An Introduction to Some Recent Developments in Gestural Musical Instruments

by

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SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2010

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in Gestural Musical Instruments

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Submitted to the Department of Mechanical Engineering
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Abstract

Humans have been making music for millennia, yet the processes of developing existent
musical instruments and even inventing new ones are ongoing as technology advances and tastes
change. Many recent developments have been made in a category of instruments I have chosen
to refer to as “gestural instruments”- mainly electronic instruments which can map the
performer’s gesture to musical output in a variety of ways. In this thesis, I provide an overview
of several gestural instruments of the last twenty years, showing some of the variety of gestures
captured and the diversity of contexts in which musical and technological innovators see their
work. To do this, I reference several recent patents as well as current work occurring at the MIT
Media Lab. Finally, I discuss some of the advantages and disadvantages of gestural instruments
as compared to traditional instruments.

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Acknowledgment

The author wishes to thank Professor Makris for his ideas, guidance, and assistance with this project.
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Introduction

Music is a phenomenon which finds vastly different expressions in different cultures around the world. Even within one culture, it is difficult to arrive at a single definition of the term, because many types of sounds are considered music by some but noise by others. One definition which has been offered is “sound that is generated deliberately to create emotion.” Musical instruments, then, are the tools which are used to create such sound.

Musical instruments vary as dramatically as the music they are used to produce, and various systems of classification are common. Within orchestras in the Western tradition, instruments fall into the string, woodwind, brass, or percussion families, based upon their method of sound production. However, a more general classification system developed by Hornbostel and Sachs (with later contributions from Galpin) divides instruments into five major classes based upon method of sound production, then into further subcategories based on method of excitation, among other characteristics. Idiophones’ sound is produced through the vibration of a rigid object- by striking, plucking, rubbing, or shaking. Familiar idiophones include xylophones and triangles. Kazoos as well as various types of drums fall into the membranophones category- instruments whose sound is produced by striking, rubbing, or singing into a stretched membrane. Chordophones are string instruments, such as pianos, harps, and violins, whose strings may be struck, plucked, or bowed. Aerophones, whose vibrating air may be excited by an air jet, mechanical reed, or lip reed, include the instruments in the brass and woodwind families as well as pipe organs.2

Virtually all of the instruments discussed in this thesis, however, fall into the final category: electrophones. Electrophones’ sound is physically produced by a vibrating loudspeaker. Their categories include electronic instruments such as synthesizers, electromechanical instruments such as the Hammond organ, and electroacoustic instruments such as electric guitars.3 More specifically, I will be looking at some representatives of a category I will refer to as “gestural instruments”- instruments which map the performer’s gesture to a sound, usually electronic, in such a way that the same gesture can be mapped to different

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3 Ibid.
sounds, depending on the setup of the instrument. For example, in normal use of a traditional piano, the performer's gesture is striking a key with a particular amount of force. This gesture is physically mapped to one sound - the sounding of that particular note at the volume determined by the force. A gestural instrument, in comparison, is the continuous keyboard discussed later in the thesis. On the continuous keyboard, the striking of a particular spot on the control surface could trigger the playing of a sound of many different pitches, timbres, or volumes, since the sound is produced electronically based on whatever set of characteristics is desired for that particular set of coordinates.

A comprehensive cataloguing of gestural musical instruments, even within the last twenty years, is not within the scope of this thesis. Rather, I have attempted to pick a few examples which begin to show the variety of gesture captured, and the diversity of contexts in which musical and technological innovators see their work. To do this, I reference several recent patents as well as current work occurring at the MIT Media Lab. Finally, I discuss some of the advantages and disadvantages of gestural instruments as compared to traditional instruments.
The finger musical instrument is designed to be a portable, interactive toy which increases children's interest in music. The novel aspect of the invention is not a new method of sound production itself - the instrument in the present embodiment encompasses a range of three octaves of the diatonic scale, produced electronically. Rather, instead of pressing a lever which causes a hammer to strike keys (in a piano) or depressing a key which, through one of various means, causes an air flow to sound a pipe (in an organ), the battery-powered invention removes the necessity for an outside instrument beyond the gloves on the musician's hands. The familiar finger motions of playing a keyboard instrument now are directly mapped to the electronically produced notes as the pressure applied at the fingertip closes a circuit.

Schematics of the electronics are shown in Figure 1, a) with and b) without their accompanying gloves. The instrument consists of two double-layered gloves with a performance key (Figure 1b, K₁-K₁₀) at each fingertip and a soundbox (Figure 1a, 31 and 32; 81 and 82 on Figure 1b indicate the speakers only) on each glove. Each performance key contains two conductive elements separated by a flexible insulator; when pressure is applied to the glove tip the insulator is deformed and allows the conductive elements to make contact. Each glove also has a combination key (Kₐ and Kᵦ) positioned at the palm heel, as well as a controller (Figure 1b, 91 and 92) and a range selection switch. When the range selection switch is set to the lower option, the performance keys K₁-K₅ correspond with the notes c, d, e, f, and g, respectively, and the performance keys K₆-K₁₀ with the notes c¹, d¹, e¹, f¹, and g¹, respectively. The last three notes of each scale (a, b, and c¹ or a¹, b¹, and c²) correspond respectively to the first three

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In this and all references up to and including that for the Continuous Music Keyboard, the site referenced after the instrument title should be assumed to be the source for both the information (but not the text itself) about the instrument and for all figures corresponding to that instrument, though the figures may be slightly edited from their original versions.
performance keys of each glove played with their respective combination keys. When the range selection switch is set to the higher option, the first glove corresponds to the scale from $c^1$ to $c^2$, and the second glove to the scale from $c^2$ to $c^3$.

**Figure 1:** A schematic view of the electronics in the finger musical instrument, a) with and b) without the double-layered gloves which encompass parts of them.
The controller, which is connected to the other electronic components by means of a soft circuit board, also has a selection switch which can be set to either performance mode, which would function as described above, or teaching mode, which would encompass additional functionality to help children learn new melodies through imitation.
MUSICAL ICE SKATES

Inventors: Valeri Nenov, Xiao Hu, Marie-Laure Leglise
Patent No.: US 7,673,907 B2
Date of Patent: March 9, 2010

The musical ice skates described in the patent and shown in Figure 2 are actually a kit which can be used to retrofit a pair of ice skates or rollerblades. (The implementation of the device will be described in terms of skate blades, but the rollerblades are analogous.) Like the finger musical instrument, their novelty is not in a method of sound production, but in the method of mapping gesture to sound. However, rather than being a child’s toy, the musical ice skates are intended to add a live musical dimension to amateur or professional skating, or to be a musical feedback tool about a skater’s form to supplement or replace some coaching of the performer.

Figure 2: The right skate: the blade bracket (110) supports the tilt sensor (121), while the motion sensor (120) and the logical module (200) are attached to the boot itself. The speaker (250) is one of several sound output options.

A pair of ice skate blades can be described by the adjectives right or left, forward or backward, and outside or inside. Therefore, there are eight distinct edges (left forward outside, right forward inside, left backward inside, and so forth) which can be sensed and mapped to the notes of a diatonic (or any other eight-note) scale. Figure 3 shows several different possibilities for a diatonic mapping, with the preferred correspondence bolded.

<table>
<thead>
<tr>
<th>Notes</th>
<th>Edges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Do (C)</td>
<td>LFO LFO LFO LFO LBI LBI LBI LBI</td>
</tr>
<tr>
<td>2 Re (D)</td>
<td>RFI RBO RFI RBO RFI RFI RBO RBO</td>
</tr>
<tr>
<td>3 Mi (E)</td>
<td>LBI LBI LBI LFI LFO LFO LFO LFO</td>
</tr>
<tr>
<td>4 Fa (F)</td>
<td>RBO RFI RBO RFI RFI RBO RFI RBO</td>
</tr>
<tr>
<td>5 Sol (G)</td>
<td>LBO LFI LFI LBO LBO LFI LFI LBO</td>
</tr>
<tr>
<td>6 La (A)</td>
<td>RBI RBI RBI RBI RBI RBI RBI RBI</td>
</tr>
<tr>
<td>7 Ti (B)</td>
<td>LFI LBO LBO LFI LFI LBO LBO LFI</td>
</tr>
<tr>
<td>8 Do' (C')</td>
<td>RFO RFO RFO RFO RFO RFO RFO RFO</td>
</tr>
</tbody>
</table>

*Figure 3:* Several possibilities for edge-to-note mapping; the preferred option is bolded.

Detecting these edges requires a set of sensors on each skate. Forward or backward motion is detected by a motion sensor (Figure 2 120) which may be a pressure, optical, or other type of sensor. Tilt sensors (Figure 2 121) are supported by a bracket (Figure 2 110) clipped to the blade; they measure the blade's degree of lean by infrared distance measurements or other means. These inputs are interpreted by a logical module (Figure 2 200), and the sound is played through speakers (Figure 2 250), headphones, or through an outside sound system via wireless broadcast. The device is battery-powered and includes synthesizer and calibration controls. (The calibration controls are particularly important, as ice conditions may affect sensor thresholds.)

Other musical elements can be incorporated into the system without addition of further sensors or electronics. For example, Figure 4 shows how the blade angle, already measured by the tilt sensor to detect inside or outside edges, can be mapped to dynamic level (loudness) of the pitches played. Additional motion sensors could allow the detection of fast clockwise or counterclockwise turns, which in turn could be used as a switch between the notes corresponding to a piano’s white keys (the diatonic scale in C major) and a piano’s black keys (the omitted half-steps.) Alternately, additional position sensors would allow chromatic notes to be mapped to
logic involving the relative positions of the feet to one another. An octave selector switch could be incorporated into gloves worn by the skater or a flex sensor under the arms of the skater such that the position of the arms relative to the torso determines the octave of the pitches played.

<table>
<thead>
<tr>
<th>Level</th>
<th>Angle (degrees)</th>
<th>Notation</th>
<th>Description</th>
<th>Relative loudness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45</td>
<td>fff</td>
<td>Fortississimo</td>
<td>Super loud</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>ff</td>
<td>Fortissimo</td>
<td>Very loud</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>f</td>
<td>Forte</td>
<td>Strong</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>mf</td>
<td>Mezzo-forte</td>
<td>Half-strong</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>n</td>
<td>normal</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>mp</td>
<td>Mezzo-piano</td>
<td>Half quiet</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>p</td>
<td>piano</td>
<td>Softly, quietly</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>pp</td>
<td>pianissimo</td>
<td>Very softly</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>ppp</td>
<td>pianississimo</td>
<td>Almost audible</td>
</tr>
</tbody>
</table>

Figure 4: A suggested mapping of blade angle to dynamic level: the farther the skater leans, the louder the pitch played.
YAMAHA MIBURI

Yamaha’s Miburi system is a natural extension of the gestural ideas explored in both the finger musical instrument and the musical ice skates, though it preceded them by several years. Introduced in 1997 and marketed in Japan, the system uses a vest containing sensors at the shoulders, elbows, and wrists, as well as hand buttons and shoe inserts to map body movements to music played through a speaker. The system allows not only for selection of pitches, but also for timbral modification and pitch bending. Figure 5 shows the system’s wearable components as well as a user in action.

Figure 5: The Yamaha Miburi music system, shown in its constituent parts and (inset) in action.

CONTINUOUS MUSIC KEYBOARD

Inventor: Lippold Haken
Patent No.: US 6,703,552 B2
Date of Patent: March 9, 2004

The continuous music keyboard gains its name from its resemblance of a traditional keyboard both in size and the ten-finger technique by which it may be played, as shown in Figure 6. However, "keyboard" is somewhat misleading— the instrument does not have any discrete keys. Rather, the instrumentalist depresses a control surface (2 on Figure 6) which is sensitive to three parameters for each finger on the surface: X, or left-to-right position; Y, or front-to-back position; and Z, depth of depression or pressure. These degrees of freedom can be linked to any

Figure 6: A person playing a continuous music keyboard (1) through interaction with the control surface (2), using the marked pattern (3) as a pitch reference.

desired musical parameters, though the most common and intuitive would be pitch, timbre, and volume, respectively. (If the X coordinate is linked to pitch, the suggested sensitivity is 160 cents per inch, meaning that the sizes of a continuous keyboard and a traditional keyboard with identical ranges would roughly correspond.)

The keyboard is constructed of many thin, parallel rods (31 or 36 in Figure 7). A magnet (32, 37, or 49) is mounted at each end of every rod, allowing displacement of the rods to be

![Diagram](image_url)

**Figure 7a)** A cutaway view of the slender rods (31) which underlie the control surface (33). **b)** A top view of three rod-ends (36) and their guiding pins (38 and 39). **c)** An end view of one rod (36), with its pins (38 and 39) and supporting spring (47).
measured by stationary Hall-Effect sensors (34). Vertical displacement of both ends of the rods is guided by a system of pins (38 and 39) and springs (35 or 47) which are perpendicular to the rods.

Once every few milliseconds, a controller attached to the control surface collects data about rod displacements from the Hall-Effect sensors. X and Z values for each detected finger are determined by calculating the shape of a parabola through three (or more) consecutive depressed rods, as in Figure 8. Since the minimum of this parabola need not be exactly aligned with a rod, these coordinates can be calculated with much greater accuracy than the spacing of the rods themselves. The Y coordinate is calculated from the ratio of normalized displacements of the two sides of the rods impacted by a particular finger- if the top of the rods is further depressed than the bottom, the finger must be above the midway point on the rod, and vice versa.

![Diagram](image)

**Figure 8:** Using the displacements of three or more rods to calculate a parabola, which in turn yields the precise X and Z coordinates. In this example the minimum of the parabola, indicated by the arrow, is located just to the left of the most-displaced rod.

Once each set of coordinates is calculated, it is compared to a set of predicted values calculated from one-, two- or three-dimensional derivatives of the positions associated with previously-detected fingers. If the two sets of coordinates match, the calculated coordinates become the new value for that finger. If the calculated values do not match any predicted values, a new finger is added. If a set of predicted values do not match any set of calculated values, that previously-detected finger is removed. In this way, the performer can change pitch, timbre, and volume (or whatever other sound qualities are mapped to the X, Y, and Z coordinates) in a smooth, continuous fashion. Furthermore, a skilled performer could simultaneously increase the volume of some notes, while decreasing the volume of others, for example.
DEATH AND THE POWERS

One division of the MIT Media Lab whose research is particularly relevant to the topics of music and gestural mapping is the Opera of the Future, or Hyperinstruments, group, led by Professor of Music and Media Tod Machover. As the group describes its work,

Through the design of new interfaces for both professional virtuosi and amateur music-lovers, the development of new techniques for interpreting and mapping expressive gesture, and the application of these technologies to innovative compositions and experiences, we seek to enhance music as a performance art, and to develop its transformative power as counterpoint to our everyday lives. For example, one of the group's past large-scale projects was the Toy Symphony, which involved both professional musicians on traditional instruments and gestural instruments with which

Figure 9: Instruments involved in Tod Machover's Toy Symphony project: a) Beatbugs and b) Music Shapers

children could interact with the music. Shown in Figure 9 are Beatbugs, which can create and manipulate rhythmic motives, and Shapers, which shape “high-level musical parameters such as contour, timbre, density and structure” by measuring how and how much the instruments are squeezed\(^\text{10}\).

A current major project of the Opera of the Future group, however, takes the idea of gestural mapping much further than toys which can be tapped or squeezed to make or adjust sounds. *Death and the Powers* is an opera composed by Tod Machover which “tells the story of Simon Powers, a successful and powerful businessman and inventor, who wants to go beyond the bounds of humanity\(^\text{11}\).” This desire leads him to create “The System,” physical objects which become animated with his consciousness, preserving his “essence and agency” after his physical death\(^\text{12}\). Simon himself enters The System during Scene I; thus, for the majority of the opera, the actor-singer portraying the main character is offstage. However, he still maintains an active presence in the story, and, indeed, the plot revolves around his continuing relationship, through The System, with the outside world.

This offstage performance is an artistic and technological challenge which is addressed through techniques developed in a research area the Opera of the Future group calls “Disembodied Performance.” In Disembodied Performance, the behavior and emotional state of the performer must be sensed, interpreted, and mapped to its onstage embodiment—this instance, “The System,” with its “robotic, visual, and sonic elements\(^\text{13}\).” The measurement is achieved by means of various sensors, some of which are shown in Figure 10. The sensors include accelerometers on the forearms and hands, a wearable breath sensor, and foot pressure sensors. Cameras are used for visual tracking of the position of LEDs near the accelerometers, as it is difficult to accurately integrate the accelerometer data to find instantaneous position. Finally, Simon’s voice is analyzed for its amplitude, instantaneous frequency, and “consonance:” whether the voice is producing only one note and its overtones, as in a pure singing tone, or producing many different frequencies, as in speaking. Though the actor portraying Simon is

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\(^{10}\)“Music Toys.” Toy Symphony. http://www.toysymphony.net/


offstage, the sensors are designed to be as unencumbering as possible to allow him to act as he would were he onstage immediately in front of an audience; the intention is not that he consciously try to control The System. The specific mapping of gesture to emotional states ventures into the field of psychology and is described in some detail in Peter Torpey's thesis about Disembodied Performance. The mapping of emotional states to the stage obviously depends upon many choices made by the director, artistic director, set designer, and other personnel for its implementation. In this staging of this production, the gestural mapping has moved past the idea of gestural mapping purely of music and sounds, and incorporates robots, other moving set pieces, and lights as well (though the sensors do also affect the processing of Simon's voice before it is heard by the audience.)

![Image](image_url)

**Figure 10:** James Maddalena, the baritone portraying Simon Powers, and some of the sensors which transmit his performance from backstage.

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One particularly interesting set piece through which Simon communicates from offstage is the Chandelier—though it seems like a sculpture or actual chandelier in Scene I, after Simon enters the System it becomes associated with his voice. The Chandelier, as shown in Figure 11, is a pitched, stringed instrument, whose many strings can be actuated by electromagnets vibrating at the fundamental or a harmonic of each particular string. In this way, the Chandelier is different from many of the instruments already discussed— it is gestural in that the movements or voice of an offstage operator can be mapped to its music, but it is not simply a computer which produces predetermined electronic tones. It is a physical instrument producing sound (though the vibration is translated back to audio signal by means of guitar pickups), and for this reason it can simultaneously be played by a remote and a tactile performer. Options open to the tactile performer include “touch[ing] an actuated string, damping it, changing its length, or touching a node to produce a harmonic” as well as simply plucking or hitting the strings.\(^{17}\)

\[\text{Figure 11: The Chandelier, a setpiece and musical instrument, encompassing the wife of Simon Powers.}^{18}\]


\(^{18}\) “Gallery.” Death and the Powers: A New Opera by Tod Machover.  
Discussion and Analysis

Gestural instruments have some clear advantages over their traditional counterparts, some of which have already been noted in the preceding descriptions. Some, such as the Finger Musical Instrument or the Musical Ice Skates, allow people to bring music into situations where it would be inconvenient or impossible to use traditional instruments. Instruments such as the Finger Musical Instrument or the Continuous Music Keyboard allow, respectively, a child to independently begin exploring diatonic melodies while or before being introduced to an instrument, or an adult to intuitively control volume, timbre, and indiscrete pitches without having mastered a fretless string instrument.

The gestural instruments have several disadvantages as well, though some are more subjective than others. Unless the instrument achieves a high degree of complexity (compare the Finger Musical Instrument to the Continuous Music Keyboard), a performer with a basic level of competency on a traditional instrument will probably have a greater range of pitches, timbres, or perhaps volumes with which to work. Further, many people prefer a timbre which sounds “real” rather than “electronic;” for this reason, makers of many electronic instruments spend a great deal of time and energy gathering sound samples from their instruments’ acoustic counterparts (electronic vs. pipe organs come to mind.) Sometimes the electronic sound becomes an artistic choice on the part of musicians or directors, as in the case of *Death and the Powers*. In his thesis, Peter Torpey admits that the use of sound reinforcement (vocal processing) in an operatic context is “controversial,” yet he argues that such a choice makes sense on a practical level, to blend the voices with electronic and electronically amplified instruments in the orchestra, and to reinforce the theatrical reality which is The System\(^{19}\).

Another possible disadvantage of gestural instruments is a loss of connection to and intuition of the sound. For example, it is obvious to a violinist and most people watching him or her that the position of the fingers on the left hand correspond to pitch, and that “wobbling” this position therefore causes vibrato. However, a gestural instrument, in order from worst- to best-case scenario: might not have this capability at all, leading to a loss of flexibility and creativity; or might have the capability, but mapped to a completely different gesture (pressing a pedal, for

\(^{19}\) P. Torpey. “Sound in Space.” *Disembodied Performance: Abstraction of Representation in Live Theater.*
example) or finally might have the capability, but mapped to a gesture which is only intuitive with relation to the instrumentalist’s prior knowledge of the acoustic instrument. (Wobbling a finger back and forth on the Continuous Music Keyboard is a bit like wobbling a finger back and forth on the violin, but it is not intuitively obvious why changing the X coordinate detected by Hall-Effect sensors ought to produce vibrato.)

The work of Tod Machover creates new categories for itself. He uses gestural mapping, but for combined musical and theatrical affects. On one hand, it is easy to see how this research has varied and useful applications outside the theater (remote robotic control comes to mind.) On the other hand, one could imagine scenarios in which its use within the theater, even in an opera whose focus is the technology itself, could distract from rather than enhance the skill and artistry of performers and composer. (Peter Torpey himself speaks of “maintain[ing] a compelling experience despite technology” [emphasis mine]20.) That question will be presented to audience assessment when the opera opens in Monte-Carlo in the fall of 2010 and during its subsequent planned tour. On a practical note, however, it seems that “this story... will reach audiences of all ages and backgrounds, and will catapult live performance, creative expression, and artistic technology far into the future, in bracing, expectation-defying, and moving ways” is perhaps too lofty a goal for an opera whose technological requirements preclude its performance by all but a few organizations21.

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