Electronic Controllers for Musical Performance and Interaction

Joseph A. Paradiso

Draft 1.0 for MIT Press

1) Introduction

1.1) Why New Controllers?

The primal drive for humans to create music spans eons and cultures. Music probably predates civilization, and certainly impacted the communal rituals upon which society was structured. In order to make music, people harnessed extensions beyond the voice, hands, and feet with which they were born; artifacts that evolved into musical instruments. Although the first musical implements may have been percussive in nature, these are difficult to disambiguate in the archeological record. Flutes, however, are easier to discern because of their tuned airholes – bone flutes are suspected in Neanderthal artifacts dating circa 50,000 years ago [1] and definitively found at 9000 year-old Chinese Neolithic sites [2]. The exponential march of technology has been relentlessly bent towards refining musical craft, from prehistoric sticks, rocks, and bone flutes to today's synthesizers and musical computers. Our desire to explore new capabilities for musical expression is so strong that the delay between the introduction of a technology and its application in music is very slim – indeed, in some cases, even reversed, with groundbreaking technology sometimes inspired by a musical instrument (e.g., the player piano led to the first proposed realization of spread spectrum communication in the 1940's by George Antheil and Hedy Lamarr [3]).

Each set of technologies has ushered its own set of revolutions in the way people generate and interact with music. Acoustic musical instruments have settled into canonical forms, taking centuries, if not millennia, to evolve their balance between sound production, ergonomics, playability, potential for expression, and aesthetic design. In contrast, electronic instruments have been around for little more than the last century, during which rapid advances in technology have continually opened new possibilities for sound synthesis and control, keeping the field in revolution. Although people are still driven to invent new acoustic instruments [4], and new materials periodically provide opportunities for new designs, their principles and concepts are fairly established. On the contrary, any book on "electronic music controllers" is by definition a snapshot of a rapidly evolving field, as every decade Moore's Law dramatically revises the capabilities of music synthesis, electronic transduction, and machine perception, three broad areas that unite in electronic music interfaces. Hence, most chapters in this book tend to take a historical perspective, describing how different genres of electronic music controllers evolved to become what they are today.

Electronic instruments that abandon the interface conventions of familiar acoustic instruments are termed "alternative controllers." Although many different alternative controllers have been made, few have any virtuosic players. This occurs for several reasons, prime among which is that a large number of these controllers aren't playable beyond a basic level, as elaborated later in this chapter. Another major cause, however, is the aforementioned lack of stability in this field. With the exception of a few classics (e.g., the Theremin [5], Radio Baton [6], or Buchla Lightning [7]), interfaces that feature different modes of control are rapidly ousted by new devices. They haven't stayed around long enough to gain adherents or have significant pieces written for them, expert technique from another instrument can't be leveraged into playing them, and their inventors have moved on to other ideas. Accordingly, archiving a piece of music using a vintage controller can be a significant task, as its hardware, communication protocols, and software must be properly maintained to enable future performances.

Perhaps because electronic instruments were then in such an obvious contrast with their highly-expressive acoustic contemporary cohorts, the very early pioneers of electronic music were motivated to explore expressive and unusual channels of articulation and control for achieving an evocative performance, even though they were bound by the capabilities of available analog and vacuum tube or dynamo-based technologies. As will be illustrated in the next chapters, we see this in the depression-sensitive, just-intonation keyboard and timbre controllers of the turn-of-the-century Telharmonium [8], the radical free-gesture Theremin interface around 1920, the movable keyboard, knee pedal, and timbre stops on the 1930-era Ondes-Martenot [9], and the wonderfully expressive left-hand controller and multimodal keyboard of the Electronic Sackbut in the late 40's [10]. Although the rise of the voltage-controlled synthesizer in the 1960's and then the advent of MIDI (the Musical Instrument Digital Interface [11]) in the 1980's encouraged bursts of development in alternative controllers [12], the commercial world of synthesizers was long associated with a simple on-off organ manual, lacking any dynamic or expressive control beyond a pair of wheels for the left hand.

This is now changing, for many reasons. One cause comes from the low barriers to entry. Formerly expensive electronic sensors [13] are now quite cheap and widely available, and there are many inexpensive interface devices [14] that can readily connect essentially any number of sensors to a personal computer or MIDI system. Likewise, the chore of building software to connect the sensor data to musical events has been greatly simplified by software packages such as MAX [15], which provides a convenient graphical interface to build complex dataflow programs for controlling and generating musical processes from sensor-driven events [16]. This has led to an explosive flurry of electronic music controller development over the past decade – new controllers are being developed nearly everywhere, from student projects for university classes [17] to the studios of independent artists and musicians. Although much of this work involves playful (yet often creative and enthusiastic) exploration, there is a serious and still unmet need for new musical controllers, especially as synthesis algorithms have become much more advanced and are capable of providing real-time control over nearly infinite shades of expression.

Accordingly, synthesis technology has outstripped the capability of controllers to provide adequate input. Physical modeling [18], for example, aims to give electronic sound the responsive nuance and complexity of acoustic instruments by simulating the dynamics of real structures. As acoustic instruments can have massively fine-grained input degrees of freedom (e.g., the many ways of plucking, bowing or fretting a string, blowing a horn, fingering a flute…), performers have their hands quite literally on the sound. Although physical modeling promises to give the electronic player a similar sound-generating capability, there are no interfaces that can match the intimacy of control that binds the acoustic player to their instrument – although research continues into distilling the right parameters to transduce in order to increase the granularity of electronic gesture capture, today's common sensing systems are just too coarse.

Figure 1 illustrates the evolution of the boundary between mainstream electronic musical controllers and synthesizers. It's a construct balanced between the establishment

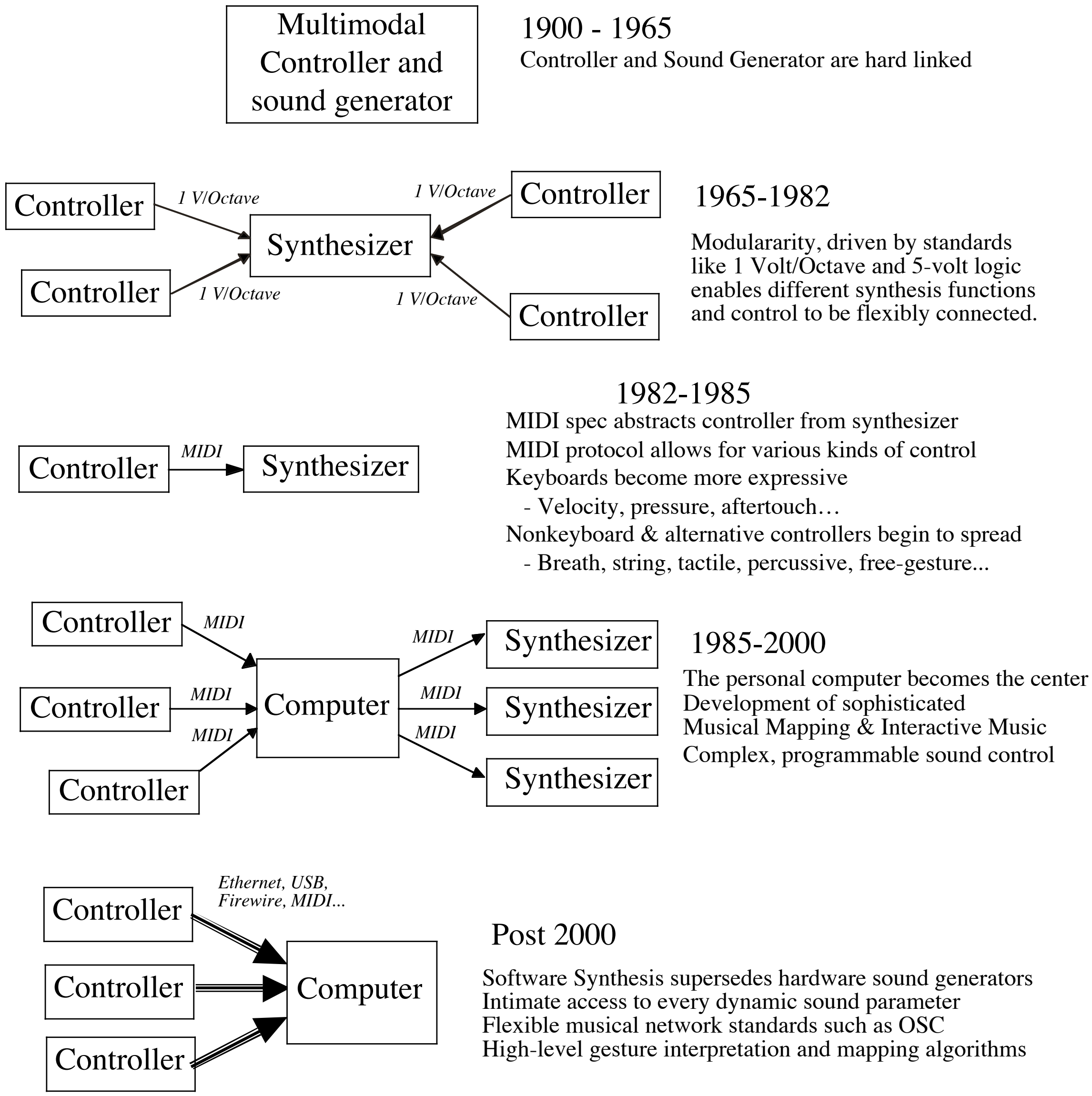

Figure 1: Evolution of the boundary between music synthesis and control

of communication standards and the feasibility of commercial markets. For the first half of the century, electronic musical instruments were essentially standalone constructs, like acoustic instruments. The electronic music controller, sound generator, and frequently the amplifier and speaker were housed in one package and didn't readily interoperate with others of its ilk. The subsequent dawn of modular synthesis, however, had a deep impact on the structure of electronic instruments. The one-volt-per-octave analog standard and triggering conventions such as 5-volt logic enabled different synthesis functions to be abstracted into discrete hardware modules, which could flexibly connect to one another and to a variety of discrete controllers - now the controller and the synthesizer were different physical and conceptual entities. In the early 1980’s, the advent of MIDI resulted in an even cleaner separation between the interface and the sound production module, with a simple serial cable connecting control and synthesis. By the middle of the decade, widely available personal computers were a standard fixture between the MIDI

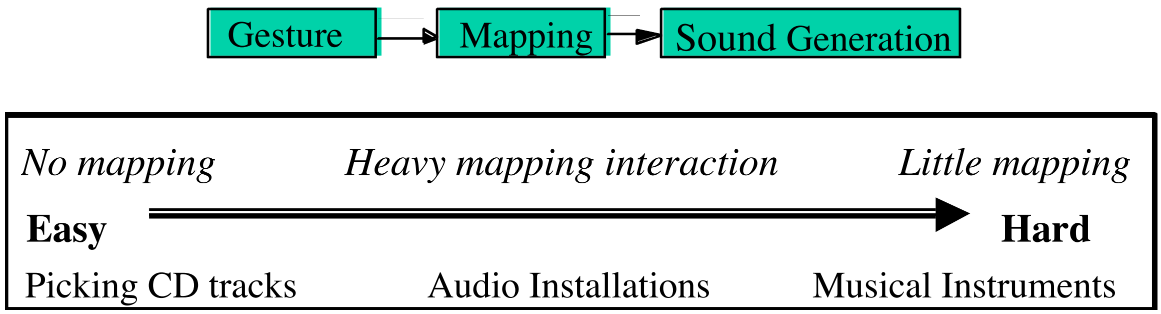

Figure 2: The Role of Mapping in Musical Interaction vs. Musical Instruments

controller and the sound source. This enabled the rise of commercial software music sequencers [19], then musical mapping packages, including MIDI utility libraries for computer languages (both commercial [20] and academic [20a], standalone mapping and composition packages [20b], and graphical dataflow editors like MAX [15]. These allowed the controller information to be stored, processed, manipulated and interpreted into audio in arbitrary ways, leading towards new capabilities for musical performance and enabling complex interactive music and what are often termed "Hyperinstruments" [20c].

Although MIDI provided a standard that allowed musical controllers to interoperate with any synthesizer, it likewise choked multimodal expression because of its limited bandwidth and restricted base specification [21]. The dawn of the millennia, however, has seen widespread adoption of a new genre of electronic instrument – namely the software synthesizer, with all real-time sound generation running on a personal computer, eliminating the need for standalone hardware. Now that the synthesizer is a software module, musical controllers can be coupled to the computer via any available physical port (e.g., serial, firewire, USB, ethernet) and support essentially any desired bandwidth. Similarly, although garden-variety MIDI remains dominant, software music networking standards have evolved somewhat [21a], passing through a number of promising starts (e.g., [21b]) before resulting in frameworks such as U.C. Berkeley's Open Sound Control (OSC) [22], Yamaha's MLAN [22a], and Gibson Lab's MaGIC [22b] that begin to be adopted by several user communities and manufacturers. Some of these protocols offer a framework within which any number of sound synthesis parameters can be driven in various ways by a controller's data. Processors have become fast enough to devote significant attention to gesture analysis while generating simultaneous real-time audio, producing an environment where, in one platform, sophisticated action-to-audio mapping algorithms can intelligently interpret controller input into digital sound.

Figure 2 (top) shows a very simplified organization of the logical flow of information between sensed gesture and produced sound, indicating the role of the mapping layer in defining the personality of the instrument via the way gesture is interpreted to generate what one hears. As will be discussed in Chapter 12, the mapping logic can either be thought of as a standalone algorithm or as a part of the synthesis process, for example via nonlinearity and coupling between variables in a physical model. At bottom, the role of mapping is presented along an axis of playability, where we see different musical activities ranked. At left, picking CD or MP3 tracks is generally considered an "easy" musical activity, and the action-to-trigger musical mapping is likewise trivial. At right, it is noted that "hard" musical instruments also tend to involve fairly simple or immediate mapping rules, putting the performer in direct touch with the musical process. The difference between these two lies in the choices available in the control space - deciding when to push the button and perhaps what track to play are the only choices in playing the CD, whereas the complex instrument involves several parameters that are directly mapped onto a player's physical capabilities. The immediate link between a causal audio response and a performer's muscles allow a potentially virtuosic intention-to-movement mapping to be developed in the performer's brain after years of practice. Today's interactive musical instruments and audio installations tend to be in the middle of the line - they generally involve a sophisticated set of rules in the sensor-to-music mapping process, hence nearly any gesture can make an interesting and very complex sound. On the other hand, the elaborate digital interpretation of gesture here can remove the player from simple causality, making such an instrument or environment counter to learning to play with any real skill. Although there are some exceptions, where the players lived with a static controller and stable mapping for years, most heavily-mapped musical environments are built for the limited attention span of the general public, and not for the practicing musician.

A host of musical applications that exploit electronic controllers in very different ways span the difficulty/mapping axis of Figure 2. Indeed, the practitioners in this field spring from many walks of life – academic researchers, musical performers and composers, dancers and choreographers, designers, video game developers, interactive and media installation artists, teachers (from university to grammar school), and therapists (special needs, exercise, and relaxation), to name a few. The vocabulary in this field is likewise developing – as this range is so broad, no common set of standards exists to evaluate designs, and since goals are so varied in different applications, its unclear whether this can ever be effectively accomplished. It's certainly exciting to have many perspectives under one umbrella, although such a wide convergence may be a temporary phenomenon. The field of musical interfaces is becoming so diverse that it threatens to fragment into subgenera with different goals and motivations, yet researchers seek universal principles to hold the community together beyond a set of commonly-used tools and technologies. Similarly, even though they have some aspects (and several researchers) in common, one can ask what kind of union research in musical controllers will be able to forge with the larger field of Human-Computer Interfaces (HCI) [25]. Certainly, as indicated at the bottom of Fig. 1, the musical synthesizer is now a computer, hence musical controllers are computer interfaces. Although perhaps working in differently dimensioned control and temporal spaces with very different requirements, both computer and musical instrument users exploit their interfaces to accomplish tasks. HCI, however, tends to favor early adoption and ease-of-use, whereas musical instruments, in the traditional sense, emphasize difficult interfaces that one becomes very good at after long practice (e.g., the right part of Fig. 2). Aesthetic design can influence both endeavors, but its emphasis is far greater with musical instruments. The electronic performer (or perhaps performance artist) is often a modern shaman, dazzling the audience with an armada of technology and instruments that want to look interesting and provide some degree of spectacle, from glittering electric guitars and massive modular synthesizers to laser harps and necktie-keyboards. Additionally, the bond that the longtime player feels with their instrument is much deeper than any link established with the mouse and keyboard - the intimacy of the musical interface encourages anthropomorphization, as players tend to see a great instrument as an extension of self. Perhaps a more appropriate analogy to another field would be a comparison to cockpit [23] or automotive interfaces [23a], where the user is multimodally engaged in a demanding real-time task that provides immediate and immersive sensorial feedback.

1.2) What is a musical controller, and what makes it good?

Considering the prior discussion, it's somewhat difficult to define exactly what a musical controller is. As electronic music instruments liberate the action of musical control from the sound production mechanisms, their form doesn't need to be limited by the corresponding physical constraints and is free to move in many other directions. As covered in the following chapters, the modality and form factors of conventional instruments (e.g., keyboards, wind, strings, etc.) have been abstracted many times into the world of electronic controllers, leveraging familiar routes to expression and available expert technique. On the other hand, an electronic controller can sense and musically map essentially any gesture, from the most delicate and intimate control of a virtuoso playing a fine interface to the limited, high-level direction of a child stomping through an interactive installation, leaving controller designers free to realize their wildest dreams of possible musical interaction.

Perhaps the broadest definition is that a musical controller is a device senses a user's action and exploits appropriate connections (logical and/or physical) that map it appropriately onto sound. Looking at the right end of the complexity axis in Figure 2, we can go further, and say that a "hard" musical controller facilitates a performer in launching a sound with a particular musical pitch, timbre, and/or timing; in addition, the controller may also offer facility in dynamically articulating pitch, amplitude, and other timbral aspects of the sound as it evolves. Moving to the left, another kind of musical controller puts the player in charge of a higher-level musical or audio process, verging into a "mixer" analogy rather than an "instrument" metaphor. The player's operations are more akin to selecting parameters, adjusting controls, and nudging a dynamic process. Perhaps in past decades, one could discount this regime as not being an "instrument," but in today's world of laptop concerts and DJ performances, controllers of this sort are quite relevant and can hardly be omitted as "unmusical".

The next level of discussion is one of quality - having defined a set of controllers, what mades them good musical interfaces? Again, as the variety is so broad, it's difficult to establish general evaluative parameters, although some researchers [24,25] have attempted this. While bearing in mind that any particular controller will prioritize such metrics according to its targeted application, I'll define a few qualitative criteria in the remainder of this introduction that could help to set the stage here.

The first factor is one of enjoyment. A good musical interface should be fun to play, at least after forcing oneself to become adept at it. This may well be a dependent parameter that is defined by the more detailed points below, but it's nonetheless of prime importance. The interface must be designed such that the experience a trained user has with it not only isn't frustrating, but is highly engaging, enjoyable, and intimate.

Another important, perhaps more specific criterion is the feel of the instrument. A good interface must have an efficient layout and appropriate haptic response - the way the instrument fits your fingers, feet, or whatever parts of your body that drive it must feel natural, and the response to interaction needs to give the player appropriate feedback to naturally gauge the gesture, e.g., through the force on your fingers, pressure on your cheeks, resistance to the hand, etc. [25a]. The configuration and dynamics of the control interface can't slow the player down or make them loose precision. Haptics are one area in which acoustic instruments have an advantage - as your fingers are very close to (or on) the mechanical sound production mechanism, an acoustic player feels the instrument vibrating and uses this information in directing musical gesture. Electronic controllers, apart from certain research devices or those based closely on acoustic interfaces that will be introduced in later chapters, don't offer this kind of feedback, and must get along with the passive mechanical response offered by the buttons, breath sensor, control surfaces, or other constructs in contact with the player (note that free-gesture controllers, described in Chapter 9, offer no external haptic reference, which makes them quite difficult for developing virtuosic technique [26]).

Although they may lack the direct-to-audio haptic connection, today's electronic instruments are very flexible in producing expressive sound. Even though, as proclaimed above, essentially any gesture can be mapped to any kind of sound, a good controller maps appropriate gestures to appropriate sounds. Research [27] has supported the common intuition that certain classes of gesture are associated with particular timbres (e.g., a simple example is that a hard strike or fast gesture produces a loud and potentially brittle timbre, whereas a soft strike or gentler gesture launches a softer and perhaps duller timbre); intuitively-mapped controllers should behave accordingly.

A good controller should be able to navigate through a wide sonic vocabulary in an expressive manner. Although some of this is again an issue in how sound is mapped onto controller data, the interface device must be able to sense gestural modes appropriate for expression, and the instrument designer must exercise proper taste in connecting these modes to timbral manipulation.

One of the most important factors in musical interface design is to maintain reliability - a good controller must produce stable and causal data in response to similar classes of gesture. It's too easy to make a musical controller that produces unpredictable sound in response to unreliably-sensed parameters. Performers can quickly tire of such interfaces, and they offer no path to technique.

That said, a good musical interface, like a fighter jet [23], rests at the edge of stability, offering a trained performer an extremely expressive platform, while perhaps frustrating a novice (e.g., you never give a starting violinist a Stradivarius, cost not withstanding). The best musical instruments are nearly all initially hard to play. Perhaps an advantage of an electronic controller is that aspects of this "stability edge" can be addressed via mapping - e.g., the same instrument can electronically adapt it's sonic vocabulary to the level of the player, allowing one to grow from novice to adept on the same physical interface, gradually losing the “training wheels” as you progress.

Generalizing on the above discussion, a good musical interface should allow one to improve with practice - there should be enough depth in the interface to develop technique.

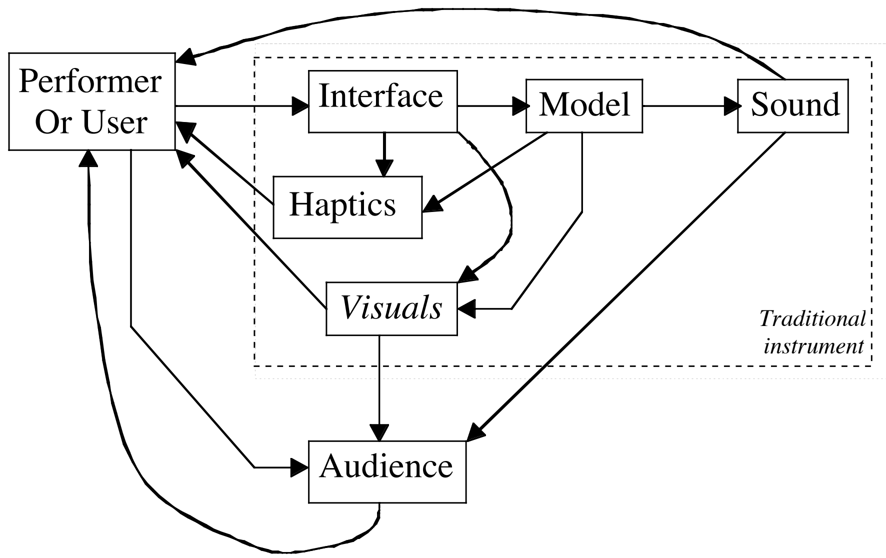

Figure 3: Different multimodal interactions between performer, audience, and various components of a musical instrument

Finally, a major problem with many electronic music interfaces is their lack of causality, not only for the player, as mentioned above, but also for the audience, who watch the performer with a real-world mental model that provides a set of expectations between the musician's gesture and the resulting sound. It's not uncommon for electronic music controllers to be so heavily mapped that it's difficult for an audience to figure out what sound the performer is generating at any particular time in a concert. Although opinions on the relevance of this may vary [28], it's not uncommon to see an audience unable to follow the performance of a piece featuring electronic controllers, and begin leaving the show. In some cases, this can't be helped (e.g., in concerts featuring musical control derived by measuring the performer's brain waves [29] or the electrical potential of a house plant [30]), and is perhaps endemic to the structure of the composer's piece. But in the case of a composition that involves active physical performance, the composer and player must allow for some level of audio-visual causality in order to maintain a high level of engagement with an audience. One solution is to produce mappings that, at least periodically, strip away layers of abstraction (moving to the right in Fig. 2), allowing the audience to smell the digital sweat as the artist pushes their instrument to the edge. A virtuosic performance is a fragile and exciting thing to witness at any musical event - it's a prime factor that attracts many of us to concerts, and needn't be abandoned when using electronic controllers.

Figure 3 shows a diagram of the interactions between a performer, the audience, and various components of an instrument that captures much of the discussion in this chapter and provides a structure through which some of these issues can be addressed. The performer interacts via a physical interface, which drives a model that produces sound. In an acoustic instrument, this model is essentially the physics [31] of vibrating strings, soundboards, drum membranes, reeds, air columns, and other components of the instrument. In an electronic instrument, the model is a synthesis engine or algorithm, and potentially the mapping architecture. The physical interface itself will produce a haptic response that is fed back to the player. In an acoustic instrument, the model will also generate its own haptics (perceived as vibrations, string tensions, etc.) as mentioned above, which are likewise perceived by the performer. Some electronic instruments have been built to artificially produce a haptic output [32], which can also be lumped into the model block. In addition, visual feedback can be important to the performer - this is generated immediately by the layout and dynamic appearance of the interface itself and the model (e.g., strings vibrating, perhaps LEDs or displays for an electronic instrument). Performers adapt their playing technique in response to all of the feedback paths discussed above, in addition, of course, to the resultant sound, and perhaps their perception of the audience or other members of their ensemble, depending on their musical context.

The audience doesn't have access to the player's haptic channels, but they can, by necessity, hear the instrument's sound and they can usually see the performer and the instrument's visual presentation (at least whatever portion is visible from their seat). It's through these channels that a performance is appreciated (audience members can also perceive one another, which can be an important contributor to the sense of presence in a public performance as their enthusiasm can collectively build or decay [34]). In large rock concerts, for example, a breakdown in both visual and audio performer-to-audience channels can occur, namely when a band amplified by an array of speakers placed across a massive arena look tiny from remote seats, leading to a loss in situatedness as no direct sound or discernable gesture is perceivable on the stage (the interaudience dynamic can accordingly become dominant at these shows). Today's solution is usually to hang a very large screen behind the band that shows a live video mix highlighting the more interesting events happening on the stage, while potentially integrating other modes of entertainment (e.g., pyrotechnics, large robotic props, film clips, etc.) that work well in a large venue.

Compromises in the visual channel similarly create much of the audience's disconnect in modern electronic music concerts. As mentioned above, an abstract mapping of action to sound leaves an audience with no causal chain to follow, and the increasing ubiquity of "laptop" concerts, that use the standard interfaces at a personal computer as musical controllers, give an audience very little to see, as the player's attention is focused onto a small screen while their activity is confined to a very limited area. One technique that helps with this issue involves projecting captivating and causal real-time graphical representations that tightly correlate with the audio component. The dotted line in Figure 3 bounds a conventional musical instrument – in an electronic controller, the internal state of the instrument (generated by the model) can be graphically interpreted in any manner desired, and exposed to the outside world via a projection. In this way, the performer nudges and stokes a musical process that produces visuals, which, in some sense, replace the presence of an easily discerned physical instrument. The graphics produced by the audiovisual environment ground the audience and the performer, effectively becoming the instrument's "body." In some sense, this concept dates to the days of the light shows and color organs [36] of 60's psychedelia [35] and before [37]. With a computer embodying the instrument, however, the visual complexity and ties to the model can be much deeper – most of the old light shows independently tied the visuals to the sound, but modern media environments can generate both audio and video streams at a higher level, often through the same algorithm (providing strong causality) or via a video-game metaphor (providing visual analogies that people can relate to). Such audiovisual musical environments are becoming increasingly common, e.g., [38].

In general, a good musical controller should look great in performance – through its physical design, associated visuals, and its mode of interaction. Audiences should *want* to watch the musician at work, and not just close their eyes as in the days of tape music performances.

Advances in bioinstrumentation promise new interfaces that may one day revolutionize our notion of a musical interface. Already for several decades, people have been exploring the use of biological signals (e.g., EMG's, heart rate, skin resistance, brain waves, etc.) [29,39] to control music, as described in Chapter 10. At the moment, such noninvasive measurements tend to be quite coarse, but once direct neural/electrical connections are perfected (as are now being pursued for application in aural/ocular/muscular prosthetics [40]), this situation may flip and direct bioelectrical musical interfaces could prove to enable a much more agile and intimate musical interaction than their clunky mechanical forebears. Were this to be realized, the audience's experience of a performer playing a concert through their implant could suffer from a break in the performer-audience perceptual channel and invoke a causal disconnect. As discussed above, however, the situation may be addressed via visual representations, adjunct physical expression, or, better yet, piping the multimodal neural symphony into the audience's own neural interfaces.

1.3) Structure of this book

This book is laid out as a taxonomy of electronic music interfaces, with each chapter giving a historical overview of a particular controller genre, a snapshot of the current state-of-the-art, and discussion of the principles and core technologies involved. Although most chapters are labeled with what sound like conventional instrument families, this serves only as a point of departure and organization, as electronic controllers that exploit a certain modality or manner of excitation can grow to be quite divergent from their acoustic forebears.

Chapter 2 follows this discussion with more background on the limitations and capabilities of human performance on a musical interface, interface requirements, and more discussion on the human-factors issues and organizing principles behind musical controllers. The following chapters trace through the different families of interfaces. Chapter 3 covers controllers that are derived from keyboards (including microtonal controllers, large button-bank interfaces, control stations, and touchpads). Chapter 4 covers interfaces for percussion and impulsive controllers. Chapter 5 discusses the many types of controllers that have been developed around string modalities, e.g., interfaces that are plucked and fingered like guitars or bowed like violins. Chapter 7 introduces the use of the human voice as a controller. Chapter 8 discusses baton interfaces – e.g., handheld controllers used both for conducting and performance. Chapter 9 covers free gesture interfaces – controllers that assume no contact between the user and a control surface, translating free motion into sound – that have no counterpart in the acoustic world. Chapter 10 discusses wearable interfaces – e.g., multimodal musical controllers built into clothing (e.g., gloves, shoes, suits) as well as bioelectric interfaces. Chapter 11 finishes our treatment of interface hardware by covering the niches that are left, e.g., continuous tactile interfaces and HCI input devices (mice, trackpads, touchscreens) that are adapted for musical control. Chapter 12 switches to software and algorithms with a survey of approaches and issues in musical mapping, and Chapter 13 closes the book with a few general remarks on controller evolution.

References

[1] Holden, C. (ed), "Early Music," Science, 275(5297), Jan. 10, 1997, p. 205.

[2] Zhang, J., Harbottle, G., Wang, C., and Kong, Z., "Oldest Playable Musical Instruments Found at Jiahu Early Neolothic Site in China," Nature, 401(6751), September 23, 1999, pp. 366 – 368.

[3] Braum, Hans-Joachim, "Advanced Weaponry of the Stars," American Heritage of Invention and Technology, Vol. 12, No. 4, Spring 1997, pp. 10-17.

Markey, H.K. and Antheil, G., "Secret Communication System," US Patent Number 2,292,387, August 11, 1942.

[4] Hopkin, B., **Gravikords, Whirlies & Pyrophones**, Ellipsis Arts, NY, 1996.

Hopkin, B., **Orbitones, Spoon Harps & Bellowphones**, Ellipsis Arts, New York 1998.

[5] Glinsky, A. (2000). **Theremin: Ether Music and Espionage (Music in American Life)**. Urbana-Chicago: University of Illinois Books.

[6] Mathews, M.V., "Three Dimensional Baton and Gesture Sensor", US Patent No. 4980519, Dec. 25, 1990.

[7] Rich, R. (1991). Buchla Lightning MIDI Controller. Electronic Musician, 7(10), 102-108.

[8] Weidenaar, R. (1995). **Magic Music From the Telharmonium**. Metuchen, NJ: The Scarecrow Press.

[9] Rhea, T. (1984). Electronic Keyboards – Early Tube Oscillators. In Darter, T. (ed.), The Art of Electronic Music, Cupertino: Quill/GPI Publications, pp. 25-36.

[10] Young, G. (1989). The Sackbut Blues: Hugh LeCaine, Pioneer in Electronic Music. Ottawa: National Museum of Science and Technology Press.

[11] MIDI Manufacturers' Association (MMA), **Complete MIDI 1.0 Detailed Specification v 96.1 (second edition)**, 2001.

[12] Wiffen, P. (1988). Keyboards are for Wimps. Keyboard Magazine, Vol. 14, No. 10, October, 1988, p. 117.

[13] Fraden, J. (2004). Handbook of Modern Sensors: Physics, Designs, and Applications, 3'rd edition, New York: Springer-Verlag.

[14] Fléty, E. and Sirguy, M. (2003). EoBody : a Follow-up to AtoMIC Pro's Technology. Proc. of the New Interfaces for Musical Expression Conference (NIME 2003), Montreal, Canada, May 22-23, 2003, pp. 225-226.

Sensorlab (2003). See: http://www.steim.org/steim/sensor.html

Wilson, S., Gurevich, M., Verplank, B., Stang, P. (2003). Microcontrollers in Music HCI Instruction: Reflections on our Switch to the Atmel AVR Platform. In the Proc. of the New Interfaces for Musical Expression Conference (NIME 2003), Montreal, Canada, May 22-23, 2003, pp. 24-29.

Allison, J.T. and Place, T.A., "Teabox: A Sensor Data Interface System," in the Proc. of the 2005 International Conference on New Interfaces for Musical Expression, Vancouver, BC, Canada, May 26-28, 2005, pp. 56-59.

See: http://infusionsystems.com

[15] Puckette, M., "Combining Event and Signal Processing in the MAX Programming Environment," Computer Music Journal 15(3), pp. 68-77, 1991.

Puckette, M., "Max at Seventeen," Computer Music Journal, 26:4, Winter 2002, pp. 31-34.

[16] Winkler, T., **Composing Interactive Music: Techniques and Ideas Using Max**, MIT Press, Cambridge, MA, 2001.

[17] Lehrman, P.D., "Bridging the Gap Between Art and Science Education Through Teaching Electronic Musical Instrument Design," Proc. of the 2005 International Conference on New Interfaces for Musical Expression, Vancouver, BC, Canada, May 26-28, 2005, pp. 136-139.

D'Arcangelo, G., "Creating a Context for Musical Innovation: A NIME Curriculum," in the Proc. of the New Interfaces for Musical Expression Conference (NIME 2002), Dublin, Ireland, May 24-26, 2002, pp. 102-106.

Verplank, B., A Course on Controllers, in the Proc. of the NIME Workshop at CHI 2001, Seattle, Washington, April 1-2, 2001, see: http://www.nime.org.

[18] Smith, J.O. (1988). Principles of Digital Waveguide Models of Musical Instruments. In Kahrs, M. and Brandenburg, K. (eds.), Applications of Digital Signal Processing to Audio and Acoustics, Boston: Kluwer Academic Publishers.

[19] Tobenfeld, E., "A General-Purpose Sequencer for MIDI Synthesizers," Computer Music Journal, Vol. 8, No. 4, Winter 1984, pp. 43-44.

Yavelow, C., "Music Software for the Apple Macintosh," Computer Music Journal, Vol. 9, No. 3, pp. Fall, 1985, 52-67.

Yavelow, C., "MIDI and the Apple Macintosh," Computer Music Journal, Vol. 10, No. 3, pp. 79-82.

[20] DeFuria, S. and Scacciaferro, J., **MIDI Programming for the Macintosh**, Redwood City: M & T Books, 1988

Conger, J., **C Programming for MIDI**, Redwood City:M&T Books, 1989.

[20a] Chung, J., “Hyperlisp Reference Manual,” MIT Media Laboratory Technical Report, Music and Cognition Group, 1988.

Dannenberg, R., “The CMU MIDI Toolkit", in Proceedings of the 1986 International Computer Music Conference, pages 53-56. International Computer Music Association, San Francisco, 1986.

[20b] Zicarelli, D., “M and Jam Factory,” Computer Music Journal, Vol. 11, No. 4, Winter, 1987, pp. 13-29.

[20c] Machover, T., “Hyperinstruments: A Progress Report,” available from the Media Laboratory, Massachusetts Institute of Technology, Cambridge, MA, 1992.

[21] Moore, F. Richard. 1988. "The dysfunctions of MIDI." Computer Music Journal, 12(1): 9-28.

[21a] Selfridge-Field, E., **Beyond MIDI: The Handbook of Musical Codes**, MIT Press, Cambridge MA, 1997.

Knoepfel, Henning, MIDI vs. Alternative: The Future of Musical Instrument Control. Specialized Research Project Report, SAE Institute, London UK, August 2004.

[21b] McMillen, K. (1994). ZIPI: Origins and Motivations. Computer Music Journal, Vol. 18, No. 4, pp. 47-51.

[22] Wright, M., Freed, A., Momeni, A. OpenSound Control: State of the Art 2003. Proc. of the New Interfaces for Musical Expression Conference (NIME 2003), Montreal, Canada, May 22-23, 2003, pp. 153-159.

[22a] See: http://www.mlancentral.com/

[22b] Juszkiewicz, H., Yeakel, N., Arora, S., Beliaev, A., Frantz, R., and Flaks, J., “Media-accelerated Global Information Carrier Engineering Specification,” Revision 3.0c, May 3, 2003. Available at: http://www.gibsonmagic.com/

[23] Aviation Safety and Pilot Control: Understanding and Preventing Unfavorable Pilot-Vehicle Interactions, National Academy Press, Washington, DC, 1997.

[23a] Waller, P.F. and Green, P.A., “Human Factors in Transportation”, in Salvendy, G., ed., **Handbook of Human Factors and Ergonomics**, Second Edition, John Wiley & Sons, New York, 1997, pp. 1972-2009.

[24] Cook, P., "Principles for Designing Computer Music Controllers," in the Proc. of the NIME Workshop at CHI 2001, Seattle, Washington, April 1-2, 2001, see: http://www.nime.org.

Jorda`, S., "Digital Instruments and Players: Part I – Efficiency and Apprenticeship," in the Proc. Of the 2004 Conference on New Interfaces for Musical Expression (NIME04), Hamamatsu, Japan, June 3-5, 2004, pp. 59-63.

[25] Wanderly, M.M. and Orio, N., "Evaluation of Input Devices for Musical Expression: Borrowing Tools from HCI," Computer Music Journal, 26:3, Fall 2002, pp. 62-67.

[25a] Cadoz, C., Luciani, A., and Florens, J., "Responsive Input Devices and Sound Synthesis by Simulation of Instrumental Mechanisms: The Cordis System," Computer Music Journal, Vol. 8, No. 3, Fall 1984, pp. 60-73.

[26] O'Modhrain, M.S., Chafe, C., "The Performer-Instrument Interaction: A Sensory Motor Perspective," in Proceedings of ICMC 2000, Berlin, Germany, August 27-September 1, 2000, pp. 145-148.

[27] Canazza, S., De Poli, G, Drioli, C., Roda`, A., and Vidolin, A., "Modeling and Control of Expressiveness in Music Performance," Proceedings of the IEEE, Vol. 92, No. 4, April 2004, pp. 686-701.

Clynes, Manfred. **Sentics: the Touch of the Emotions**. New York: Doubleday and Company, 1977.

Merrill, D. and Paradiso, J.A., "Personalization, Expressivity, and Learnability of an Implicit Mapping Strategy for Physical Interfaces," in the Proc. of CHI 2005 Conference on Human Factors in Computing Systems, Extended Abstracts, ACM Press, Portland, OR, April 2-7, 2005, pp. 2152-2161.

[28] Rothenberg, D. (1996). Sudden Music: Improvising across the Electronic Abyss. Contemporary Music Review, 13(2), 23-46.

Winkler, T., "Participation and Response in Movement-Sensing Installations," Proc. of ICMC 2000, Berlin, Germany, August 27 - Sept. 1, 2000, pp. 137-140.

[29] Rosenboom, D. (ed.) (1976). **Biofeedback and the Arts: Results of Early Experiments**, Vancouver: A.R.C. Publications.

Miranda, E.R. and Brouse, A., "Interfacing with the Brain Directly with Musical Systems: On Developing Systems for Making Music with Brain Signals," Leonardo, Vol. 38, No. 4, 2005, pp. 331-336, 2005.

[30] Brouse, A., "Conversation," in Concert Program for NIME 2003, May 23, 2005, see: http://www.music.mcgill.ca/~brouse/conversation.

[31] Fletcher, N.H. and Rossing, T.D., **The Physics of Musical Instruments**, Springer-Verlag, New York, 1991.

[32] Oboe, R. and De Poli, G., "Multi-instrument virtual keyboard – The MIKEY project," in the Proc. of the New Interfaces for Musical Expression Conference (NIME 2002), Dublin, Ireland, May 24-26, 2002, pp. 23-28.

Cadoz, C., Luciana, A., and Florens, J-L., "Modular Feedback Keyboard," in the Proc. Of the ICMC 1990, Glasgow England, pp. 379-382.

Baker, R., "Active Touch Keyboard," US Patent No. 4,899,631, February 13, 1990.

Nichols, C. (2002), The vBow: A virtual violin bow controller for mapping gesture to synthesis with haptic feedback," Organised Sound: Vol. 7, No. 2. Cambridge: Cambridge University Press: 215-220.

Gillespie, B., "The Virtual Piano Action: Design and Implementation," Porc. Of the International Computer Music Conference, Aahus, Denmark, Sept. 12-17, 1994, pp. 167-170.

[34] Ne'da, Z., Ravasz, E., Brechet, Y., Vicsek, T., and Baraba'si, A.-L., "The Sound of Many Hands Clapping," Nature, Vol. 403, No. 6772, pp. 849-850 (2000).

[35] Lancaster, D., "Musette Color Organ," Popular Electronics, Vol. 25, No. 1, July 1966, pp. 56-62, 98-99.

Meyer, D., "Build the "Sonolite"," Popular Electronics, Vol. 28, No. 5, May 1968, pp. 27-30.

Lancaster, D., "Psychedelia 1," Popular Electronics, Vol. 31, No. 3, September 1969, pp. 27-44.

[36] Erlewine, M., "Interview with Light Show Artist Bill Ham," available at: http://www.classicposters.com/eposter/showArticle.do?id=CP000014&secId=001.

See also: http://www.billhamlights.com

[37] Current, R.N. and Current, M.E., **Loie Fuller: Goddess of Light**, Northeastern University Press, Boston, 1997.

[38] Levin, G., "A Personal Chronology of Audiovisual Systems Research," in the Proc. of the New Interfaces for Musical Expression Conference (NIME 2005), Vancouver, Canada, May 26-28, 2005, pp. 2-3.

Levin, G (2000). Painterly Interfaces for Audiovisual Performance. MS Thesis, Cambridge, MA: Massachusetts Institute of Technology, Media Lab.

Collopy, F. (2000). Color, form, and motion: Dimensions of a musical art of light. Leonardo, Vol. 33, No. 5, pp. 355-360.

Stanza (2002). Amorphoscapes & Soundtoys. Proc. of the New Interfaces for Musical Expression Conference (NIME 2002), Dublin, Ireland, May 24-26, 2002, pp. 186-187. See: http://www.mle.ie/nime/.

Several others to perhaps cite…

[39] Knapp, R.B. and Lusted, H.S., "A Bioelectric Controller for Computer Music Applications," Computer Music Journal, Vol. 14, No. 1, 1990, pp. 42-47.

Tanaka, A. and Knapp, R.B., "Multimodal Interaction in Music Using the Electromyogram and Relative Position Sensing," in the Proc. of the New Interfaces for Musical Expression Conference (NIME 2002), Dublin, Ireland, May 24-26, 2002, pp. 43-47.

[40] Geary, J. (2002). **The Body Electric: An Anatomy of the New Bionic Senses**. London: Orion Publishing Group.