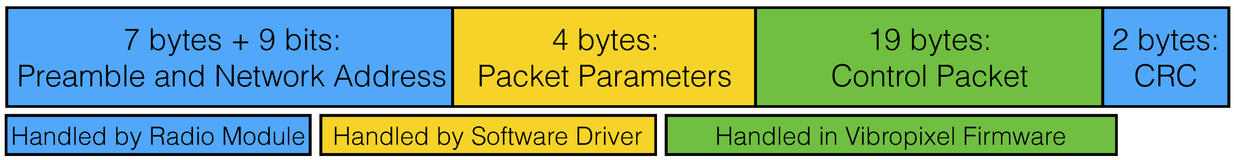

Fig. 5.5 Detail of the VibroPixel control packet structure.

5.3.4 Serial communication protocol

The serial protocol we developed is based upon that used in an earlier system developed in the lab (Hattwick and Wanderley, 2015), and utilizes double-ended *Serial Line Internet Protocol* (or SLIP) encoding for segmenting packets (Romkey, 1988). The software interface layer utilizes the Radiohead library for the Arduino programming environment, developed by Mike McCauley.[10] As the nRF24L01 implements a CRC error check, our serial protocol scheme utilizes a simple packet size check to ensure that a packet arrived in one piece.

Packet structure: In our system, each wireless packet contains elements which are handled by three layers: the radio transceiver itself, the software library which handles communication between the microcontroller and the transceiver, and the VibroPixel firmware, shown in figure 5.5a. The control parameters generated by the control computer are encapsulated in a *control packet*. This packet includes two components, a packet header and the control message, and the entire packet is processed using double-ended

[10] http://www.airspayce.com/mikem/arduino/RadioHead/.

SLIP encoding. The packet header consists of the 2-byte packet address, consisting of a 7-bit group ID and 9-bit device ID, a packet number, which is an 8-bit value incremented by 1 for every control packet sent, a packet size, which is used to test that the packet arrived intact, and an additional byte reserved for future functionality. An overview of the control packet is shown in figure 5.5b.

Lost packets are a fact of life in any wireless application. In a system which doesn't include an acknowledgement protocol there is no way of knowing whether a message has been received or not. With this in mind, we took care that all of the information needed for a device to perform its function is contained within a single packet. This means that there are no parameters which are sent to and remembered by the VibroPixel, with the exception of the device's address which is set and stored in EEPROM as described in section 5.2.4.

In the *Ilinx* garment we accomplished this by transmitting packets containing well-defined actuator envelopes which begin and end with the actuator turned off (Giordano et al., 2015). In the VibroPixels, we utilize a similar strategy in which the control message contains 3 components: the parameters for a single actuator envelope; parameters for controlling the re-triggering of the actuator envelope, which we refer to as an *oscillation*; and parameters for determining the response of the LEDs.

The actuator envelope is a simple attack-sustain-decay envelope with parameters for total length, attack and decay times expressed as a percentage of the total length, and the maximum amplitude of the envelope. While the control parameters are sent as 8-bit integers, once received the length of the envelope is squared to allow for high-precision control of the length of shorter envelopes while providing for a maximum envelope length of 65 seconds.

The oscillation functionality was implemented in order to allow for the creation of

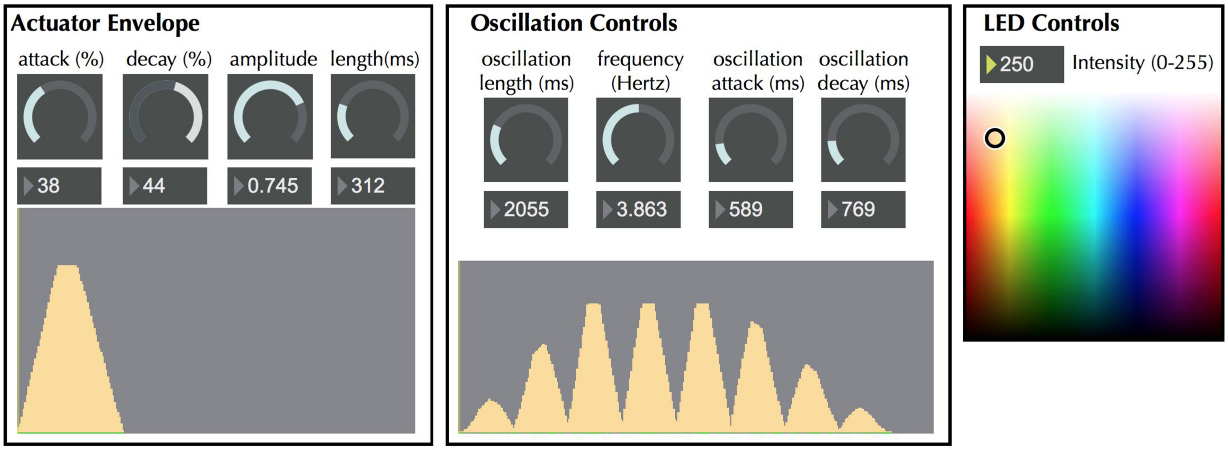

Fig. 5.6 An example user interface for generating control parameters for the VibroPixels, with sections for setting parameters for the actuator envelope, oscillation function, and LED functionality. The UI includes a visual representation of the results of the current settings both for the actuator envelope and the oscillations.

multiple stimuli over longer periods of time with a single control message, reducing overall system wireless bandwidth. The oscillation function re-triggers the actuator envelope at an oscillation rate, specified in Hertz, for a fixed duration. Controls for attack time and decay time allow for scaling the amplitude of the actuator envelope over the entire oscillation duration. Duration, attack, and decay parameters for oscillation are transmitted as 8-bit integers and are squared in the same fashion as actuator envelope length.

The LED parameters consist of an intensity value, which scales the brightness of the LEDs proportionally to the amplitude of the actuators, and a three-byte RGB colour value.

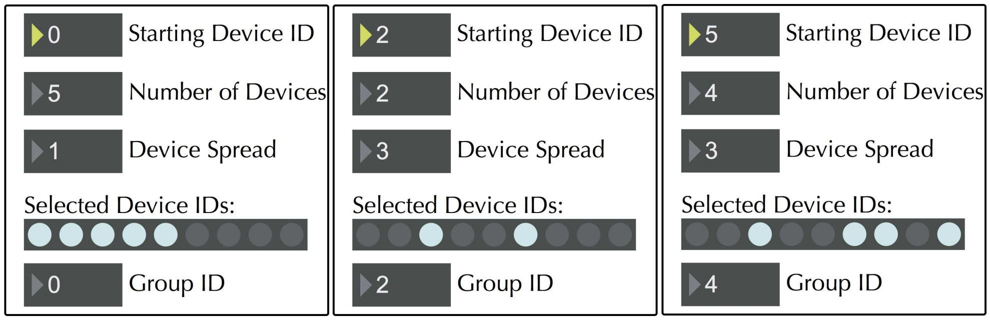

Fig. 5.7 An interface for algorithmic generation of Device IDs. Three examples are presented with different settings for starting Device ID, Number of Devices, and Device Spread. Below the controls for setting these parameters is a visual representation of the currently selected devices. Also shown is the currently selected Group ID.

5.3.5 User interface

The generation of control packets for the VibroPixels consists of three steps: generating the control parameters, generating the packet address, and passing the parameters and address to a function which generates the correct packet structure. Once the control packet has been generated it is passed via USB to a transmitter equipped with an nRF24L01 radio module and transmitted to the VibroPixels.

Generating control parameters, generating addresses, and creating the control packets are tasks which are easily implementable in a variety of programming languages. To assist in the use of the VibroPixels in an artistic context, we programmed a sample user interface, shown in figure 5.6, in the multimedia programming language Max/MSP. This UI allows for setting the values of the control parameters while also providing visual feedback regarding the resulting actuator amplitudes.

As described above, it is possible to address arbitrary combinations of actuators within a selected group. In order to facilitate the algorithmic generation of device combinations, we created a user interface with several parameters as well as visual feedback regarding the selected devices. The parameters for generating device IDs consist of base D, spread X, and number N. In this function, the device D is selected, and then N-1 additional devices are selected with X offset between subsequent devices. IDs greater than the number of devices are wrapped, and if an ID is already selected the next available ID is chosen. Figure 5.7 shows this interface with several example parameter settings.

5.3.6 Evaluation of system performance

We conducted several tests to demonstrate the performance of the system, including checking the efficacy of our addressing scheme, measuring the occurrence of dropped packets, and measuring transmission rate jitter.[11] We do not consider the results of these tests to be absolute measurements, as the performance of a wireless system is affected so drastically by environmental and application conditions. Rather, our intention was to provide a baseline expectation of the system's performance in a relatively ideal application environment. For this reason, our test configurations closely resemble the configuration of our target application.

For these tests, we used one of the transmitters created for the VibroPixels, which consists of a USB-to-UART module, an ATmega328pb microcontroller, and an nRF24L01 radio module with an analog signal amplifier which provides a stated +20dB boost to the radio transmission strength and a bandwidth of 250kbps. For the devices under test we used VibroPixels with modified firmware which builds upon our standard firmware to add functions solely for testing. The computer controlling the tests ran our standard VibroPixel control software as well software for collecting the results of the tests, both programmed in the Max/MSP software.

All tests were conducted with a 2m distance between the transmitter and the Vi-

[11] The work in this section was designed and carried out by myself.

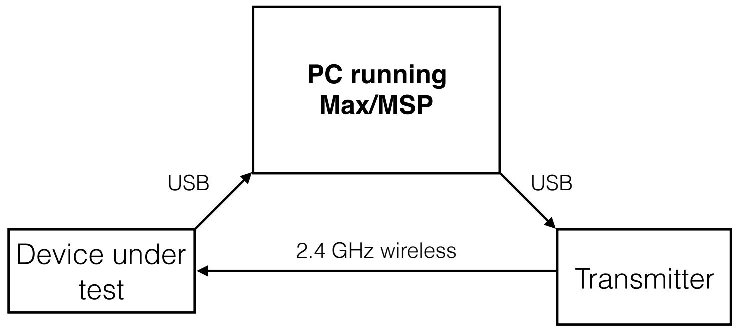

Fig. 5.8 Configuration for wireless transmission test 1.

broPixels under test. For each test 1000 packets were sent.

Evaluation of the addressing scheme: The first test we conducted was intended to validate the performance of our addressing scheme. In our test configuration, shown in figure 5.8, we modified the standard VibroPixel firmware to include a UART serial communication module. Two test conditions were carried out, one in which the packets were addressed to the VibroPixel under test and one in which packets were not addressed to the VibroPixel under test. For each condition, 1000 standard wireless packets were generated in Max/MSP, sent via USB serial to the transmitter, and sent wirelessly to the VibroPixel under test. Upon the reception of a wireless packet, standard functions on the VibroPixel verified that the packet was received without errors (an error indicating either an incomplete packet or a reception of a duplicate packet), and determined whether the packet was addressed to that VibroPixel or not. At that point, a message containing the packet number of the received packet and a byte indicating packet status (addressed, unaddressed, or error) was sent to the PC via USB.

The results of this test indicate that packets were transmitted and parsed by the addressing scheme with 100% accuracy. However, the possibility that the addition of the UART module could affect system performance led us to utilize a different test configu-

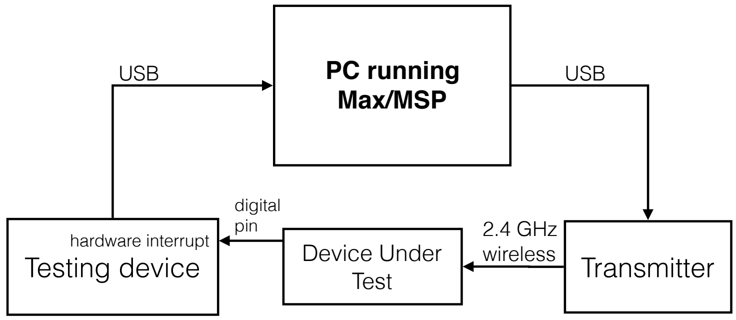

Fig. 5.9 Configuration for wireless transmission test 2.

transmission rate (Hertz)	100	125	166.6	200	250
Transmission failure percentage	0	0	0	0.8	5.7

Fig. 5.10 The results of wireless transmission test 2, showing the percentage of transmission failures at various transmission rates.

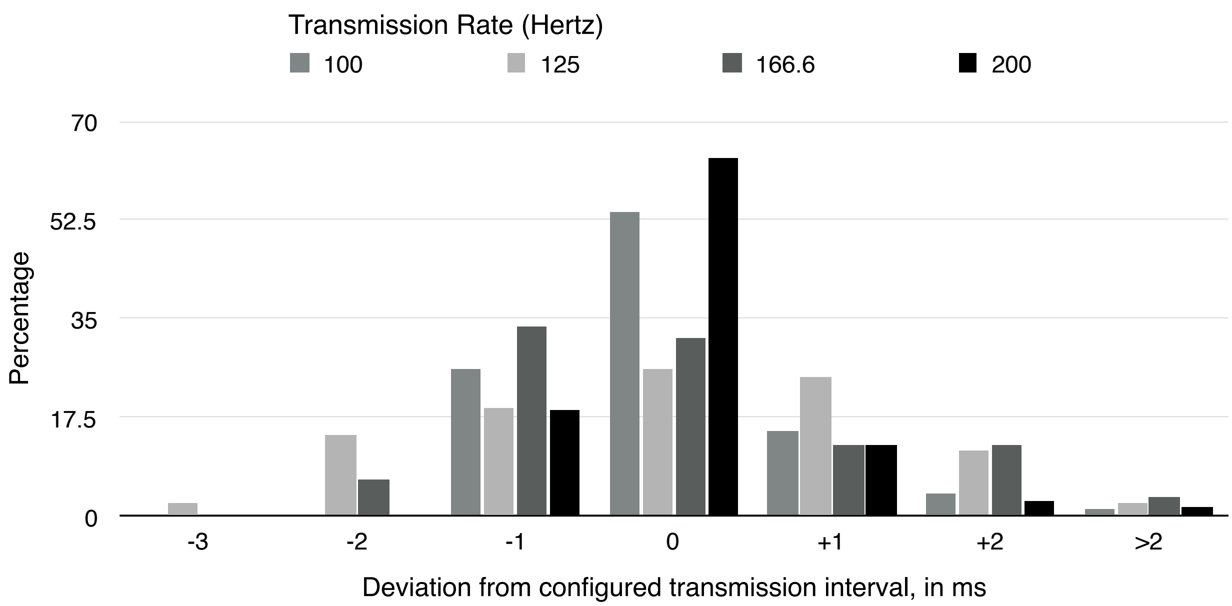

Fig. 5.11 Transmission rate jitter at various rates. The percentage of packets received for each interval between packets is shown for transmission rates between 100 and 200 Hertz.

ration to assess other aspects of the system's wireless performance.

Evaluation of wireless performance: For our second test, we removed the UART communication module from the device under test and instead programmed the device to toggle a digital pin upon the successful reception of a packet. We did not differentiate between addressed or unaddressed messages in this test as the previous test indicated the success of the addressing scheme.

An additional device, an Arduino Uno, was used to monitor the status of the device under test, as seen in figure 5.9. A hardware interrupt was triggered on this device when the device under test toggled a pin to indicate the successful reception of a packet. In the interrupt routine, a counter indicating the number of received messages was incremented and a flag was set which enabled a function outside the interrupt routine to calculate the transmission rate jitter. Following the conclusion of the test the results were transmitted over USB to a PC for analysis.

The results of these tests, shown in figure 5.10, indicate that the transmission of wireless packets was 100% successful with a transmission rate of up to 166.6Hz. At a transmission rate of 200Hz, packets begin to fail to be successfully transmitted. Where in the transmission/reception chain these failures occur is not indicated by this test.

The measured transmission rate jitter, shown in figure 5.11, is relatively consistent over the various transmission rates, with 97.4% of packets having less than a 3 ms deviation and 100% of packets having less than a 6ms deviation from the transmission rate.

Evaluation of the performance of multiple VibroPixels: The VibroPixels are configured to be passive receivers, enabling an arbitrary number of VibroPixels to be utilized in an application with no degradation of wireless communication. In order to verify that a VibroPixel's successful reception of packets is unaffected by the activity of nearby

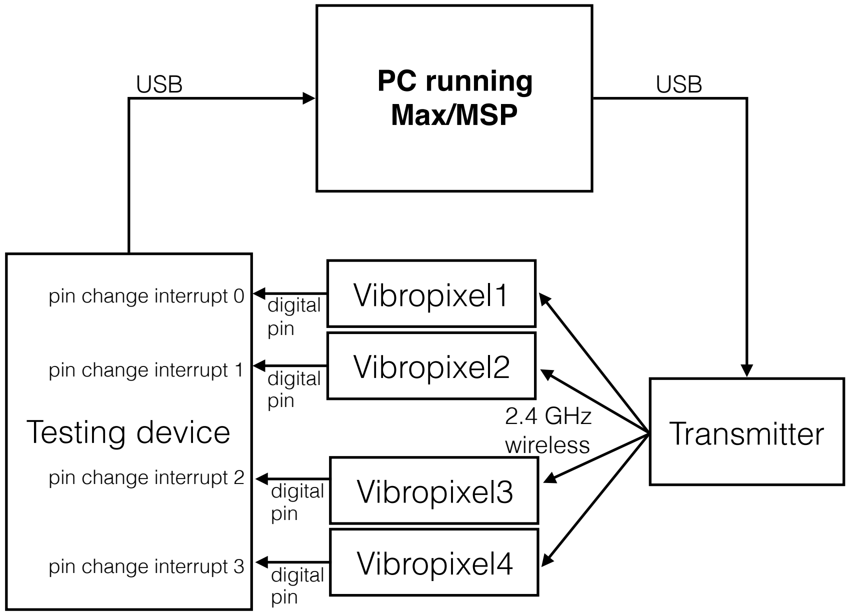

Fig. 5.12 The configuration of test 3, showing the connection of VibroPixels to the testing device.

VibroPixels, we conducted a test of measuring the reception of packets for 4 VibroPixels simultaneously. For this test, we expanded the test setup shown in figure 5.9 to add three additional VibroPixels with digital pins connected to pin change interrupts on the testing device. This configuration is shown in figure 5.12.

The results of this test, shown in figure 5.13, show that for transmission rates of 125 Hertz or greater the successful packet transmission rate was 100%. However, transmission failures began to occur at the 166.6 Hz, whereas in the our earlier tests we showed that transmission failures only began with transmission rates of 200 Hertz. We suspected that this discrepency occurred in the testing device and was caused by the overhead of the software routine to determine which pin triggered the pin change interrupt. In order to determine if this was the case, we removed the electrical connections of VibroPixels 2, 3, and 4 from the testing device (while still leaving them powered on and active) and repeated the test at 166.6 Hz. After this change our results matched that of our earlier

Vibropixel number	1	2	3	4
10ms transmission rate	100	100	100	100
8ms transmission rate	100	100	100	100
6ms transmission rate	99.8	99.7	99.8	99.7
5ms transmission rate	99.0	98.4	98.2	98.3
4ms transmission rate	87.1	87.9	88.0	87.3
6ms transmission rate with only VP 1 connected	100	0	0	0

Fig. 5.13 The percentage of transmission failures for all four devices under test.

test, even with three additional VibroPixels active and within close proximity.

5.3.7 Discussion of the tests

The communication protocol and addressing scheme of our system was designed to minimize the necessity for large numbers of packets to be sent over the wireless network. Due to this fact, for our target application we consider an adequate transmission rate to to range from 10-50Hz. At these rates our tests indicate no transmission failures in the test environment. In addition, the transmission rate jitter of +/- 3ms is below the rate at which the control signals are generated for both the actuators (generated at 200Hz) and the LEDs (generated at 50Hz). While we expect that dropped packets will be more common in real-world performance environments, these tests gave us confidence in the basic performance of the system.

5.4 The VibroPixels in Use

While the VibroPixels were designed specifically for the requirements of *Haptic Field*, their modular design has facilitated their use in several additional research projects.This section will discuss the existing applications for the VibroPixels, and any application-specific requirements and changes to the system.

5.4.1 *Haptic Field*

The initial use of the VibroPixels in a public presentation was in the artwork *Haptic Field*, presented at the Chronus Art Center in Shanghai, China from July 9 - September 3, 2016.[12] A collaboration between Chris Salter, Tez, and Ian Hattwick, *Haptic Field* is an immersive multimodal art installation in which visitors wear a garment equipped with VibroPixels as they explore a space equipped with several different sources of auditory and visual stimuli.[13]

Configuration of the VibroPixels: The VibroPixels used in *Haptic Field* served two functions: as wearable visual and tactile displays, and as ambient lighting hung from the ceiling of the installation space. Nineteen garments were created for the installation, each of which had seven VibroPixels attached via velcro and elastic straps. The VibroPixels on each garment were assigned the same group ID and unique device IDs. As there is no fixed form for the piece, with participants entering and exiting at their own speed, we considered it likely that at most half of the suits would be worn in the

[12]The conceptual design of *Haptic Field* was created by Chris Salter and TeZ. The design of the lighting and tactile effects were designed by myself, Chris Salter, and TeZ. The audio design was by Chris Salter and TeZ, and the garment design was by the clothing manufacturer JNBY.

[13]For video documentation of *Haptic Field*, visit `https://vimeo.com/193992366`.

Fig. 5.14 Visitors exploring *Haptic Field* while wearing garments with VibroPixels attached. VibroPixels can also be seen hanging from the ceiling to provide ambient light. Photo courtesy of Chronus Art Center.

installation at once, the remainder being in the dressing room as the visitors dress and undress. Therefore, in order to maintain a more constant level of activity in those moments where tactile events are traveling from suit to suit, nine group IDs were utilized, with each garment sharing a group ID with one or two others.

An additional group of 12 VibroPixels were installed permanently in the space as ambient lighting, as seen in figure 5.14. These VibroPixels did not have actuators, battery holders, or silicone covers, instead being installed in 12cm cylindrical plastic tubes with frosted paper diffusers taped to the outside. Two-conductor cable was soldered to their battery connector, and the wires were run to 5V power supplies. The ambient lighting was mostly set to create faint, gradually changing colour fields, although they were capable of being addressed with the same control messages as the worn VibroPixels. The hung VibroPixels were all assigned the same group ID and seven device IDs were distributed among them, with five device IDs being shared between two devices.

Performance of the VibroPixels: The installation ran continuously for 7 hours a day, 5 days a week. 145 VibroPixels were used continuously while the installation was open, 133 on the garments and 12 installed as ambient lighting. Several extra VibroPixels were provided in case of device failures, of which four were used over the course of the installation.

Despite the size of the performance space, 30m x 10m, a single transmitter located at one of the short ends of the room was able to successfully transmit packets throughout the performance space. While no perceptible packet loss occurred in the performance space, we were not able to conduct quantitative tests of the wireless performance due to time constraints and the installation context.

The only challenge we faced is that when the garments were in the dressing room, located behind one wall of the performance space, the radio signal strength was so low that occasionally the radios would begin interpreting noise as valid radio messages. When this occurred, a continuous stream of garbage data would be read from the radio. As always, in prototyping and the creation of the piece this problem never surfaced as the garments never spent an extended period located in a low signal strength area. The solution for this problem was the implementation of a watchdog timer which would reset the microcontroller when the program would get stuck in the function receiving data from the radio.

5.4.2 Tactile metronome

The VibroPixels are being used in an on-going research project into the development of a tactile metronome for conductors contemporary classical music. This research is being conducted by McGill Masters student Patrick Ignoto under the supervision of Marcelo M. Wanderley and Ian Hattwick, and was presented in July 2017 at the 8th International Conference on Applied Human Factors and Ergonomics in Los Angeles, California (Ignoto et al., 2017).

There are several existing implementations of tactile metronomes which focus on a variety of applications, including performer synchronization (Giordano and Wanderley, 2015) and ensemble performance of music with multiple tempos (Giordano, 2016, 138-148)[14]. The research project described here aims to explore the use of a tactile metronome for aid in conducting contemporary music. To this end, we are collaborating with Prof. Guillaume Bourgogne, the conductor of the Contemporary Music Ensemble (CME) at McGill University. The CME frequently performs pieces in which live musicians perform simultaneously with a pre-recorded audio track. Frequently, a pre-recorded audio click track is also provided to assist in synchronizing the ensemble with the pre-recorded track. However, in the context of the CME Bourgogne feels that an audible click track is problematic for two reasons. First, it is intrusive, interfering with the conductor's auditory perception of the music. Secondly, much of the music performed does not require the rhythmic precision between the ensemble and the backing track in the same manner as a popular music ensemble would, but may for musical reasons need to maintain a more flexible synchronization.

The goal of this research project is to implement a tactile metronome which does not interfere with the auditory channel and which explores the use of tactile cues with continuous envelopes rather than discretely defined beats. To generate the tactile stimuli, a single VibroPixel is worn by Bourgogne as he conducts the CME, with a transmitter connected to the computer which plays the prerecorded audio file.

[14] Also discussed in section 4.3.3 of this thesis.

Modifications of the VibroPixel system: Early explorations of the use of continuous waveforms for display of tempo information made clear that it would be necessary to clearly articulate the peak of each waveform, where the actual beat would lie. In order to do this, we decided to use the VibroPixel's coin cell actuator for the overall envelope, and the cylindrical actuator for the beat articulation. Since the system designed for *Haptic Field* uses a single control message for both actuators, in which each actuator's response is scaled separately to create the widest possible range of vibration amplitudes, it was necessary for Ignoto to modify the VibroPixel's firmware and communication protocol to allow for individual control of the actuators.

5.4.3 Haptic game sculptures

Another application for the VibroPixels is being created by Ida Toft, a Ph.D. student working in the Technoculture, Art, and Games research centre at Concordia University. As part of her research, she is creating social games in which participants receive a repeating tactile pattern, and have to identify other players, objects, and locations that share the same tactile pattern.[15] While the bulk of the creation of the gaming system is Toft's own work, I collaborated with her on several aspects, including the generation of control messages for the VibroPixels as well as the sound design for the game.

Modifications of the VibroPixel system: In the current game implementation, there are teams which each consist of four players, an object, and a base location, and each team receives the same tactile pattern. Using the existing VibroPixel control message protocol, it would be easy to assign each team to a group ID and address them with the team's tactile pattern with a single control packet. However, as the teams change

[15] `http://tag.hexagram.ca/projects/haptic-game-sculptures/`, accessed April 4, 2017.

dynamically for each game cycle repetition, with the groupings of players, objects, and locations which make up a team changing in each cycle, the group ID of each VibroPixel would also have to be dynamically changed. While it would be technically possible to send a message changing the group ID of individual VibroPixels, it would break one of the design decisions articulated in section 5.3.4, which specifies that packets should never depend upon the successful reception of a previous packet.

For this reason, we compromised on a solution which determines the minimum number of control messages are necessary once random assignment to groups have been made. To implement this, all of the VibroPixels being used are distributed evenly across four group IDs. For each team, we determine which team members share the same group ID, and send a control message to those members with a single control message. With four teams and six devices team, the worst case scenario is when each team consists of at least one device per group ID, necessitating that a control message be sent to each group ID. However, in practice teams are unlikely to consist of devices from all four group IDs, allowing us to reduce the number of control messages necessary.

5.5 Discussion

Much of the development of the VibroPixels was directly influenced by my experience in my previous work, examples of which will be shown in Chapter 6. In this section, I will briefly discuss several specific aspects of the development of the VibroPixels, including the support for the artistic creation process through the system's development, the way the system's design facilitates use in other projects, and specifics regarding the manufacturing process.

5.5.1 Supporting the artistic creation process during the system's development

As described above, the overall VibroPixel system consists of four elements: the hardware of the VibroPixels, firmware which runs on the VibroPixels, the communication protocol, and software tools for generating control messages. During the development process, I chose to maintain the same strategy as used during the development of the *Ilinx* garment, in terms of exposing multiple levels of access to the hardware functionality. Many of the design decisions during development were made explicitly to facilitate exploration and modification of the system. For example, the software tools were created in Max/MSP as that is the software environment used by my collaborators; the firmware for the VibroPixels was created in the Arduino IDE as that is also widely used in artistic and academic settings; and the development of the communication protocol was carefully documented and communicated to my collaborators.

Use of the system in the creation of *Haptic Field*: I provided a variety of software tools and information to my collaborators over the course of the development of the VibroPixels and the creation of *Haptic Field*. These include the hardware itself, the software which runs on the VibroPixels, an assortment of written documentation, a software tools for generating device addresses, a software tool for formatting messages to send to the VibroPixels, and a software UI similar to that shown in figure 5.6 but without the visual representation of the envelopes. Over the course of the development process my collaborators used several of these, including the written documentation and tools for generating addresses and formatting messages. Ultimately, however, I observed that the only tool which they modified and incorporated into the final system which ran *Haptic*

Field was the software UI.

While my collaborators expressed interest in possibly exploring and modifying the device firmware or other elements of the system in the future, the time pressures of the development and artistic creation process made it difficult for them to do more than utilize the tools made available to them. One exception to this is the ambient lighting of the piece, which was provided by 12 hanging VibroPixels. As these VibroPixels were permanently installed, we decided that it would be better for them to be powered by a wired connection rather with batteries. In order to accomplish this, we soldered cables connected to a USB power supply to the positive and negative battery terminals on the VibroPixels. The cables both provided power and held the VibroPixels up as they were hung from the ceiling.

Use in other applications: While the above discussion focuses on the use of the system for its original intended application, my intention was for the system to be suitable for a variety of applications. The strategy of providing access to working with and modifying the system on multiple levels was adopted as much for this purpose as for the creation of *Haptic Field*. The success of this strategy has already been shown in section 5.4, in which I describe how modifications of the firmware, communications protocol, and software tools allowed for the use of the VibroPixels in two additional applications.

5.5.2 Manufacturing the VibroPixels

One of the goals of the VibroPixels is to support the creation of distributed tactile displays which involve multiple participants. In order to make this possible, I focused on designing the hardware to be easy to manufacture and cost-efficient. In order to accomplish this, I leveraged the digital manufacturing resources which I had access to, and utilized industrial manufacturing techniques when possible. Our primary resource for digital manufacturing of the VibroPixels was equipment located at the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT), which includes two commercial 3D printers, a Stratasys uPrint SE and a Stratasys Fortus 400mc, and a commercial lasercutter, a Trotec Speedy 300.

One primary mechanical manufacturing concern was fabricating the enclosures for the VibroPixels, which serve both to protect the electronics and also to diffuse the LEDs, as shown in figures 5.1 and 5.15. Several other considerations arose during the design process. First, the cover needed to be able to securely attach to a VibroPixel while also being removable. Secondly, I decided to explore using soft materials in order to enhance the wearable aesthetics of the device.

I initially considered 3D-printing covers out of the translucent materials available to the Fortus 400mc, but the cost of the materials as well as the time to manufacture were prohibitive. As the creation of a soft cover was aesthetically appealing, I decided to explore making the cover out of soft silicone. To accomplish this, I 3D-printed moulds which I used to cast the covers out of Mold-Star 20T silocone rubber.[16] This allowed me to take advantage of the capabilities of 3D-printing to create intricate structural details, while the actual material cost was limited to the 3D-printed materials used in making the moulds and the silicone material used for casting the covers. Some of the mechanical details include a small lip at the bottom of the cover, which slipped underneath the PCB to securely attach the cover, and cutouts in the cover to accommodate the battery holder, button, and straps. Printing eight moulds allowed for casting eight covers per hour at the price of $1/cover in silicone material.

[16] https://www.smooth-on.com/products/mold-star-20t/, accessed April 1, 2017.

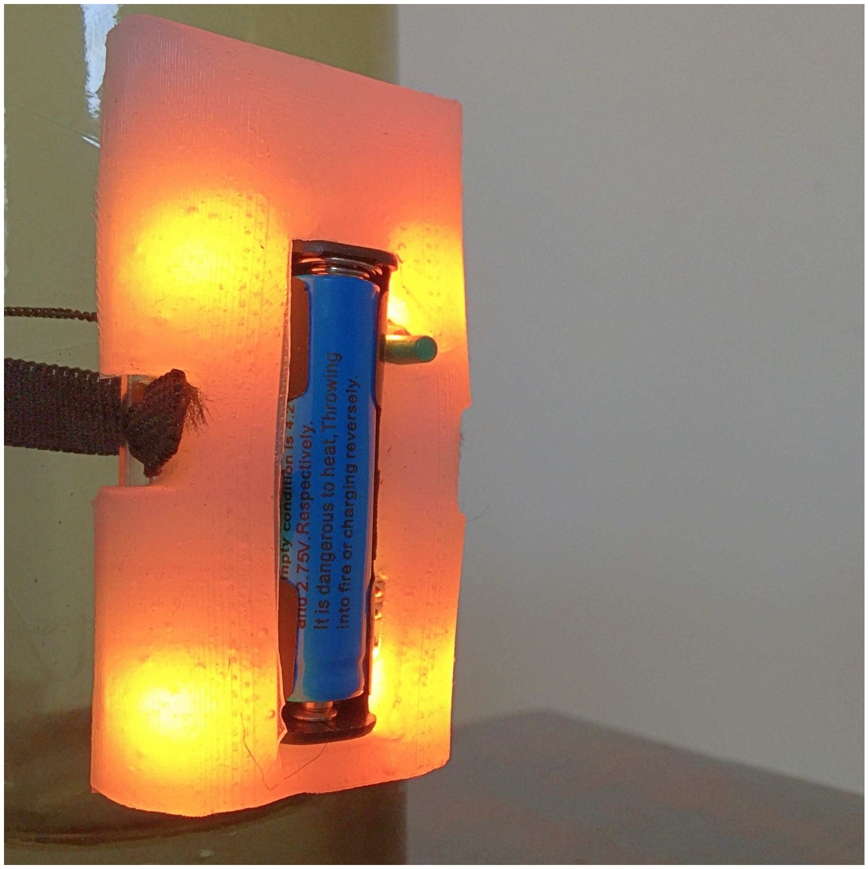

Fig. 5.15 The silicone cover of the VibroPixel diffusing the LEDs.

5.6 Conclusion and future work

This chapter presented the VibroPixels, a wireless tactile display system suitable for applications which require a distributed tactile display. The system was developed to support the creation of the artwork *Haptic Field*, which was premiered in China in the summer of 2016, and has since been used in several other applications, including the creation of a tactile metronome system and the creation of social games which explore tactile perception.

The conception of the VibroPixels began with a vision of massive, shared, distributed tactile experiences. In order to accomplish this vision, it was necessary to consider many different design aspects, ranging from the system's functionality, its system architecture, its use in artistic creation, its tactile and visual aesthetics, its manufacturability, its robustness, and its ability to support a variety of future applications. A discussion of these seven design aspects will form the bulk of the next chapter.

I should note that work on the VibroPixels is ongoing, with additional major public productions using the system planned for the fall of 2017, and an additional manufacturing run currently in development. I am also currently working on providing a framework for using the on-board accelerometer on the VibroPixels. I am evaluating two approaches for supporting transmission of accelerometer data: peer-to-peer data sharing of accelerometer data, in which data from one device would be sent directly to other devices, and another approach in which features derived from the accelerometer data, such as orientation, peak acceleration, or periodicity, are sent to a central computer. The central computer would request data from individual VibroPixels, use the data in algorithms for generating control messages, and then transmit control messages to other VibroPixels.

I am also making VibroPixel kits, consisting of a transmitter and a small number of VibroPixels, in order to send to other researchers and artists to allow them to evaluate the use of the VibroPixels in their own work. However, this is a substantially different model than the context of the VibroPixels development, with a different set of considerations and design decisions.

Chapter 6

Design Aspects and Principles

In the previous three chapters we have presented hardware systems which were created for use in professional artistic productions, discussed the ways in which those systems were used, and highlighted important elements of their design and design process. Drawing on my experience in creating these systems, in this chapter I will present a framework which considers the many different requirements of designing for such contexts, as well as a set of design principles which are intended to assist in meeting these demanding requirements.

The perspective of this chapter: While there exist many stakeholders in the design of digital musical instruments, which include performers, composers, technology developers, and manufacturers (Modhrain, 2011), the framework and principles presented in this chapter will focus on the point of view of the technology developers. By doing this, I am making an implicit assumption that there is a distinction between the technology developers and the artists/researchers involved in the design process. In practice, this distinction is frequently highly blurred, as the research goals of the developers generally will go beyond the development of new technology, and the artists/researchers may also have an active hand in development. In addition, for much DMI reseach the artist and developer may be situated in the same person. Nonetheless, by separating the two in our discussion I seek to present an overview of the challenges of technological development without making any assumptions regarding the artistic use of the systems beyond the fact of their use in professional performance.

6.1 A framework for designing hardware systems for professional artistic productions

The definition of design specifications is a central part of most design processes, and may also be referred to as identifying design requirements or creating a design brief. This activity is so important that Cather et al. state "[t]he lack of a complete and thorough written specification is now generally accepted as being one of the main reasons for design failure" (Cather et al., 2001, p. 36).

No matter how they are conceptualized, design specifications represent specific characteristics a device must possess in order to successfully meet the device's objectives. However, it is challenging to create a set of specifications which addresses the entirety of the challenges faced by a design, especially in contexts such as ours where requirements are subject to change over the course of the design process. One way to assist in this task may be the articulation of a framework which presents a consistent view of these challenges throughout the design process.

Functionality	What the system is designed to do, and how the user interacts with it.
Aesthetics	Aspects which qualitatively affect the experience of the user.
Support for artistic creation	How the system is designed to allow for its use in the artistic creation process.
System architecture	How the different elements of the system interact, and how the system interacts with the overall production environment.
Manufacturing	How the system will be manufactured, and how the system's design supports the manufacturing process.
Robustness	How the system successfully meets the challenges of use in its intended context.
Reusability	How the system and its subsystems support use in other contexts.

Table 6.1 The seven design aspects comprise a framework for addressing the requirements of designing hardware systems for use in professional artistic productions.

6.1.1 The design aspects

The seven design aspects comprise a framework for addressing the requirements of designing hardware systems for use in professional artistic productions, and an overview of the framework is shown in Table 6.1. Each design aspect presents a different perspective on the requirements of designing for this context in order to assist in the creation of design specifications.

I was influenced in the creation of the design aspects by Stuart Pugh's concept of *Total Design*, which presents an overall look at the challenges involved in product design from market identification to aftermarket support (Pugh, 1991). The core of Total Design is the creation of a complete Product Design Specification (PDS), addressing a total of 32 elements which Pugh argues are necessary in a complete PDS (Pugh, 1991, 44-66). While many of these, such as shelf-life storage, competition, and market constraint, may have little impact on applications in our contexts, many of them are surprisingly pertinent, including aesthetics, performance, shipping, installation, and maintenance.

As we have seen, there is no preexisting literature presenting the same total perspective on the design of DMIs. I created the design aspect framework in order to provide such a perspective.

The definition of the design aspects: While Pugh's PDS presents an approach suitable for industrial-commercial product design contexts, the context within which I conducted my research was significantly different. Therefore, for the identification of the design aspects for our context as I describe in this chapter I relied primarily upon the practice-based knowledge reported in the literature and covered in chapter 2, as well as my personal experience as described in this dissertation. Many of the design aspects, including manufacturability, robustness, and aesthetics, emerged during my reflection on the design process of the Prosthetic Instruments. Others, including support for artistic creation and reusability, only became apparent after the later projects.

As the design aspects arose out of the experience of practice, they are inherently somewhat subjective, and their applicability will likely vary given the variety of contexts within which DMI research is carried out. Nonetheless, I argue from my experience that the perspectives presented by the seven aspects will be useful for the design of any DMI intended to be used in professional contexts.

Sections 6.1.2 to 6.1.8 present overviews of the seven design aspects. I stress that these design aspects are not necessarily mutually exclusive, and the differentiations described here are more to provide a way for designers to gain a perspective on the overall requirements of a system rather than necessarily generating a complete technical description of a system.

6.1.2 Functionality

Generally speaking, any new hardware device will be created in order to provide some mechanical or electronic functionality. As discussed above in section 2.1, this aspect tends to be one of the primary research focuses in DMI design. While this preeminence will be manifest throughout the design process, focusing on functional design alone will not ensure the success of the device in context.

The functionality of the systems we have created tend be influenced by the needs of the project's research goals. For the Prosthetic Instruments, for example, the goal was to investigate the ways in which a DMI could be designed for dancers. Immediately, this creates a requirement that the instrument allow for sensing the dancer's actions, and as the design for the Prosthetic Instruments took shape the details of the sensors became increasingly well-defined.

Mechanical aspects of a system's design can also provide technical functionality. The forms of the Prosthetic Instruments, for example, served as extremely important functional characteristics, as were their mounting systems.

6.1.3 Aesthetics

While a proper discussion of the role of aesthetics in hardware design is outside the scope of this dissertation, we will consider here those aspects of aesthetics which are most directly pertinent to the technical design, and which come from the perspective of the system's designer. Generally speaking, we will define aesthetics from this perspective as being those aspects of the design which qualitatively impact the experience of the user or audience. While artistic collaborators will often bring strong aesthetic preferences with them, frequently the designer will also play a key role in defining the aesthetics of a system. The visual aesthetics of a system's design, for example, provides cultural referents, subtle guidance as to the system's intended use, and frames the user's interaction with the system.

For wearable devices, form and fit are also a key aspect of aesthetics. While placing technological devices on the body brings with it a long history of cultural attitudes toward technology, more generally it will also impact how comfortable and safe the user feels in interacting with the system.

6.1.4 Support for the artistic creation process

The systems we have described in this dissertation were developed in collaboration with professional artists, and one of our main concerns was supporting the use of the systems throughout the artistic creation process, primarily through providing software tools. The design of software tools for this purpose is a complex subject, and one of the research topics in the field of Human-Computer Interaction (HCI).

However, maintaining a clear vision of user interaction is difficult when creating systems in collaboration with artists. In their overview of software engineering practices in the design of systems for creating interactive art, Trifinova et al. found that "requirements are difficult to capture, vague at the beginning and frequently changeable" (Trifonova and Jaccheri, 2008). An understanding of the functionality and material manifestation of a system often changes during the development and use of a system, making the creation of fixed software tools a moving target. In particular, an exploration of the material qualities of the system often plays a fundamental role in the artistic creation process, and Trifonova and Jaccheri (2008) found that some artists expressed a desire to expand their engineering knowledge in order to be able to experiment with and modify lower level components of systems.

One approach to addressing this issue is the creation of basic programming interfaces in order to allow a certain amount of reprogrammability of the system. Colin Machin describes these interfaces as a sort of middle-layer, providing artists with the ability to change parameters of the system while shielding them from the system's underlying complexity (Machin, 2002). In our systems, we tend to create these tools in common New Media programming languages such as Processing, Pure Data, and Max/MSP, allowing collaborators with experience in these languages to control the system's parameters algorithmically. The abstractions presented in section 4.2.2, created to allow for the creation of tactile effects in the *Ilinx* garment, are one example of such tools.

Support over the development process: In addition, fully-developed software tools may only make sense once the final system is designed and available to the artists. In earlier stages of development, however, there may still be a need to provide elements of the system-in-development to help facilitate the artistic creation process. Throughout the development of the Prosthetic Instruments, for example, working prototypes of the instruments were continually shared with our collaborators in order for them to gain an understanding of how to integrate them into their artistic process, as well as providing an opportunity for their feedback and experience to influence the development of the instruments.

A different example of supporting our collaborators' processes occurred later in the project, in which a full-set of instruments with no electronic functionality was provided to the choreographer and dancers in order to allow them to experiment with developing a practice of performing with the instruments. Similar scenarios occurred during the development of the *Ilinx* garment and the VibroPixels, in which a subset or rough prototype of the system was given to our collaborators for them to experiment with while the final system was being designed and manufactured. In such scenarios, we find it is helpful to focus on what will be easy to provide while also paying attention to the specific needs of our collaborators, as many times they will not need fully functioning systems early in the development process.

6.1.5 System Architecture

A system's functionality can often be conceptualized as consisting of modules, each of which fulfills one or more functional requirements. The architecture of the system comprises the ways in which these modules are designed to work together in order to allow them to function as required in the final system. This includes both technical functionality, such as communication protocols and power management, as well as the system's integration into the actual performance context, which involves interaction with other systems used in the production. The following sections discuss these issues individually. Generally speaking, specifications which primarily engage with this aspect are not visible during the device's use, but may be critical in allowing that use to take place.

Communication protocols: Communication protocols are a key element of the system architecture, as is the configuration of the network when multiple devices need to communicate with each other. Without an effective communication protocol, technical functionality may be unusable, as we will see in section 6.1.10. Conversely, an effectively designed communication protocol may support the system's functionality, as we have seen with the VibroPixels.

Codependent modules: Occasionally, the performance of a module depends upon the behaviour of other modules, or interacts with another module. In these cases, it is important to identify the codependencies to make sure the implementation meets all of the module's specifications. Power management is a common case where systems are codependent. Wireless systems, for example, typically depend upon rechargeable batteries. We choose, as mentioned in section 5.2.2, for batteries to be able to be physically removed and replaced in order to allow for systems to be continually used in rehearsals and performances. This necessitates separate battery chargers and a protocol for battery maintenance in order to assure that batteries are charged and ready to be used when required. In this case, the protocol consists of the training of the production staff and an incorporation of the chargers into the show setup, as described in section 3.2.4.

Another aspect in which power management depends upon the functionality of other modules is in terms of power consumption. In order to prolong battery life in wireless devices, it is common for components to have low-power or standby modes, in which their functionality is disabled in order to reduce power consumption. In some systems, the proper implementation of these components is essential in order for the system to meet its specifications for battery life.

Integration into the production: The integration of systems into professional productions also produces opportunities and challenges in terms of coordination with other systems. The physical integration of the system with the production is an important factor to consider, as in the careful placements of the Prosthetic Instruments backstage, described in section 3.2.4, as well as in the dressing rituals for the *Ilinx* garment, described in section 4.3. When possible, it is nice to identify opportunities for the system being created to directly support another aspect of the work, as in the lighting of the Prosthetic Instruments, as well as in the VibroPixels which were used as installed lighting in *Haptic Field*, as described in section 5.4.1.

In addition, it is likely that the system will be controlled by a central PC which will also be controlling other systems. In these circumstances, it is important the communication with various systems not interfere with each other. While this has not been an issue in these systems, it is not uncommon for multiple systems to utilize 2.4GHz wireless transceivers, in which case it would be necessary to configure the systems such that their wireless transmission doesn't interfere with each other.

6.1.6 Manufacturability

One of the biggest challenges for all of the projects discussed in this dissertation was manufacturing the final system in the desired quantities. The best way to approach the manufacturing of a DMI depends upon the instrument's intended purpose. Many instruments fulfill their purpose in research labs, demo sessions, and performances by their creators. However, use in professional productions places additional demands upon a design's robustness, maintainability, ease-of-use, and reliability.

Once an instrument is ready to move from a prototype to a stageworthy design there are many different approaches to manufacturing. The following sections describe four generalized examples of mechanical construction, which we compare in terms of their pre-production time, post-production time, and ease of recreation. It should be noted that many instruments combine manufacturing approaches, which we will see is true of the Prosthetic Instruments as well.

Artisanal: In the artisanal approach the materials used for construction of the instrument are shaped and assembled by hand. This is the approach closest in spirit to prototyping and it has many associations with traditional manufacturing of musical instruments. Since it is common for small adjustments to be made to the parts of the instrument during assembly this approach is tolerant of variations in materials or in the sub-assemblies. The primary benefit of the artisanal approach is flexibility during manufacturing. The ability to make adjustments during manufacturing means the instrument's specifications do not need to be precisely defined ahead of time. The primary disadvantages are the time it takes to manufacture an instrument as well as the difficulty of precisely recreating an instrument.

A good example of this approach are the hand-formed wooden objects which form the basis for the Digital Poplar Consort, designed and built by Kevin Patton and Maria del Carmen Montoya.[1] The design of these instruments explicitly "recalls the aged art of musical instrument making and takes this practice into the realm of experimental electroacoustic chamber music."[2]

Building Block Approach: In the building block approach pre-existing forms are reutilized as the basis for the design. In this approach the look and mechanical construction of an instrument are often determined by the characteristics of the building block. One example is the hemispherical speakers used by the Stanford Laptop Orchestra, which are built using a wooden kitchen bowl.[3] Any instrument which attaches sensors to an existing product, such as Perry Cook's PhISEM or TapShoe can also be considered to utilize a building block approach (Cook, 2001).

The building block approach can substantially cut down on manufacturing time and increase the ease of recreation. However, if significant alterations to the pre-existing forms are needed, in order to install electronics for example, these benefits may not be as significant. The amount of work to fit together pre-existing elements with custom elements makes this approach closer in practice to artisanal approaches as opposed to the CAD approaches described below.

Rapid Prototyping: The rapid prototyping approach utilizes the capabilities of generally available computer-controlled manufacturing machines such as laser cutters, vinyl

[1] `vimeo.com/3015548`, accessed February 4, 2014.
[2] `www.steim.org/steim/download/DigPopConsortDocument.pdf`, accessed February 4, 2014.
[3] `ccrma.stanford.edu/~njb/research/slorkSpeaker/`

cutters, or CNC milling machines. An excellent guide detailing one approach to rapid prototyping is Charles Guan's "How to Build Your Everything Really Really Fast" (Guan, 2013). The benefits of this approach are the ability to manufacture precise duplications of instruments as well as a decrease in manufacturing time. However, this approach demands considerably more time for the creation of CAD models as well as a solid understanding of material tolerances. In addition, commonly available rapid prototyping equipment can place limitations on the characteristics of the parts they create. Most laser cutters cannot be used to cut metal foils or certain plastics which contain chlorine, for example, while CNC machines may have limitations on their manufacturing envelope and cannot easily create sharp internal corners.

Additive manufacturing, or 3D printing, can be seen as a special case of rapid prototyping which allows for the easy creation of a wide variety of 3-dimensional forms which are more typical of industrial manufacturing processes. The 3D printers to which a research lab is likely to have access tend to have significant drawbacks, including limited availability of materials, high material cost, issues with material durability, and small build envelopes. However, these drawbacks may be seen as inconsequential compared to their ease of use, especially given the increasing availability of 3D printers which are both decent-quality and low-cost.

Industrial Manufacturing: The hallmark of this approach is the creation of single-purpose manufacturing tools such as molds and jigs. Frequently the creation of these tools is more expensive and time-consuming than the artisanal manufacture of a single instrument. However, their use provides a flexibility in the form and materials of the parts created, depending on the process, as well as the rapid creation of multiple identical parts. While this approach is typical for almost all commercial products it is less commonly used for NIME design since the complexity and cost of designing manufacturing processes is typically seen as uneconomical for the creation of small quantities of instruments. One example of the use of industrial manufacturing are Weinberg and Aimi's Beatbugs (Weinberg, 2008), which were cast in clear urethane from rubber molds.[4]

6.1.7 Robustness

Any professional artistic production will require a system that is reliable enough to withstand its use in context, including mechanical, electronic, and digital elements. Robustness in this context means: that the system is able to function without failing; that it will continue to work without failing over the course of its intended use; that maintenance of the system is specified and within the capabilities of the system's users; and that provisions for accommodating potential failures have been made, typically through the provision of backup devices. In section 3.4.1, we discussed ways in which the design of the Rib was modified in order to make it more robust, and also discussed how the robustness of a system is a function of its intended use, and in particular the way in which a Rib breaking in rehearsal went from being seen as the fault of the design being fragile to the fault of the user not using it as intended.

While mechanical failures are often obvious, failures of electronic and digital systems can be more subtle. The wireless transmission failure discussed in section 3.4.5, for example, had an obvious effect but the cause was not apparent until further examination the next day. Tests such as those conducted to verify the performance of the VibroPixels, described in section 5.3.6, can help to validate the performance of these aspects of a system, and provide a baseline from which to conduct troubleshooting in the case of

[4] R. Aimi, personal correspondence, April 29, 2014.

unexpected failures.

Providing consistent performance over time within the context of artistic productions can be challenging. As in any system, avoiding any unnecessary changes from performance to performance is essential, as is training the staff on a simple, consistent procedure for setting up, initializing, running, and tearing down the system, as we detailed with preparing the Prosthetic Instruments for touring in section 3.2.4. In addition, for any system with a large number of hardware components, some device failures are inevitable given enough time, which was one of our key reasons for designing the VibroPixels as a modular system in which it is easy to replace a failed unit with a new one.

6.1.8 Reusability

The final design aspect is the ability of a system to support for applications. In this context, we are not necessarily concerned with staging the same performance repeatedly, or with moving towards commercialization or mass-manufacturing, but rather in leveraging the creation of the system to support additional research projects and artistic performances. Given the amount of work that goes into the design and manufacturing of hardware systems, it makes sense to attempt to facilitate their repeated use in order to benefit as much as possible from their creation. There are several forms this can take – either reusing the system as-is for another project, modifying the system to be useable for another project, developing a sub-system to be useable across different projects, or using and disseminating knowledge gained during the design process.

However, for wearable systems and systems designed for specific artistic contexts, it may be difficult to make a system that is not so highly tailored to the application as to preclude easy re-use. The design of the Prosthetic Instruments, for example, makes it difficult to reuse the entire system as-is for other contexts. In section 3.4.3, we saw how the size of the instruments themselves became a limiting factor, making them difficult to use for performers with different body types. While one early design consideration was to be able to use the instruments mounted in different body locations, their final forms made this difficult, as shown by my attempts to use the Ribs as controllers strapped to my forearms as described in section 3.3.1. On the other hand, their use as windchimes in section 3.3.1 demonstrates how sometimes removing a system from its intended use can allow for creative re-use.

The development of the *Ilinx* garment (Lamontagne et al. (2015); Giordano et al. (2015)) and the VibroPixels (Hattwick et al. (2017)) provide examples of how considering reusability in the design process can lead to different outcomes. While both systems are wearable tactile displays intended to create full-body tactile stimuli in immersive artistic installations, in section 4.4.3 we discussed ways in which the design of the *Ilinx* garment made reuse difficult, due to the fixed location of the actuators, while in Chapter 5 we discussed how reconfigurability of the system was a primary design specification for the VibroPixels.

Reusability and design specificity: Within the design aspects, reusability presents a special case, as by itself it does not make a large contribution to a specific system. However, within the larger context of NIME research, in which a researcher will make many systems over the years, a concern with reusability can greatly ease system design and facilitate achieving design specifications for other aspects. For example, the creation of new sensing solutions can allow for novel applications, but with the creation of a new system comes the reality that it is difficult to predict its reliability over time. The use of a subsystem created for an earlier work will make it easier to predict how the subsystem will work in a new context, and over time.

I also do not want to privilege reusability too much, as much of what makes the creation of new designs interesting is the specificity required by the intended application. The Prosthetic Instruments, for example, are an example of a system that was created by necessity to complement the bodies and performance practice of two specific dancers. While a certain amount of reconfigurability allowed for limited use by other dancers and in other applications, attempting to make a general-purpose dance DMI would have led to a much different outcome.

6.1.9 Interdependencies of the aspects

While the design aspects each have their own perspective, in practice device specifications frequently relate to multiple aspects, and when considering changes in one specification it can be helpful to consider ways in which they will affect the specifications of other aspects.

The Evolution of the Ribs: An example of this occurred during the design of the Ribs as discussed in section 3.4.1. As we showed in that section, the evolution of the Ribs' design moved through several stages: small shapes with copper touchpads; small shapes with clear touchpads; larger shapes with clear touchpads; and finally layer, multi-layer forms.

This example shows how the specifications of the various aspects interact: the functionality (capacitive sensing) suggested appropriate materials (copper and conductive plastic); changes in the aesthetic (larger transparent forms) created issues with robustness and flex (due to the material properties of acrylic); changes in the form to meet robustness and stiffness specifications led to the need for new manufacturing techniques

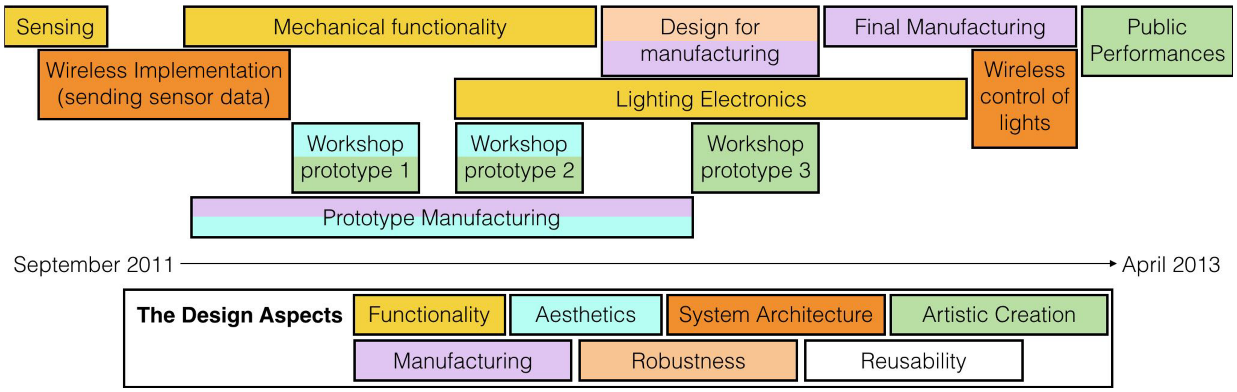

Fig. 6.1 A simplified timeline of the development of the Ribs, depicting the late attempts to implement wireless control of the lighting. The different activities are colour-coded according to the design aspects they were most directly addressing.

(laminated layers of acrylic and polycarbonate). We note these interdependencies may pose problems, but they also offer opportunities for design improvements. In the case of the Ribs, we were quite happy with the properties of the laminated construction across many aspects, including functionality (mechanically stiff but light form), aesthetics, robustness, and manufacturability (it proved to be efficient to manufacture).

6.1.10 Temporality of the aspects

Given their different perspectives, it is common for design aspects to be highlighted at different stages of the development process. Again in the case of the Ribs, the functional design and system architecture supporting the sensing was determined quite early, followed by the mechanical functionality, aesthetics, and manufacturing. While this sequence is fairly common, the precise ordering is likely to change from project to project.

Occasionally, changes to certain specifications which are made out of step with the overall design process may cause problems. The lighting in the Prosthetic Instruments, for example, was developed more as an afterthought (a timeline of the Ribs' development which depicts this is shown in figure 6.1), and it wasn't until meeting with the production's lighting designer that we fully committed to lighting all of the instruments. Leading up to the performances, our efforts were mostly directed towards manufacturing, and although we worked on providing wireless control of the lights to the lighting designer we were not able to implement it to our satisfaction before the final rehearsals. In the end, this caused us to set the lighting for the instruments to be permanently on for the performances.

One of the goals of considering the design aspects is assisting in consideration of all of the design aspects, even before they become the primary focus of the design activity. Due to the interdependent nature of the aspects, specifications for manufacturing and reusability considerations may suggest approaches to creating the functional design. Similarly, considering the complete set of design aspects over the entire development process may help to prevent the need for extensive redesigns.

6.2 Principles for the design of hardware systems

In this section I present principles for the design of hardware systems designed to be used in professional artistic productions, an overview of which is presented in table 6.2. Like Cook's principles (Cook, 2017, 2009), my principles reflect my current approach to research practice rather than being intended as generalized prescriptive recommendations. Nonetheless, I argue that a crystallization of practice presented in this way may be useful to other researchers working in these contexts.

While many of these principles interact with multiple design aspects, for organizational purposes I present them here in relation to their primary design aspect.

Principles of functionality	
	Novel solutions are cool, but risky
	Re-use existing systems when possible, but be prepared to start from scratch
	It is more important that it work than how well it works
	Perform quantitative tests of the system when possible
Principles of aesthetics	
	Inspire confidence with the system's design
	Form and fit are important, and subjective
	Be conscious of ways in which the system's form may exclude users
	Don't harm the system's users
Principles of support for artistic creation	
	Create video documentation
	Allow the ability to program the system at multiple levels
	Design to allow for continuous use
	Pay attention to your collaborators' process, and be prepared to provide prototypes with the appropriate functionality
	Provide visual feedback regarding system status
Principles of system architecture	
	Every interface between modules is a potential point of failure
	Design to allow for continuous use
	Be aware of wireless details
	Consider the context of the system's use
Principles of manufacturability	
	Use appropriate manufacturing techniques
	Begin manufacturing early
	Identify opportunities to speed manufacturing
Principles of robustness	
	Repairability vs. replaceability
	Pay attention to material properties and points of failure
	Learn and use standard techniques for protecting electronics
Principles of reusability	
	Keep an eye towards future applications
	Keep documentation of the design process as well as the system
	Clarify the possibilities of system reuse from the beginning

Table 6.2 Design principles based on the seven design aspects, categorized by aspect.

6.2.1 Principles of functionality

1. Novel solutions are cool, but risky
2. Re-use existing systems when possible, but be prepared to start from scratch
3. It is more important that it work than how well it works
4. Perform quantitative tests of the system when possible

Novel solutions are cool, but risky: Engineering design often requires compromises between conflicting design specifications. Trying to find novel solutions to these conflicts can be an exciting aspect of the design process; however, it also brings with it risks. In the case of the capacitive sensing in the Ribs, for example, we chose to utilize conductive plastic which satisfied various specifications: functional (eight touchpads), aesthetic (transparent), manufacturable (able to be lasercut). Conductive plastic like this is not a commonly used material, and the vendor we found for it actually marketed it for use as protection from electromagnetic fields (EMF).[5]

Two unanticipated problems occurred due to our choice to use this plastic. The first is that the conductive layer would wear off due to the dancers touching it. To mitigate this, we sprayed a layer of protective polyurethane over the touchpads, although not before some degradation of the sensing occurred. More problematic was that, just before our final manufacturing run, the vendor ceased stocking the material we had been using, which had an adhesive backing applied to it by the manufacturer.[6] The vendor still stocked a version of the plastic without an adhesive backing, so we applied a conductive backing ourselves. However, the results of this were inferior to the adhesive backing

[5] `lessemf.com`, accessed April 4, 2017.

[6] In a discussion with the vendor they said the manufacturer had decided that manufacturing that product was not cost-effective.

provided by the manufacturer.

These results demonstrate two common problems with using novel solutions: the inability to predict performance over time, and the difficulty of assuring a consistent supply of materials.

Re-use existing systems when possible, but be prepared to start from scratch: The re-use of existing systems and components greatly simplifies the design process, as commercially available solutions will have quite a bit of engineering embedded within them. Nonetheless, sometimes it is necessary to start from scratch, even when the problem seems fairly basic. The clips in the Prosthetic Instruments, for example, are a fairly basic design, but we spent weeks looking for commercial solutions before deciding we would have to manufacture our own. Over the course of the design process we went through dozens of clips designs in order to create a solution which would meet the specifications for creating a firm connection, releasing easily, and being easy to manufacture and assemble.

It is more important that it work than how well it works: In the projects we have discussed, we have worked under the strict deadlines of public performances. In this context, meeting all of the device specifications can extremely challenging. In addition, our systems are generally used within a larger work comprising of several systems. In terms of functionality, this often means that the performance of individual aspects of the performance of the system are less important than the overall system being useable in context.[7] In the production of *Les Gestes*, for example, the lighting of the Prosthetic

[7] There are many examples with commercial engineering of companies getting in trouble by focusing on performance rather than overall design, as in the attempt to perfect compressor blade causing the collapse of Rolls-Royce (Pugh, 1991, 4-5).

Instruments was not implemented in the way we had hoped. Nonetheless, the mere fact of the lighting working had a large effect on the overall production design.

Perform quantitative tests of the system when possible: On the other hand, it can be helpful to perform quantitative tests in the interest of ensuring that the system does work as expected. While it is easy to put these off due to time pressures, quantitative tests nearly always help improve a system's performance, and also aid in preparing publications describing the system's functionality.

6.2.2 Principles of aesthetics

1. Inspire confidence with the system's design
2. Form and fit are important, and subjective
3. Be conscious of ways in which the system's form may exclude users
4. Don't harm the system's users

Inspire confidence with the system's design: During the development process it is tempting to show functional prototypes in a very raw form. But often it is difficult for others to see the potential of these prototypes rather than their current state, especially in terms of visual aesthetics. In addition, a prototype which consists of a few modules connected with loose wires can cause people to focus on the fragility of the system rather than its capabilities.[8] A few extra minutes to assemble components inside of a case, or a little extra thought in terms of creating a system that looks well-put together, can help collaborators focus on what the primary functionality of the system, and avoid encouraging feedback on elements that aren't the current focus. For example, we wonder

[8] An observation also addressed in Marshall (2008, 221-230).

how much the raw appearance of the early Rib prototypes impacted our collaborators' perceptions, which may have made transparent touchpads seem like a more attractive option.

Form and fit are important, and subjective: When constructing wearable systems, form and fit are extremely important considerations. This is especially true when the coupling between device and body plays an active role in the device's functionality. In these cases, rigid devices may need to be custom-fit, as we found with the Visors. We also found that many users found the pressure of the soft, stretchable attachments of the *Ilinx* garment to be a perceptible part of their experience, perhaps affecting their experience of the tactile display itself.

Be conscious of ways in which the system's form may exclude users: Systems are often designed considering the physical capabilities and preferences of people involved in the project. When working directly with the system's intended users, it is possible to get feedback during the system's design to ensure it is comfortable and useable, as was the case with the Prosthetic Instruments. But when the system will be used by a diverse audience it can be difficult to accommodate every potential user. While not every device needs to accommodate the entire population, whenever possible avoid creating a system that creates unnecessary limitations.

Providing for a wide range of resizability is extremely important. One of the benefits of the *Ilinx* garment is that the open design of the arms and leggings, as well as the three sizes of garment manufactured, made it possible to accommodate a wide range of body sizes.

Being aware of cultural differences can also be important. The design of the *Ilinx* garment, consisting of jacket and leggings, created a problem when the piece was shown in Tokyo, as women in Japan are much more likely to wear skirts rather than pants. This meant that many women who experienced were only able to wear three out of five garment sections.

When possible, anticipating and making small changes to the system may help to make it more accessible. For example, the *Ilinx* garment could have been designed to be aware of when the leggings were not plugged in, in which case signals sent to the legs could have been rerouted to the arms. For *Haptic Field*, it would be possible to have a set of VibroPixels not attached to a garment but able to be attached to a variety of lengths of resizable straps.

Don't harm the system's users: While this should go without saying, it is a reality that there are many ways in which a hardware device may create risks to the user, and it is imperative for the designers to be aware of these risks so as to mitigate them. For example, when lasercutting plastics or working with metals it is possible that the cutting process could form sharp edges. Before giving prototypes of finished devices to users attention should be paid to identify if this has occurred, and to sand down the edges if it has.

In addition, electrical systems create certain hazards to the users. The majority of system we have worked with utilize low-voltage DC circuits, which are not generally hazardous. However, when using batteries certain risks do arise, in particular with high-density lithium-ion battery formulations, which may create high temperatures or fire hazards when damaged or short-circuited. Due care should be given to protect these kinds of batteries, and to include protection against excessive current draw, short circuits, and over and under voltage situations.

6.2.3 Principles of support for artistic creation

1. Create video documentation
2. Use commonly available software environments
3. Allow the ability to program the system at multiple levels
4. Pay attention to your collaborators' process, and be prepared to provide prototypes with the appropriate functionality
5. Provide feedback regarding system status

Create video documentation: When creating software tools for our collaborators, we frequently find ourselves needing to explain how the tools are intended to be used. While written documentation can be useful, many times a short video tutorial showing us using the tool can be the most effective way to communicate with our collaborators. In addition, once the video is made it can be shared with multiple collaborators all over the world, avoiding the need for one-on-one tutorials.

Use commonly available software environments: Consider the community the system is designed for, and use the software environments used by that community to create your software tools. Avoid the use of proprietary software that is not extremely common, or that doesn't offer the ability to use the software free of charge. Max/MSP, for example, is a proprietary software tool that is extremely common, and, although it does not allow for editing patches without purchase, does allow for the use of existing Max patches without having to buy or register the software.

Allow the ability to program the system at multiple levels: In most of the projects we have worked on, the artistic process of our collaborators has involved some degree of programming, which may include programming sound synthesis and mappings, or programming generative compositional structures. We try to avoid unnecessarily limiting their ability to program our system through the use of fixed user interfaces or control structures. While, as discussed in section 5.4.1, we found that providing high-level tools is helpful to our collaborators, we also found that providing lower-level access allows them the ability to create their own tools as well as modifying the system for other applications.

Pay attention to your collaborators' process, and be prepared to provide prototypes with the appropriate functionality: When developing hardware systems in parallel with artistic development, artistic collaborators will often depend upon prototypes being made available which enable them to explore the material properties of the system. Sometimes the prototypes made during the course of iterative hardware development will suffice for this purpose, but occasionally it will be necessary to create prototypes which address specific design characteristics. For example, in the development of the Prothetic Instruments it was necessary at a certain point to provide a full set of prototypes for choreographic workshops, but these prototypes did not need to have any electronic functionality. The feedback regarding your collaborators' experiences with these limited prototypes will provide important feedback regarding the system's overall design, as is true throughout the design process.

Provide feedback regarding system status: The use of feedback to provide information regarding system status plays different roles in the artistic creation process and the performance process. In general, this primarily refers to visual feedback, but can also apply to other sensory modalities. In artistic creation, visual feedback within the software user interface helps artists to understand the results of parameter changes and programming decisions as they program the system. A visual mockup or proxy for the current state of the system and its response to control messages can help them to conceptualize the work as well as helping them to understand the system's intended responses.

During the performance process, we find it essential to provide simple visual feedback indicating that the system is working as intended. The most basic elements are ensuring that wireless communications are functional and that power is provided. Also helpful is the ability to monitor sensor signals and battery life.

6.2.4 Principles of system architecture

1. Every interface between modules is a potential point of failure
2. Design to allow for continuous use
3. Be aware of wireless details
4. Consider the context of the system's use

Every interface between modules is a potential point of failure: In general, the simpler the architecture of a design, the fewer possibilities there are for failures to occur. In particular, the connections between modules may create problems if not carefully designed, including physical failures of cable assemblies and attachment points (one of the most common failures in electronic systems), as well as errors in data transmission, whether wired or wireless. In the *Ilinx* garment, for example, we initially had a problem with SPI data transmission errors in between the minicomputer and the driver boards due to electrical noise, which we solved through the addition of extra filtering on the SPI data lines.

Design to allow for continuous use: In our applications, we strive to allow for continuous use of the system both through the use of removable batteries and also through the use of generous battery capacities. Generally speaking, we opt to integrate extra battery capacity rather than concern ourselves with power efficiency, for two reasons. First, when in use our systems tend to be continually active, reducing the amount of efficiency to be gained by placing components in standby mode. Secondly, with removable batteries it is a simple matter to change batteries, as opposed to devices with permanently integrated batteries which are unable to be used when charging.

Be aware of wireless details: In 2001 Perry Cook wrote that wires aren't that bad, compared to wireless; in 2009, he modified his stance to say that wireless options had improved to the point they could be reliably utilized (Cook, 2017, 2009). For our purposes, we find that any wearable and most handheld devices will likely be required to be wireless.

While there are currently many ways of easily implementing wireless communication between devices and computers, there are many pertinent details which need to be addressed, including reliable packet transmission, communicating with multiple devices, being aware of conflicts with other wireless networks, and total data throughput. As we saw with the VibroPixels, the details of a wireless network are heavily application dependent, and it is important to consider these issues in designing the system.

Consider the context of the system's use: Our systems have generally been used in artistic applications with a variety of collaborators, some of whom we worked with closely and some of whom we barely interacted with at all. In addition, there are generally a variety of systems at play in the final production, including sound, lighting, staging, costuming, etc. Being aware of the entire context of the system can help to identify potential problems and possibilities in the use the system. For *Les Gestes* and *Haptic Field*, for example, being aware of the context led us to suggest the use of our systems as part of the lighting design.

6.2.5 Principles of manufacturability

1. Use appropriate manufacturing techniques
2. Begin manufacturing early
3. Identify opportunities to speed manufacturing

Use appropriate manufacturing techniques: The biggest manufacturing decision will be the choice of manufacturing processes. Being aware of the manufacturing techniques and the possibilities and limitations of each technique will help to identify techniques which will allow the system to meet its overall design specifications.

Begin manufacturing early: It can be helpful to spend a considerable amount of time manufacturing during both the design process as well as in the beginnings of the final manufacturing process, as an awareness of the material properties of the system will greatly depend on interactions with the system both during its manufacturing and use, and many mechanical design considerations will be easier to identify and solve during the manufacturing process. In addition, designing the manufacturing process itself is an important step, as each decision will have important ramifications in terms of manufacturing time, device robustness, and system reusability.

Identify opportunities to speed manufacturing: Nonetheless, be on the lookout for ways to create more efficient manufacturing processes as the system moves towards its final manufacturing stages. Using digital manufacturing techniques throughout the prototyping stage can help ensure the properties of the final devices are the same as the prototypes, while also making it easier to outsource the final manufacturing stages to commercial contractors or research assistants. Do be aware, though, of material and manufacturing tolerances when outsourcing to different vendors.

6.2.6 Principles of robustness

1. Repairability vs. replaceability
2. Pay attention to material properties and points of failure
3. Learn and use standard techniques for protecting electronics

Repairability vs. replaceability: Consider what happens when a device fails. During a performance, mechanical failures may be best solved by providing replacement devices, with a protocol for the actual replacement process. Software resets should be facilitated by minimizing (and ideally eliminating) initialization procedures, and potentially by automating the reset process through watchdog timers and similar processes.

Consider a process for repairing devices as well. How can we make it obvious which component has failed? Is replacing a failed module something unskilled staff can do? Are backup modules available for repairs?

Pay attention to material properties and points of failure: The mechanical design of components should be based on the properties of the materials used in its construction, and these properties should be considered over the whole design process. Potential points of failure should be reinforced or redesigned so as to minimize potential problems.

Learn and use standard techniques for protecting electronics: There are many industry standards for protecting electronic circuits, covering everything from electro-static discharge to ability to withstand mechanical vibration. A full application of these standards is a considerable engineering challenge, and will typically be outside the scope of our applications. Nonetheless, being aware of the most common and easily implemented techniques is good practice.

In particular, understanding and respecting the properties of lithium-ion batteries is extremely important, not only for safety reasons but also in order to prolong the overall lifespan of the batteries. This lifespan can be compromised by situations in which batteries are charged too quickly or allowed to fall below specific voltage limits.

6.2.7 Principles of reusability

1. Keep an eye towards future applications
2. Keep documentation of the design process as well as the system
3. Clarify the possibilities of system reuse from the beginning

Keep an eye towards future applications: While the exigencies of designing under a deadline makes it difficult to think too far ahead, it can be helpful to try as much as possible to keep aware of potential future applications, and of ways in which small changes to the system may facilitate future re-use. If a sub-system seems like it may be useful in the future, it may be worth investing time in developing this potential. In the *Ilinx* garment, for example, we placed the MARG sensor on a small PCB which mounts on top of the driver board. This decision allowed us to use the MARG module in a variety of other applications.

Similarly, the wireless protocol created for the Vibropixel may also be useful for a variety of other applications, and we are creating documentation and developing it into a software library for this purpose.

Keep documentation of the design process as well as the system: System documentation is extremely helpful for future use of the system, but documentation of the design and manufacturing processes also can be very helpful. Keeping track of software versions, for example, may be crucial in situations where multiple sub-systems need to work together. Electronic and mechanical modifications and replacements will be facilitated not only by the CAD files and schematics, but also by written descriptions explaining the choices made in the system's design.

Clarify the possibilities of system reuse from the beginning: In a collaborative context, there is often some degree of ambiguity regarding the contributions and ownership of the design outcomes. It is important that all collaborators are clear on what the possible future uses of the system may be, and that any limitations on reuse are agreed to beforehand. This does not necessarily mean formal agreements, which bring with them a different set of challenges, but at least expectations can be set through discussions of each of the collaborators long-term goals. For us, this means communicating that our goal is that our systems be used as often and in as many different contexts as possible.

6.3 The design aspects and principles in NIME practice

In this section I will review the ways in which the design aspects and principles described above are and are not reflected in the existing literature of DMI research.

6.3.1 The design aspects and earlier DMI overviews

As discussed in Chapter 2, existing overviews of the DMI design process have focused primarily on system functionality. For example, seven out of the ten issues addressed in Pressing (1990) focus explicitly on control functionality, including the number and types of control variables, and how the user interacts with controls (including the necessity for continuous interaction versus intermittent, discrete interactions). For the remaining three issues, Pressing restricts his discussion to the experience of the user, include considering whether the interfaces utilizes existing performance techniques, modifies existing techniques, or proposes a completely new technique, as well as the relationship between gestures and the parameters which are being controlled.

A consideration of design from the perspective of the user is particularly common in more recent overviews. The goal of the framework presented in Overholt (2009) is "to allow humans to be musically expressive through the use of advanced technologies", and although Morreale (2015) purports to present a "framework for the identification of the elements involved in the design of interfaces for musical making" (Morreale, 2015, p.129) it also clearly identifies its focus "on the experience of the player" (ibid).

6.3.2 The design aspects and practical reports of experience

While structured overviews of DMI design focus on issues of functionality, there is abundant evidence of the other design aspects in reports of practice, as we discuss in Chapter 2. To highlight this, below I present ways in which the aspects can be see in the literature.

Functionality: Functionality, of course, remains a core concern in reports of practice. Weinberg (2008), for example, discusses how the interaction techniques of the Beatbugs reflected the requirements of their use by children in the workshops and performances of the *Toy Symphony* (Weinberg, 2008, 9-11).

System architecture: At the same time, the reports of the creation of the Beatbugs also discuss the architecture of the system, which was developed in response to the demands of the production (Aimi and Young, 2004, 24-24). In particular, the concerns with battery life led to wired connections with the central computer of the system, which also allowed for analog sensor signals to be sent via wire to an off-board commercial sensor-signalling unit.

Aesthetics: Marshall (2008) describes one way in which the visual appearance of a DMI can impact the experience of the user, claiming that "DMIs which have lots of visible wires and components can look fragile and so people will be restrained in how they interact with them. There is a fear of damaging the instrument" (Marshall, 2008, p.230).

In discussing the FM Gloves Pestova et al. (2009) reports on concerns of ergonomics, form, and fit, describing how a consideration of the "physical comfort of the performer was also necessary. This meant that the distance of the right hand from the body while using the infrared sensor and the angle of the left hand for the accelerometer required adjustment and modification" (Pestova et al., 2009, 298.), and additional observation that "[i]n the final version, the gloves themselves were replaced in order to accommodate smaller hand size [sic]" (ibid).

Support for artistic creation: The creation of software tools to support the artistic creation process has been a major research topic in computer music since an early date, a fact that is reflected in the consideration of graphical notation editing and software composition environments in Pennycook's early survey of computer-music interfaces (Pennycook, 1985). While there are many commonalities between the kinds of software systems Pennycook describes and the hardware systems we have been focusing on, in practice we find that hardware systems tend to be more tightly defined, especially when they are created within collaborative artistic projects such as ours have been. As we discussed in section 5.5.1, the challenge is in providing a well-defined interface which conceptually represents the core functionality of the hardware while also preventing arbitrary limitations on the system's use.

One approach to navigating this challenge is by avoiding developing an interface at all, instead offloading the actual creation process to commercial software. The composition of tactile effects for use with the system of wearable tactile transducers presented in Gunther and O'Modhrain (2003), for example, took place entirely within the Protools digital audio sequencing environment. This was made possible by the fact that the transducers were able to be driven by audio signals sent via wire to the transducers.

Another approach is the support for software tools and protocols which facilitate interaction of the system with other hardware and software systems, for example through the adoption of the MIDI[9] or Open Sound Control (OSC) (Wright and Freed, 1997; Freed

[9] The 'Musical Instrument Digital Interface' protocol, (The Midi Manufacturers Association, 1995).

and Schmeder, 2009) communication protocols. One software tool that is specifically intended to facilitate the artistic creation process is the LibMapper software, developed at IDMIL, which allows for the easy creation of mappings between hardware control signals and software synthesizer parameters (Malloch et al., 2007, 2008; Malloch, 2013; Malloch et al., 2014).

There are also ways in which the development of a system itself can facilitate the artistic creation process. Ryan (1991) observes that the creation of a physical interface between the composer/performer and the computer can provide ‘handles’ which can be “just as useful for the development or discovery of the piece as for the performance itself” (Ryan, 1991, p.5).

Manufacturing: Manufacturing is a topic that is frequently touched upon in descriptions of the practice of DMI designers, but rarely receives substantive discussion. Examples of the different approaches to manufacturing are presented in our discussion of the manufacturability design aspect in section 6.1.6, and many additional examples can be found in the literature, including artisanal (Jensenius et al., 2006, 2010), building block (Cook, 2001), digital manufacturing (Freed et al., 2013; Barrass, 2014), and industrial approaches (Place et al., 2014).

Robustness: The need for robustness is often described in descriptions of practice. Weinberg and Driscoll (2005) describes how the bend sensors used for the Beatbugs’ antenna frequently broke, causing the next iteration to change to a hall-effect based solution. Beyond just physical robustness, Malloch (2008) describes how importance it was for musical performers to be able to take T-Sticks home and practice without technical support during the McGill Digital Orchestra Project (Malloch, 2008, 2-3).

Reusability: Reusability is a commonly described goal in the sense that a DMI can be used to perform many compositions over years of artistic practices (Freed et al., 2013). Certainly, there are DMIs which have successfully supported this kind of practice – for example, Michel Waisvisz's 24 years of performing with the Hands (Waisvisz, 1985; Krefeld, 1990; Dykstra-erickson and Arnowitz, 2005) or the T-Stick, which has been used in at least 25 concerts from 2006-2013 (Malloch, 2013, 142-144).

But reusability in the sense of carrying the knowledge and craft from one DMI to the next can also be seen in attempts to identify and crystallize modular elements of a design. Ryan (1991) explicitly describes the practice of modular design at STEIM, describing how once "one aspect of a problem becomes 'well understood', it can be factored out into its own module" (Ryan, 1991, p.13).

6.3.3 Application of the aspects to NIME research

The design aspects discussed here were developed over the course of research projects conducted in collaboration with professional artists, and which were focused on creating systems suitable for professional artistic productions. As such, they reflect my personal experience and conceptions of how to structure research and design activity. However, I would argue that a consideration of these aspects can be beneficial for many different research contexts within the NIME community, and that interface designers who utilize their interfaces in performance engage with these aspects at some level, whether they consider them explicitly or not.

The degree to which design specifications need to be formalized may be disputed, and certainly the approach presented in this paper is coming from the perspective of the technology developer. However, the simplified set of design aspects (as opposed to Pugh's 32 elements) is intended to focus only on those perspectives that will contribute most directly to the ability of new devices to meet the challenges of artistic contexts. From a practical standpoint, failure of any of the design aspects (barring, perhaps, reusability) will make it much less likely for a new system to be used for an extended period. This speaks directly to the frequently made observation that new instruments and installations frequently have a very short lifespan (Dahl, 2014; Berdahl, 2011; Freed et al., 2013). If continued use of a new interface has the potential to add to the knowledge created by that interface's construction (and I would argue it does), then creating interfaces which support continued use should be encouraged.

Finally, it is clear that the explicit consideration of the design aspects should be in proportion to the amount of time invested in the design process.[10] For work which will only be shown within conference settings, or will only be used in its creator's own artistic practice, the formal consideration of the design aspects presented here may not be necessary. However, I believe that the NIME community would benefit from the exploration of many interesting research questions (including longitudinal use of new interfaces, creation of new interfaces for professional artists, ensemble use of new interfaces, etc.) which require the creation of systems which do engage with the complete set of design aspects. It is my hope that the discussion presented in this dissertation encourages other researchers to take on the challenge of developing such systems.

6.3.4 The design principles and application to existing DMI literature

As we discussed in Chapter 2, design principles represent general goals which are drawn from personal experience. While the articulation of design specifications and require-

[10]Or as Pugh puts it, "it is preferable that the degree of total design rigour expected should increase in sympathy with increased engineering input" (Pugh, 1991, p.p. 29).

ments are not uncommon in the literature, Perry Cook's two papers remain the only clearly articulated sets of design principles in the literature (Cook, 2017, 2009). Table 2.1 itemizes Cook's principles in indicates their relationships to the design aspects.

6.4 Summary

In this chapter I presented a framework for the design of hardware intended to be used for professional artistic productions, as well as a set of personal design principles which I utilize in my own work. In my discussion, I tied the design aspects and principles to existing work in the literature. I have also shown how the design aspects have impacted previous work despite the fact that there is no existing framework or overview in which they are clearly articulated. Together, these two discussions crystallize the knowledge gained during the research conducted for this dissertation, and present it in a way that will help inform other researchers working within similar contexts.

Chapter 7

Conclusions and Future Work

In this dissertation I have presented three hardware systems created for use in professional artistic productions, a framework consisting of seven design aspects which contribute to the ability of a hardware system to support professional artistic applications, and a set of design principles which draw upon my experience in the creation of such systems. In this chapter I will discuss the contributions of work presented in this dissertation, and discuss future work building upon these contributions.

7.1 Contributions

7.1.1 The Prosthetic Instruments

The Prosthetic Instruments are a family of digital musical instruments created for dancers to wear and utilize in interactive performances. The family consist of three types of instruments, the Ribs, Visor, and Spine, which were designed in collaboration with composers, dancers, and a choreographer. A combination of capacitive touch sensing and motion sensing are implemented on the instruments, and data from these sensors are streamed wirelessly to a central PC to control sound synthesis parameters in real-time. More than 40 instruments were manufactured during the total design process, and the final set of instruments consisted of 12 Ribs, 4 Visors, and 4 Spines.

The contributions of the Prosthetic Instruments are multipart. First, their design presents a novel approach to the control of digital sound processes by dancers, in the form of removable, hypothetical prosthetic extensions to the body, which were custom-created to complement the forms of the dancers' bodies. Second, we present a description of the system which consists of several parts, including a description of the design evolution and decisions made over the course of the design process, a technical description of the system covering its mechanical and electronic functionality, and a description of the use of the system in professional artistic productions. These descriptions will serve as valuable guides for researchers designing such systems in the future.

Finally, the instruments have been used in several artistic and research projects, including presentations of the choreography-concert *Les Gestes* in Quebec, the Netherlands, Belgium, and France in March-April 2013, in performances as part of the Koumaria art residency in the Fall of 2013, in a joint composition and research project between Seth Woods and myself (Hattwick et al., 2014), and as part of a research project investigating the real-time control of quadcopter choreography in the Spring of 2015.

7.1.2 The *Ilinx* garment

The *Ilinx* garment is a wearable full-body tactile display designed to be worn by visitors in the immersive multisensory art installation *Ilinx*. The system consists of several parts: actuators and actuator housings, which are sewn into a custom-designed garment; actuator driver boards, which generate the appropriate signals for the actuators; a central control unit which distributes power and manages wireless communication with a central PC; and an assortment of software tools to facilitate programming the system. A total of six copies of the *Ilinx* garment were manufactured.

The contributions of the *Ilinx* garment takes several forms. First, its design presents an implementation of a full-body tactile-enhanced garment suitable for use by visitors to an immersive art installation, a concept we have not seen implemented elsewhere. Second, we present a description of the system which consists of several parts, including a description of the ways in which its design was based on existing knowledge of haptic perception, the choice of intended tactile stimuli which led to the system's architecture, a technical description of the electronic and software components, a description of software tools created to facilitate the programming of tactile effects, and a description of the use of the garment in the *Ilinx* artwork.

Finally, the garment has been worn by more than a thousand visitors in the presentation of the *Ilinx* artwork, which has been shown in TodaysArt 2014 in the Hague, CTM/ Transmediale 2015 in Berlin, and at TodaysArt.JP 2015 in Tokyo.

7.1.3 The VibroPixels

The VibroPixels are a reconfigurable wireless tactile display system, designed in response to my experience with the *Ilinx* garment. Consisting of an array of self-contained devices, each of which contain an actuator, wireless transceiver, microcontroller, battery, and lighting and sensing systems, the VibroPixels allow for the creation of massive distributed tactile displays. The key to the flexibility of the system is the configuration of the wireless network, in which each actuator is a passive receiver with a unique combination of device ID and group ID. This combination of two ID types allow for flexible addressing of combinations of devices with a minimum of wireless messaging.

The contributions of the VibroPixels take several forms. First, the system is an example of a reconfigurable, scalable tactile display in a form which we have not seen presented elsewhere. Secondly, we have presented a description of the system which consists of several parts, including an overview of the challenges of designing wearable tactile displays, a description of the design decisions which informed the VibroPixels, a technical description of the electronic and software components which comprise the VibroPixels, a discussion of software tools created to assist in the creation of tactile stimuli using the system, and a description of the use of the system in several contexts, most notably in the immersive art installation *Haptic Field*.

Finally, the VibroPixels have been used in several artistic and research projects, including the immersive art installation *Haptic Field*, which has been shown in 2016 at the Chronus Art Center in Shanghai, in June 2017 at the Wiener Festwochen in Vienna, and in July 2017 at the Martin Gropius Bau in Berlin. Future planned uses of the system include at TodaysArt 2017 in the Hague and at the Muffethalle in Munich in November 2017.

7.1.4 Design aspects

In Chapter 6, I draw upon my experience in designing the three systems described above in order to propose a framework consisting of seven design aspects, which each represent a different perspective on the design of a hardware system for professional artistic productions:

1. *Functionality* – What the system is designed to do, and how the user interacts with it.

2. *Aesthetics* – Aspects which qualitatively affect the experience of the user.
3. *Support for artistic creation* – How the system is designed to allow for its use in the artistic creation process.
4. *System architecture* – How the different elements of the system interact, and how the system interacts with the overall production environment.
5. *Manufacturing* – How the system will be manufactured, and how the systems's design supports the manufacturing process.
6. *Robustness* – How the system successfully meets the challenges of use in its intended context.
7. *Reusability* – How the system and its subsystems support use in other contexts.

As I have shown in Chapter 2, existing overviews of the DMI design process primarily focus on the design of a system's functionality, while accounts of the practice of DMI designers reveal the relevance of the other design aspects. To date there has not been an attempt at providing a coherent overview of the challenges of designing hardware systems for professional artistic productions.

The design aspect framework was created to address this lack. Its primary contribution is an explication of the challenges faced by DMI designers in designing systems intended for use in professional artistic productions. As we have shown, the design aspects inform the entire design process, from conception to use, and the interdependency of the aspects plays a key role in the final design specifications. A clear understanding of these aspects at the outset of the design process should not only facilitate the identification of design specifications, but may also assist in the identification of novel solutions to conflicting design requirements.

7.1.5 Design principles

Also presented in Chapter 6 are a set of design principles which are derived from my personal experience. These principles are not meant to be specific guidelines with recommendations for design decisions, but instead reflect general design goals for my work in designing systems for professional artistic productions.

The primary contribution of these principles is the crystallization of the knowledge developed through the countless hours of prototyping, testing, designing, and manufacturing I have undertaken in the course of the design of the systems described above. The description of these principles should help DMI designers to more rapidly understand the requirements of designing for professional artistic productions, provide guidance as to the establishment of their own design goals to support this context, and provide advice to facilitate the design process from a system's conception to its use.

7.2 Future work

There are a number of ways to build upon the work presented in this dissertation. First of all, in the creation of the design aspect framework I have built upon descriptions of experience in the literature, and while I found many relevant descriptions they were not presented in an organized fashion. Future work may include conducting interviews with experienced DMI designers in order to identify the ways in which their work reflects the design aspects. The outcome of these interviews may include validation or refinements of the design aspect framework, as well as helping to create coherent descriptions of their personal design practices.

Secondly, a framework such as the design aspects takes a high-level approach in order to take into consideration the many challenges of designing systems in our context. Further work may make it possible to propose more concrete guidelines which address both specific design aspects as well as applications in a variety of contexts. The discussion of manufacturing techniques presented in section 6.1.6 is a first step in this direction, and one possible approach would be to further build upon this to create manufacturing guidelines for creating performance-ready DMIs using the kinds of digital manufacturing equipment that an academic lab would be likely to have access to. An example of one form this might take is Charles Guan's guide "How to Build Your Everything Really Really Fast", created for robotics applications (Guan, 2013).

Regarding design principles, in this dissertation I have presented principles drawn from my personal experience. While design principles by their nature reflect personal design decisions, it may be possible to draw from the experience of experienced DMI designers a set of generally applicable principles for the design of digital musical instruments. This may start with interviews with designers to get reactions to Cook's principles (Cook, 2017, 2009) as well as the principles I have presented, and continue with soliciting and reviewing suggestions for additional or modified principles.

One model for the results one might hope to gain from such feedback is the expert commentary on Cook's 2001 paper provided by Marcelo Wanderley in the 2017 "NIME Reader" (Wanderley, 2017). While Wanderley's comments provide a general discussion of Cook's principles, two significant points emerge: a disagreement on the relative importance of focusing on a specific musical composition when designing DMIs, and the identification of specific principles which remain bedrocks of DMI design. Together, these observations both suggest that new principles may be necessary to reflect design practices which differ from Cook's, and also provide independent verification that some of the principles remain applicable for both different times and different researchers.

As far as the hardware systems described in this dissertation, there are several ongoing research projects involving the VibroPixels which take advantage of its reconfigurability to explore the use of a tactile display in various social contexts. As described in section 5.4.3, Ida Toft from the Technoculture, Art and Games research centre at Concordia is creating a multiplayer game which is based on the distribution of tactile stimuli. We are also beginning development on an application which will distribute tactile stimuli across 100 participants, and will be exploring ways of entraining the participants so they can recognize how their tactile perception is a shared part of a larger communal experience.

A new generation of VibroPixels are currently in production, incorporating IR sensing and signaling in order to facilitate automatic recognition of their spatial arrangement. Several further future research challenges include the creation of a software framework for integrating motion sensing data into tactile stimuli generation, and the creation of a process for self-organization in which VibroPixels utilize their motion data to detect where on the body they are located.

Appendices

Appendix A - Participants in the *Gestes* research/creation project.

Name	Affiliation	Dates Involved	Role/ Responsibilities
Marcelo M. Wanderley	IDMIL Director	Sep '10-Apr '13	Tech Supervision
Joseph Malloch	IDMIL PhD	Sep '10-Apr '13	Tech Development
Ian Hattwick	IDMIL PhD	Sep '11-Apr '13	Tech Development
Aaron Krajeski	IDMIL MS	Sept '11-Apr '12	Tech Development
Anthony Piciacchia	IDMIL Intern	May '12-Apr '13	Tech Development
Sean Ferguson	DCS Director	Sep '10-Apr '13	Composer
Marlon Schumacher	DCS/IDMIL PhD	Sep '10-Apr '13	Software & Composer
Geof Holbrook	DCS	Aug '12	Contracted Composer
Isabelle Van Grimde	VGCS Director	Sep '10-Apr '13	Artistic Director
Soula Trougakos	VGCS	Sep '10-Apr '13	Dancer
Sophie Breton	VGCS	Sep '10-Apr '13	Dancer
Elinor Frey	Independent	Aug '12-Apr '13	Cellist
Marjolaine Lambert	Independent	Aug'12-Apr '13	Violinist
Pascale Bassani	Independent	Aug '12-Apr '13	Costume Design
Eliot Britton	DCS PhD	Dec '12-Apr '13	Tour Tech Director
Bruno Rafi	Independent	Dec '12-Apr '13	Lighting Designer
Erik Palardy	VGCS	Feb '13-Apr '13	Technical Direction
Joel Lavoie	VGCS	Feb '12-Apr '13	Live Sound
Nolwenn Lechat	VGCS	Sep '10-Apr '13	Production Director
Audrey-Anne Trudel	VGCS	Aug '12-Apr '13	Production Assistant

Appendix B - Timeline of the *Gestes* workshops

stage	date	goals
Workshop 1	*Aug. 2011*	Exploration of instrument forms and movements
Workshop 2	*Feb. 2012*	Exploration of mappings between sound and movement with functional prototypes
Workshop 3	*Aug. 2012*	Creation of choreographic and compositional materials for use in the final works
Workshop 4	*Dec. 2012*	Final iteration of instrument design; creation of larger sections of choreographic and compositional materials
Rehearsals	*Feb.–Mar. 2013*	Delivery of final instruments construction of shipping containers
Initial Performances	*Mar. 2013*	Initial public performances of *Les Gestes*.
Tour	*Apr. 2013*	European tour with performances in Paris, Bruges, and Arnhem.

Appendix C - Participants in the creation of the *Ilinx* artwork

Name	Affiliation	Role/ Responsibilities
Marcelo M. Wanderley	IDMIL Director	Tech Supervision
Ian Hattwick	IDMIL PhD	Tech Direction
Marcello Giordano	IDMIL PhD	Tech Development
Ivan Franco	IDMIL PhD	Tech Development
Deborah Egloff	IDMIL PhD	Tech Development
Joseph Malloch	IDMIL PhD	Tech Development
Chris Salter	Concordia Professor	Artist
Morgan Rauscher	Concordia PhD	Artist
Ian Arawjo	Concordia RA	Artist
Maurizio Martinucci	Optofonica Lab	Artist
Panagiotis Tomara	Optofonica Lab	Production Assistant
Valerie LaMontagne	3lectromode	Garment Design
Marie-Eve Lecavalier Lemieux	3lectromode	Garment Design
Isabelle Campeau	3lectromode	Garment Design

Appendix D - Schedule of the *Disequilibrium* project

stage	date	goals
Conceptual Exploration	*Oct - Dec, 2013*	Exploration of moving tactile signals on the body
Hardware Development	*Jan - Jun 2014*	Iterative development of the hardware/software system
Garment Manufacturing	*July - Sept 2014*	Integration of the actuators and electronics into the garments
Artistic Creation	*Aug - Sept 2014*	In-studio creation of the work
Pre-Production	*Sept 21 - 24, 2014*	Installation of the equipment into the presentation space, and refinement of the work
Initial Public Presentation	*Sept 25 - 28, 2014*	Initial public performances of *Ilinx* at *TodayArt 2014*.

Appendix E - Participants in the creation of the *Haptic Field* artwork

Name	Affiliation	Role/ Responsibilities
Marcelo M. Wanderley	IDMIL Director	Tech Supervision
Ian Hattwick	IDMIL PhD	Tech Direction
Ivan Franco	IDMIL PhD	Tech Development
Juline Neri	IDMIL Masters	Tech Development
Alex Nieva	IDMIL Masters	Tech Development
Patrick Ignoto	IDMIL Masters	Tech Development
Louis Fournier	IDMIL Intern	Tech Development
Chris Salter	Concordia Professor	Artist
Maurizio Martinucci	Optofonica Lab	Artist
JNBY Fashion		Garment Design

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