Forming Shapes to Bodies: Design for Manufacturing in the Prosthetic Instruments

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ABSTRACT

Moving new DMIs from the research lab to professional artistic contexts places new demands on both their design and manufacturing. Through a discussion of the Prosthetic Instruments, a family of digital musical instruments we designed for use in an interactive dance performance, we discuss four different approaches to manufacturing – artisanal, building block, rapid prototyping, and industrial. We discuss our use of these different approaches as we strove to reconcile the many conflicting constraints placed upon the instruments' design due to their use as hypothetical prosthetic extensions to dancers' bodies, as aesthetic objects, and as instruments used in a professional touring context. Experiences and lessons learned during the design and manufacturing process are discussed in relation both to these manufacturing approaches as well as to Bill Buxton's concept of artist-spec design.

Keywords

DMI, digital fabrication, manufacturing, dance

1. INTRODUCTION

The Prosthetic Instruments are a family of digital musical instruments (DMIs) designed to be used for interactive dance performance [1]. The Visor, Ribs, and Spine are able to be worn as attachments to the body and can also be detached and manipulated as handheld instruments. They were developed during an interdisciplinary research project whose participants were Sean Ferguson and Marcelo Wanderley at McGill University and Isabelle van Grimde and her dance company Van Grimde Corps Secrets.

The instruments were created to be used within a professional artistic context, including a series of high-profile performances. This placed numerous demands on the design of the instruments – they needed to be durable, usable by technical staff with no specialized training, mechanically and electronically dependable, and also created in sufficient quantities so as to provide backup systems in case of emergency. These demands are unusual for instruments created within the NIME community, and the Prosthetic Instruments provide an example of approaches to design and manufacturing suitable for small-scale manufacturing and professional artistic use.

This paper will discuss the Prosthetic Instruments' mechanical and electronic construction as well as discuss design challenges and approaches. A more general overview of the instrument's development and design philosophy is available in [1]. The instruments' electronics draw from previous research projects conducted in our lab, the Input Devices and Music Interaction lab, and as much as possible earlier work was reutilized. However, over the course of development nearly every aspect of the electronics was modified and updated. The mechanical construction of the instruments evolved from hand-crafted early prototypes to small-scale production utilizing digital manufacturing techniques.

Working closely with dancers provided both our primary constraint and a unique design opportunity. Forming the instruments to complement the dancers' bodies was one of

Figure 1: Violinist Marjolain Lambert plays the Ribs on dancer Sophie Breton. Photo by Michael Slobodian.

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Figure 2: Dancer Sophie Breton lies downs next to the Spine. Photo by Michael Slobodian.

the primary challenges during the design and construction process, and one of the last aspects to be finalized. We conceptualized the Prosthetic Instruments as 'hypothetical' prosthetics, not replacing a pre-existing limb or body part but rather functioning as a potential new body part. To be believable as hypothetical prosthetics required that the instruments integrate well into the aesthetics of the dancers' bodies, move well with their existing limbs, and attach securely to the dancer's bodies while also being detachable in performance.

2. MANUFACTURING DMIS

The best way to approach the design 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, numerous additional demands are placed on an instrument's design when it is to be used by professional performers, including durability, maintainability, ease-of-use, and reliability.

2.1 Manufacturing for Professional Use

An important consideration in DMI design is whether the designer or a performer with a technical understanding of the instrument will be available to support its use in performance, or whether the instrument needs to be ready for use by performers with only a general understanding of the technology involved. For the latter case any technical setup needs to streamlined and reliable. This applies not only to software, but also to hardware. How is the instrument powered? If it is battery powered, what kind of battery is used, how is it charged, how easy is it to change before or during performance? How will the instrument be stored, transported to performance, setup onstage? Are there mechanical or electronic weak spots, issues which may need special consideration or explanation?

These questions go beyond the omnipresent issues of whether the electronics are reliable or the mechanical construction robust. Taking them into consideration in the design process can help make an instrument a success once it enters the world outside of the research community. We will discuss specific examples of this during the design of the Prosthetic Instruments in Section 4.

2.2 Designing for Small Run Manufacturing

Once an instrument is ready to move from a prototype to a stageworthy design there are many different approaches to manufacturing. We compare and contrast here 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.

2.2.1 *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]

2.2.2 *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 [4].

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.

2.2.3 *Rapid Prototyping*

The rapid prototyping approach utilizes the capabilities of generally available computer-controlled manufacturing machines such as laser cutters, vinyl 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".[4] The benefits of this approach are the ability to manufacture precise duplications

[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/`
[4] `www.instructables.com/id/How-to-Build-your-Everything-Really-Really-Fast/`, accessed February 3, 2014.

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.

2.2.4 *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 [9], which were cast in clear urethane from rubber molds.[5]

3. OVERVIEW OF THE PROSTHETIC INSTRUMENTS

This section will give an overview of the Prosthetic Instruments as well as the project within which they were designed.

3.1 The "Gestes" Project

The development of the prosthetic instruments took place as part of a 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*[6]. In this collaborative research-creation project three teams of artist-researchers worked together for the creation of a choreography-concert. The three teams consisted of ourselves, the instrument designers, working within the Input Devices and Music Interaction Lab in the Music Technology area of the Schulich School of Music at McGill University[7]; composers Sean Ferguson and Marlon Schumacher from the Digital Composition Studio, also at the Schulich School of Music[8]; and choreographer Isabelle van Grimde and dancers Soula Trougakos and Sophie Breton from the Montreal-based dance company *Van Grimde Corps Secrets*[9].

The project was based on an earlier collaboration between the three teams which utilized the T-Stick, an instrument designed at the IDMIL by the second author [6]. The original idea was to use the T-Stick as a conceptual model and extrapolate characteristics drawn from it to new forms and materials.

3.2 The Instruments

There are currently three members of the family of Prosthetic Instruments: the Visor, the Ribs, and the Spine. While their shapes, mounting, and electronics may differ their visual aesthetics and conceptualization as hypothetical prosthetic additions to the body help to unify them as a single family of instruments.

All three instruments utilize the 2.4 GHz XBee implementation of the ZigBee IEEE standard for wireless communication with a central computer, upon which additional sensor signal processing and mapping to sound synthesis take place. Software mapping tools developed in the IDMIL [5] were used for developing mappings from instrument data to sound synthesis, while the sound synthesis itself was designed using the CIRMMT Live Electronics Framework [7].

3.3 The Visor and Rib

The Visor and Ribs were initially intended to be interchangeable and their electronics implementation is identical. However, during the course of their development the evolution of their physical forms and their configuration on the body diverged and they assumed independent identities.

Figure 3: Dancer Sophie Breton wearing the Visor. Photograph by Michael Slobodian.

3.3.1 *Electronics*

Eight capacitive touch-sensing panels are located along the length of the Visor and Ribs. The electronics are located towards the rear of the instruments and consist of support

[5]R. Aimi, personal correspondence, April 29, 2014.
[6]"Gestures: a new generation of digital musical instruments for controlling synthesis and processing of live music by musicians and dancers."
[7]www.idmil.org
[8]www.music.mcgill.ca/dcs/
[9]www.vangrimdecorpssecrets.com/)

for the capacitive sensing, LED driver circuitry, power regulation, 3.7v lithium-ion AAA batteries, and a 3D accelerometer and XBee implemented in a Sense/Stage MiniBee [2].

The touch panels consist of a polyester film which is silver/indium sputter coated and has a nominal resistance of 27 ohms/square inch. The film has an adhesive backing applied, and is then laser cut to match the shape of the instruments. Each instrument has 8 grooves etched into its top surface which lead from the pcb location 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 the pcb.

3.3.2 Mechanical Construction

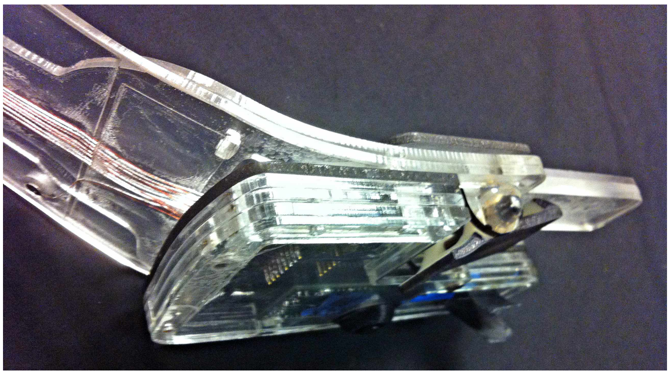

Figure 4: Detail showing the laminate construction of the Ribs, with the protrusion and clip for mounting visible on the right.

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. 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 are shaped independently and fastened together at the last stage of construction. The electronics enclosure for both instruments consists of multiple layers of laminated acrylic, with removable lids which attach via a system of dowels and magnets.

The Ribs contain protrusions in their rear as well as a clip just in front of the protrusion. These protrusions fit through mounts sewn to the back of a corset-like garment. The Visor's mounting plate has two vertical protrusions which fit into mounts located at the back of the head and just in front of the left ear, and a single clip which secures the Visor to the rear mount.

3.4 The Spine

3.4.1 Electronics

The electronics for the Spine are based on two Mongoose 9DoF Inertial Measurement Unit (IMU) boards, one located at head and one at the tail. Custom firmware was written for the Atmega processor on the Mongoose boards for sensor fusion and communication with an XBee radio modem also located in the tail. The location of these two IMUs provide absolute orientation of the head and the tail, which then provides the ability to detect twisting and bending of the Spine. A rectangular 3.7v lithium-polymer battery drives the IMUs and XBee. Separate circuit boards and lithium-ion AAA batteries allow for the control of the two LED flashlights mounted near the sensors.

3.4.2 Mechanical Construction

The Spine is constructed of 1/4" thick triangular acrylic vertebrae threaded onto two PVC hoses forming a truss-like structure. The third rail of the truss consists of a narrower flexible PET-G rod which fits loosely into the third corner of the vertebrae, and which provides an overall shape to the instrument. The PET-G rod is fixed both at the head and the tail of the Spine, causing a curve at one end to force an opposing curve in the other end of the instrument. The Spine is mounted behind the head, in the same location as the Visor's rear mount, as well as at the bottom of the back.

4. DISCUSSION

In this section we will discuss lessons learned during the design and manufacturing of the Prosthetic Instruments.

4.1 Building to Artist-Spec

In designing digital interfaces for artists Bill Buxton discovered that "artist-spec" can have more demanding standards than standard- or military-spec [3]. We found that to be an accurate description of our experience designing the instruments while working closely with artistic collaborators. We especially found working with the dancers during the design process was essential for the creation of instruments that work well with the body. Below we describe some examples of designing to artist-spec in the creation of the Prosthetic Instruments.

4.1.1 Moving From Lab to Stage

Many times we were forced to modify or radically redesign the instruments due to feedback from the dancers regarding the way the instruments constrained their movements or suggested new movements. An instance of this was in the design of the mounts for the Ribs. An early approach used magnets to secure the instruments inside a mount sewn to a corset. These mounts consisted of plastic channels with an array of 8 3/8" diameter neodymium magnets. The end of the instruments were equipped with a similar array of magnets. The instruments were then inserted into the channels where the magnets of both mount and instrument would form a magnetic connection.

In lab tests this connection was reliable – however, once the instruments were worn we encountered several problems. One was that the amount of rotational energy generated by the dancers' movements were considerably more than we expected, and threatened to overcome the magnetic connection. In addition, once the dancers began to interact with the instruments they began to perform the unexpected gesture of moving their arms between the Ribs and their torso. During this gesture their arms would occasionally touch the Ribs and exert enough lateral pressure to break the magnetic connections. Ultimately we chose to replace the magnets with a clip in order to guarantee a solid mechanical connection.

4.1.2 Engineering to Satisfy Aesthetic Constraints

Aesthetic considerations frequently place severe constraints upon the choice of materials, which can have extreme implications for design. Reconciling electronic, mechanical, and aesthetic constraints in the shape of the Ribs provided one of our greatest challenges. Our initial conception of the instruments was for the functional electronic components to be plainly visible, and early prototypes used metallic touchpads for the capacitive sensing. As part of a series of tests

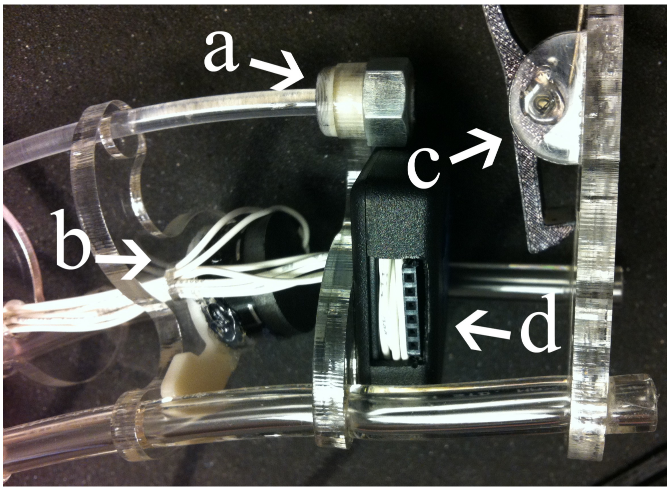

Figure 5: The head of the Spine. Labelled are a) the PET-G rod in its mount, b) the LED lighting with its mount, c) the clip for attaching to the mount on the back of the dancers headband, and d) the enclosure for the head's IMU.

of touchpad construction we created a prototype using clear conductive plastic for the touchpads, following which our collaborators and ourselves decided a completely clear construction of the Ribs was aesthetically desirable. After making this decision it became apparent that clear Ribs would need to be physically larger in order to have the desired visual impact. As the size of the Ribs grew, their overall shape changed and new opportunities for physical interaction were created – the dancers began wrapping their legs around the lower Rib, for example. These changes created additional stresses upon the acrylic construction. These stresses made it necessary for the Ribs to be stiffer along their length in order to prevent to prevent excessive flexing, which was not only aesthetically undesirable but also led to cracks. In addition, additional reinforcement was needed where the Ribs interfaced with the mount. This point is a natural weak spot due to the concentration of the cantilevered weight of the instrument, leading both to cracks in the plastic as well as causing the instrument to sag. In order to provide additional stiffness while minimizing any additional weight a second supporting layer in the form of a thin spine was laminated to the length of the Rib and a third additional layer was added to the protrusion for mounting. In order to minimize sagging a layer of PET-G plastic was incorporated into the dancer's corsets. This flexible plastic allowed the dancers to bend and twist their torsos while preventing the mounts and the attached Ribs from rotating in respect to the dancers' torsos.

4.1.3 Fitting Shapes to Bodies

Once the final form for the Ribs was determined and we moved into the manufacturing of the final instruments, we discovered the challenge of being able to precisely recreate the curvature of the Ribs. The primary materials used in the construction of the Ribs are lasercut 1/8" acrylic sheets. These acrylic sheets are laminated together and then heated and bent to their final curvature. For all of the prototypes this heat-forming was done by hand utilizing a heat gun and stainless steel bending straps. When working with the final prototypes the dancers made it clear that in order to integrate the instruments' shapes into their proprioceptive knowledge the final instruments would need to have consistent curvatures. If the curvature wasn't consistent the dancers would unintentionally strike the instruments during certain choreographed movements. For the manufacturing of the final instruments, prototypes of each size of Rib were selected and used as the basis for the creation of wooden bending jigs which served to create a consistency of curvature.

The use of bending jigs was always an intention. However, during the the development of the instruments, when the shapes of the Ribs were changing constantly, it was impractical to create a new jig for each new prototype. It was only once the final shapes of the Ribs were determined, at the very end of their development, that building jigs was seen as practical. We should note that we did not build bending jigs for the Visors. The reasons for this are that the Visor was easier to bend by hand due to its smaller and simpler construction and that the shapes of the Visors were less critical to the choreography.

4.2 Evolution of the Manufacturing Process

During the course of the design process many factors caused the instruments to assume more and more specific forms. These factors included the evolution of the aesthetics, feedback from the dancers, and the demands of use in a professional context as described in Section 2.1. This in combination with the need to manufacture significant numbers of instruments drove our adoption of a variety of manufacturing techniques.

While the initial prototypes were hand-crafted we attempted to adopt a building-block manufacturing approach in the early stages as well. Early versions of the Spines utilized square extruded plastic tubing which were then cut to form vertebrae. However, we found that as the instruments grew in specificity we had difficulty locating off-the-shelf solutions for even the simplest problem. For example, we attempted to source from an external vendor the clips used to secure the instruments to the mounts attached to the dancers' costumes. However, we were unable to find a ready-made clip which would work for our purposes and were forced to design and manufacture our own, which varied over the course of the design process in length, width, thickness, and shape.

4.2.1 Rapid Prototyping

We quickly moved to gain access to rapid prototyping equipment, including a laser cutter and 3D printer, and began creating CAD models of the instruments. The use of these digital fabrication techniques aided us greatly both during the design process as well as during the fabrication of the final instruments. We utilized a laser cutter extensively for creating two dimensional shapes out of acrylic, which formed the basis for all of the Prosthetic Instruments. The laser cutter was also used to cut the conductive plastic sheets used for touch sensing. In addition we utilized a Stratasys uPrint 3D printer extensively during the design and manufacture of the mounting system for the instruments (both the mounts attached to the dancers' costumes and the clips mounted on the instruments). The 3D printer was so easy to use, flexible, and the parts created durable and machinable, that it quickly became our go-to tool for solving mechanical problems of all sizes. For example, the final design for the Spine as seen in Figure 5 utilizes four custom 3D printed parts.

4.2.2 Final Manufacturing Techniques

Digital manufacturing techniques aided greatly in manufacturing designs which met all of our design constraints as well as being relatively easy to assemble. Each Rib, for example, consists of 13 lasercut acrylic parts and two

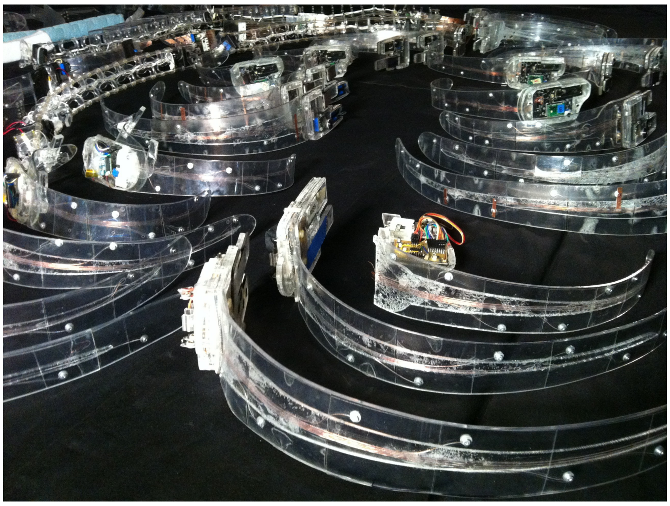

Figure 6: A collection of both prototype and final production versions of the Prosthetic Instruments.

3D-printed parts which all fit together to create a single instrument which is lightweight, rigid, and durable, while also integrating an electronics enclosure with removable lid, battery compartment, and mounting clip.

The use of digital fabrication techniques also proved critical for the manufacturing of the quantity of final instruments which we needed to create. Nine different instruments were used in the final performances, and a full set of backup instruments were constructed as well. In addition, both non-functional and functional final prototypes were created for use in rehearsals while the final instruments were being fabricated.

The most time-consuming parts of the final manufacturing process were bending the Ribs, threading the Spine vertebrae onto the PVC tubing, and integrating the electronics into the instruments, particularly the wiring. Wiring the capacitive pads of the Ribs, for example, consisted of running the magnet wires neatly between the conductive pads and the top of the Ribs, riveting the conductive pads and magnet wire together, and soldering the wires to the main PCB. While this was time-consuming it became the case that we didn't have enough time to devise a faster process.

5. CONCLUSIONS

Worn as hypothetical prosthetic extensions to the body the Prosthetic Instruments present dancers with unique constraints and opportunities beyond those presented by typical interactive dance systems. It has been noted that a highly specialized musical interface often takes months or years for sophisticated use [8]. We were fortunate to work with dedicated collaborators who took the time to develop a deep understanding of the instruments as both artifacts with which to interact physically as well as musical interfaces. The design of the instruments owes a great deal to their embracing the challenges and opportunities created by working with these new instruments.

The Prosthetic Instruments also highlight the challenges faced by DMI designers when moving from the lab and demo sessions to use in professional artistic contexts. Despite our attempt to utilize existing hardware and software solutions, extensive research was required both for the implementation of sensors within these specific instruments as well as for the instruments' mechanical design. The use of different manufacturing techniques as described in this paper were instrumental in the ability of the instruments to meet their artist-spec requirements.

While the design and manufacturing capabilities available to designers depends upon the financial and institutional infrastructure within which they work, the decreasing cost and availability of digital manufacturing services place them within the capability of even the most DIY instrument designer. We hope that knowledge of the manufacturing approaches described above will help make it easier to design for artist-spec and help foster a greater adoption of NIMEs by the professional artistic performance community.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] J. Malloch, I. Hattwick, and M. Wanderley. Instrumented bodies: Prosthetic instruments for music and dance. In J. Malloch. *A Framework and Tools for Mapping of Digital Musical Instruments*. Ph.D. Dissertation, McGill University, Montreal, Canada, 2013. Available: `http://idmil.org/_media/publications/2013/malloch_phd_dissertation_2013.pdf`

[2] M. A. J. Baalman, H. C. Smoak, C. L. Salter, J. Malloch, and M. Wanderley. Sharing Data in Collaborative , Interactive Performances : the SenseWorld DataNetwork. In *Proceedings of Conference on New Interfaces for Musical Expression*, 2009.

[3] B. Buxton. Artists and the Art of the Luthier. *ACM SIGGRAPH Computer Graphics*, 31(1):10–11, 1997.

[4] P. Cook. Principles for designing computer music controllers. In *Proceedings of the 2001 conference on New Interfaces for Musical Expression*, pages 1–4, Seattle, Washington, 2001. National University of Singapore.

[5] J. Malloch, S. Sinclair, and M. M. Wanderley. A Network-Based Framework for Collaborative Development and Performance of Digital Musical Instruments. In *Computer Music Modeling and Retrieval. Sense of Sounds*, pages 401–425. 2008.

[6] J. W. Malloch. *A Consort of Gestural Musical Controllers : Design , Construction , and Performance*. M.a. thesis, McGill University, 2008.

[7] M. Schumacher, M. Giordano, M. M. Wanderley, and S. Ferguson. Vibrotactile Notification for Live Electronics Performance : A Prototype System. In *Proceedings of the International Symposium on Computer Music Multidisciplinary Research (CMMR) Sound, Music, and Motion*, 2013.

[8] W. Siegel. Dancing the Music: Interactive Dance and Music. In R. T. Dean, editor, *The Oxford Handbook of Computer Music*, pages 191–213. Oxford University Press, Oxford, 2009.

[9] G. Weinberg. The Beatbug: Evolution of a Musical Controller. *Digital Creativity*, 19(1):3–18, Mar. 2008.