Gesture-Sensing Technology for the Bow: A Relevant and Accessible Digital Interface for String Instruments

Boyt
GESTURE-SENSING TECHNOLOGY FOR THE BOW: A RELEVANT AND ACCESSIBLE DIGITAL INTERFACE FOR STRING INSTRUMENTS

by

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Technological advances in powerful, miniaturized electronics have created a growing potential to continue the evolution of string instruments through an accessible digital interface. Although many new types of instruments and controllers have explored this goal, gesture-sensing technology, when paired with the expressive nature of the bow, has provided the most eligible solution towards bridging technology and tradition. Through a selective showcase of technical development, artistic application, and future possibilities, this thesis traces the evolution of gesture-sensing bow technology as an accessible digital interface in string instrument performance.
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# TABLE OF CONTENTS

ACKNOWLEDGMENTS ........................................................................................................ ii
DEFINITION OF TERMS ......................................................................................................... v
LIST OF FIGURES .................................................................................................................. vi

CHAPTER

1. INTRODUCTION .................................................................................................................. 1
   Narrowing the Scope ........................................................................................................... 1

2. EVOLUTION OF THE TECHNOLOGY ................................................................................ 4
   The MIDI Bow ...................................................................................................................... 4
   Hyperstrings of the MIT Media Lab ................................................................................... 9
   The Hypercello .................................................................................................................... 9
   Going Wireless with the Hyperviolin ................................................................................. 13
   New Generation Hyperstrings and the Hyperbow ............................................................. 15
   The Overtone Violin .......................................................................................................... 22
   The Augmented Violin of IRCAM .................................................................................... 27
   The K-Bow ........................................................................................................................ 34
   Conclusion .......................................................................................................................... 43

3. PERFORMANCE APPLICATION ...................................................................................... 45
   Developing the Hypersolo Voice ....................................................................................... 45
   The Improvisations of Jon Rose ....................................................................................... 45
Table of Contents—continued

The Hyperstring Works of Tod Machover .......................... 48

Hyperstring Trilogy .................................................. 49
Toy Symphony ....................................................... 54

MIT’s Collaboration with The Royal Academy of Music ...... 55
Gaia Sketches by Patrick Nunn ..................................... 56

Hyperchamber Music .................................................. 56

The Augmented String Quartet ....................................... 57
StreicherKreis by Florence Baschet ............................... 58
Douglas Quin’s Polar Suite .......................................... 59

4. CURRENT CHALLENGES ............................................. 62

Repeatable Repertoire .................................................. 62
Role of the Performer .................................................. 64
Future Technology and Research .................................... 66

BIBLIOGRAPHY .......................................................... 69
DEFINITION OF TERMS

**Accelerometer** – a device used to detect the non-gravitational acceleration of an object.

**Bluetooth** - a wireless technology communication standard for exchanging data over short distances.

**Force Sensing Resistor (FSR)** – a device made of a conductive polymer that produces measurable changes in resistance as force or pressure is applied to its surface.

**IRCAM (Institut de Recherche et Coordination Acoustique/Musique)** – a music research institution founded in Paris in 1977 known most for explorations in electroacoustic art music.

**Max** - a visual object-based programming language used most commonly for music and multimedia production currently developed and maintained by Cycling 74’.

**MIDI (Musical Instrument Digital Interface)** – a communication protocol standardized in 1983 and used primarily as a compact common language between digital instruments to convey musical variables such as pitch, velocity, and duration.

**OSC (Open Sound Control)** – a communication protocol developed for computers and multimedia devices in the late 90’s often used as a more powerful and expressive alternative to MIDI.

**PCB (printed circuit board)** – a sheet of non-conductive material laminated with an etched layer of conductive material, most often copper, providing connections between various electrical components.

**STEIM (STudio for Electro Instrumental Music)** – a research center founded in Amsterdam in 1969 devoted to the development of new musical instruments.
# LIST OF FIGURES

1. Jon Rose with his second generation MIDI Bow at STEIM – 1989 ............... 7
2. Jon Rose’s MIDI Bow – Update 3 ................................................................. 8
3. Jon Rose’s MIDI Bow – Update 4 ................................................................. 8
4. The Hypercello instrument system ............................................................... 10
5. Block diagram of bow placement and position sensors ............................... 13
6. The Hyperviolin with a wireless gesture-sensing bow .................................. 14
7. Diana Young’s second prototype with electronics mounted at the tip of the bow ............................................................................................................. 17
8. Diana Young’s third prototype with electronics mounted at the frog of the bow ............................................................................................................. 17
10. The “playable measurement system for violin bowing” developed by Diana Young .................................................................................................. 22
11. The body and various input sensors of the Overtone Violin .................... 23
12. The USB RF receiver and nylon glove with sewn in sensors .................... 24
13. The custom carbon fiber bow of the Overtone Fiddle ............................... 26
14. The first version of the gesture-sensing Augmented Violin project developed at IRCAM ............................................................................................ 29
15. The position sensor antennae of the Augmented Violin ......................... 29
16. The second version of the gesture-sensing Augmented Violin project developed at IRCAM without foam padded housing ................................. 30
17. The “bow force sensor” developed for the third version of the Augmented Violin project. Seen here without foam housing ............................... 31
List of Figures—continued

18. The third version of the Augmented Violin project................................. 33
19. Graphic representation of the variables measured by the K-bow............... 35
20. The exposed electronics housed within the frog of the K-bow .................... 38
21. A cross section diagram of the K-bow’s grip sensor............................... 39
22. The K-bow PCB fingerboard attachment .................................................. 40
CHAPTER 1
INTRODUCTION

The modern violin family as it is known today evolved from a rich history of technical innovation. Although many improvements have been made in the last century concerning the smaller mechanics of the instrument (strings, tailpiece, etc.), innovations in the primary design of the instrument were well established by the end of the nineteenth century. The advancement of the digital age however, has provided new opportunities for innovations in creative expression of string instruments.

Narrowing the Scope

The technology available in the last fifty years has created a seemingly limitless potential in reinventing the interface of the violin. My original quest in researching the digital hybridization of string instruments led me to a plethora of experimental instruments and institutional research. A sub-categorized listing of new digital musical instruments related to string instruments has been provided in *Violin-Related HCI: A Taxonomy Elicited by the Musical Interface Technology Design Space*¹:

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1. Instrument-like controllers (interfaces resembling existing instruments)
   a. Instrument-simulating controllers (mirroring playing techniques)
   b. Instrument-inspired controllers (abstractly derived techniques)
2. Augmented controllers (traditional instruments augmented with sensors)
   a. Augmented by capturing traditional techniques
   b. Augmented through extended techniques
3. Alternate controllers (interfaces not resembling existing instruments)
   a. Touch controllers (require physical contact with control surface)
   b. Non-contact controllers (free gestures – limited sensing range)
   c. Wearable controllers (performer always in sensing environment)
   d. Borrowed controllers (VR interfaces, gamepads, etc.)

While many of these new technologies are worthy of exploration, few are reproducible in string instrument performance beyond their origins of creation. There stands a need for a balance between the limitless potential of new digital interfaces and the time-honored tradition of string instrument performance technique. The question is, which human-computer interface provides the greatest potential towards the evolution of creative expression in string instrument performance? Through my research I have found gesture-sensing bow technology, when paired with traditional instruments as in categories 2a and 2b in the list above, to be the most eligible solution.

Gesture-sensing bow technology involves any number of sensors used to measure motion, relative position, exerted pressure, or any additional actions used in
bowning an instrument. Data gathered from these sensors can then be applied as elements of extended performance.

This thesis traces the evolution of gesture-sensing bow technology as it became more efficient, responsive, and capable of offering new possibilities for artistic expression that are more integrated with traditional string technique. Chapter 2 surveys key projects and improvements in accessibility and performability. Chapter 3 examines various artistic applications of this technology. Chapter 4 provides a commentary on the current state of the technology and its possibilities for future development and more widespread adoption.
CHAPTER 2

EVOLUTION OF THE TECHNOLOGY

Gesture-sensing technology applied to string instruments has taken a variety of forms throughout its development. Jon Rose and Tod Machover both claim to be the first to apply gesture-sensing technology to string instruments, but regardless of who was first, the variety of experimentation led by these two individuals inspired numerous future projects that slowly evolved as related technologies advanced. The selections presented here offer a brief overview of the most progressive and well-documented cases of gesture-sensing technology as it has been applied to string instruments.

The MIDI Bow

Composer, inventor, and violinist Jon Rose has been one of the most prominent figures in the promotion and development of gesture-sensing bow technology. His first experiments in 1985 at STEIM (the Studio for Electro-Instrumental Music in Amsterdam, Netherlands) in the application of various sensors to violin bows mark one of the first recorded attempts towards performable gesture-sensing bow technology.

Rose has described early experiments involving “bar code, microphone triggers and putting a sensor actually in the wood of the bow – none really useful in
getting a varied and workable data stream.”\textsuperscript{1} The most promising prototypes involved the use of an ultrasound transducer. An offstage ultrasound receiver would provide measurements in location, which would then be converted into MIDI signals by a small microcomputer worn by the performer.

Additionally, a pressure pad taken from a MIDI keyboard and installed between the bow hair and the stick was used to measure hair tension. Without a system to calibrate sensory input however, the signal of the bow hair sensor was dependent on a variety of influences of humidity, hair tension, and differences in the force of each previous bow stroke in performance. Rose embraced the inconsistencies of this makeshift sensor in his unique improvisatory style, which will be discussed further in Chapter 3.

This first setup never included any form of visual feedback to the performer regarding how the MIDI data was being manipulated. Eventually, the technical uncertainties and limitations of this primary setup were too much, even for Rose.

Within a few years, I realized that this kind of headless “chook” (Australian for chicken) activity was going to shorten my life, hence the introduction of foot pedal controls, the change over from Ultra Sound to accelerometers and use of the infinitely programmable STEIM Sensor Lab.\textsuperscript{2}

The switch from ultrasound to accelerometers was a particularly important change. The previous ultrasound setup was dependent on nearby receivers and was liable to


\textsuperscript{2} Rose " (Rose, The Hyperstring Project: The New Dynamic of Rogue Counterpoint 2010)Bow Wow” 62.
signal interference. Accelerometers placed on the bow or bow hand measured motion of the sensor itself, rather than its placement between external receivers. These new developments increased accuracy in measuring movement and provided more reliable parameters of application.

In addition to the switch in motion sensors, Rose’s second-generation MIDI bow, built in 1989, included a pair of “mapping switches”, two small buttons within reach of the right hand of the performer. According to Rose’s documentation of personal communication with Chris Chafe, a fellow pioneer in experimental string instruments, the performance application of such a tangle of wires was less than exemplary. Chafe later switched to an alternative hardware, the Don Buchla Lightning, using infrared emitters attached to the wrist. Rose eventually modified his own setup in a similar way, as “it is easier to handle a bow with wires coming off a wrist controller than to handle a bow with wires attached to the frog.”

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Figure 1. Jon Rose with his second generation MIDI Bow at STEIM – 1989.\textsuperscript{4}

\textsuperscript{4} Rose, "Bow Wow," 62.
Jon Rose’s MIDI bow project has evolved over the course of two decades undergoing two presentable updates displayed in figures 2 and 3. The most recent form of the MIDI bow, listed on Rose’s website, includes two pressure sensors, two accelerometers, and his usual mapping switches. This design was constructed by Jorgen Brinkman in 2008 at STEIM.

**Figure 2.** Jon Rose’s MIDI Bow – Update 3

**Figure 3.** Jon Rose’s MIDI Bow – Update 4

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6 Ibid

7 Ibid.
Hyperstrings of the MIT Media Lab

Composer and inventor Tod Machover founded the Hyperstrings project at the Massachusetts Institute of Technology (MIT) Media Lab in 1986. The powerful research ability of the MIT Media Lab and the assistance of many specialized personnel led to a succession of projects involving gesture-sensing bow technology. Although a portion of MIT Media Lab’s work has been directed towards research in analytical measurement of physical performance subtleties, the overall approach of development has been towards application in performance.

The Hypercello

The Hypercello, developed 1990 - 91, was one of the earlier successes of the MIT Media Labs developments in Hyperstring technology. The project was a collaborative effort on behalf of Tod Machover and his team at MIT Media Labs combined with performance input of the world-renowned cellist, Yo-Yo Ma. Together they evaluated and adjusted “the efficacy and evasiveness of sensing technology, the appropriateness of mapping gesture to musical result, and the integration of hyperinstrument control to musical intention and performance expressivity.”8 The Hypercello was conceived and developed for the performance of Machover’s piece Begin Again Again..., written in 1991 for Yo-Yo Ma.

Through two years of development, the team at MIT produced a highly complex system of computers and custom electronics networked into one Hyperinstrument. A diagram of this system up can be seen in Figure 4. For the sake of the thesis at hand, this discussion will focus on the multiple sensory inputs of the gesture-sensing bow.

Figure 4. The Hypercello instrument system

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9 Machover, Hyperinstruments: A Progress Report, 51.
Similar to the experiments of Jon Rose, the MIT team sought sensor capability in elements of bow position and pressure exerted by the bow arm. In both cases however, the team at MIT chose different routes of achieving not only sensor capability, but as precise a measurement as possible. In Tod Machover’s *Hyperinstruments: A Progress Report*, many of the trials and choices made by the development team are explained in detail.

In regards to bow position, the MIT team explored many methods of short-range distance measurement including the previously mentioned technique implemented by Jon Rose of using ultrasound. Other methods explored include acoustic phase, infrared strength, inductance proximity, and microwave reflectivity. After ruling these options out based on the performance-based goals of precision, reliability, and light weight, the MIT team developed their own electric field position sensor using transmission of low frequency electromagnetic transmissions (radio frequencies). In *Musical Applications of Electric Field Sensing*, Joseph A. Paradiso and Neil Gershenfeld, two of the many contributors to the Hypercello, describe the technical process that led to this solution.\(^{10}\) The eventual outcome involved a 5 cm tall antenna mounted behind the bridge transmitting a radio frequency (RF) between 50 to 100 kHz. A resistive thermoplastic electrode strip ran the length of the bow. By measuring the resulting capacitive coupling between the two, an accurate measurement of bow placement could be achieved. This system greatly expanded the capabilities of measuring bowing gestures by adding both lateral and longitudinal

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position of the bow in relation to the instrument. Paradiso and Gershenfeld’s block diagram of this sensor system can be seen in figure 5.

Machover’s attempt at measuring bow pressure, or arm weight, is relatable to the previous implementation of hair tension sensors by Jon Rose. The MIT group had also considered using hair tension as a measurement for bow pressure, but decided to avoid directly sensing hair tension and instead measure the pressure produced directly beneath the player’s hand. Machover explained this decision with the following reasons: “(1) it does not require re-hairing the bow, and (2) the finger pressure contains the same information as the bow hair tension, but can also be controlled independently (depending on whether the fingers torque or compress the bow).”

After experimenting with various previously implemented sensor options, including piezoelectric sensors, force-sensing resistors, and piezoresistors, the team again decided instead to build its own sensor system using capacitance measurement.

The most visually notable among MIT’s endeavors is the exoskeleton type wrist sensor, called the Wrist Master, made by Exos, Inc. This glove-like fitting uses magnets and hall effect sensors to measure changes in the angles of wrist joints. By measuring subtle wrist gestures, the computerized counterpart of the Hypercello instrument could recognize the performers differences in bowing style. The process of sensing wrist movement offered yet another element of bowing gesture measurement.

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Going Wireless with the Hyperviolin

Although a similar instrument setup to the Hypercello was adapted for the viola, the MIT team decided to pursue a cordless bow in the sensor bow’s adaption for violin. The first approach involved passive measurement of bow position and placement by including both the antenna and electrode on the violin and only a

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12 Paradiso, "Musical Applications of Electric Field Sensing," 73.
passive resistive strip on the bow. After failing to acquire an accurate measurement in this method, the team turned to the idea of reversing transmit and receive functions of the bow and the instrument. This proved to provide much more accurate of a result, but created a few new obstacles. The previously used capacitor measurement system for bow pressure was no longer accurate in this setup. It was instead replaced with a piezoresistive strip, the measurement then transmitted via a second bow antenna. The needed power supply for bow transmission also added some difficulty. A small six-volt battery attached to the frog inevitably added undesired weight to the bow. The MIT team acknowledged how “this system, while usable, does modify the playing characteristics of the bow.”

Figure 6. The Hyperviolin with a wireless gesture-sensing bow.

While the added battery weight may be seen as a sacrifice, the added wireless ability marked a huge leap forward in the performability of gesture sensing bows.

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13 Paradiso, "Musical Applications of Electric Field Sensing," 78.
New Generation Hyperstrings and the Hyperbow

After a few years hiatus in Hyperstrings development, The MIT Media Lab picked up where it left off under the initiative of Diana Young, then a Masters and PhD student of MIT. This new initiative, titled *New Generation Hyperstrings*, roughly spanned from 2000 to 2009 and included numerous updates and advances in sensor bow technology. Of these many updates, those discussed here involve the addition of accelerometers, wireless transmission, weight distribution of the electronics, and power consumption. The majority of bow position and placement work from previous projects was kept intact.

Diana Young approached the obstacles of pressure sensors and additional weight across three Hyperbow prototypes. Young’s experimental process is described in detail in *New Frontiers of Expression Through Real-Time Dynamics Measurement of Violin Bows*.\(^\text{15}\) Rather than measuring strictly downward force using the previous Hypercello methods of capacitance sensors, the use of strain gauges was used instead. These thin, fragile sensors, when carefully attached, measure the minute expansion and compression forces of an object. In comparison to the previous methods of measuring bow pressure with the Hypercello, the use of strain gauges, although possibly more accurate, do not offer Machover’s previously discussed possibility of independent index finger triggering by the performer. Still, the lateral force sensing was shown to be effective in representing wrist angle, giving a possible replacement.

to the Wrist Master used with the Hypercello.

With a strong focus in efficient performance use, Young gave much consideration to the weight, position, and balance of the additional electronics to the bow. The second prototype included six strain gauges, position sensing hardware, and two accelerometers. When combined with the onboard battery, this created a significant addition in weight and bulk. The first approach to this involved attaching a significant portion of the electronics near the tip of the bow in order to avoid physical contact with the instrument at the frog (see Figure 7). This proved to be rather uncomfortable to the performer. Additional weight at the tip creates more strain on the right hand, leading to fatigue over time. With the elimination of four of the strain gauges the weight and size of the circuit board decreased, allowing for replacement at the frog in the third prototype (see Figure 8). The decrease in the number of sensors also helped with power consumption, allowing for the future possibility of a smaller battery.

Young’s focus on the use of strain gauges, combined with the addition of accelerometers, shows a new appreciation in the gesture-sensing world for the extreme subtleties of bow technique. The fragility of the strain sensors and their accompanying wires are the only major disadvantages. She remarked how “the presence of wires on the bow is one of the greatest disadvantages to this sensing system, as they represent possible points of vulnerability of the system as well [as] discomfort for the player.”¹⁶

¹⁶ Young, “New Frontiers,” 68.
At first glance, the frog of the Hyperbow may also look quite uncomfortable. However, it was noted by Young and other violinists that “the presence of the bow board on the frog was easily tolerated, as the fingers of the right hand have no cause to come into contact with the side of the frog closest to the player.”

Figure 7. Diana Young’s second prototype with electronics mounted at the tip of the bow

Figure 8. Diana Young’s third prototype with electronics mounted at the frog of the bow

17 Young, “New Frontiers,” 68.
18 Young, “New Frontiers,” 48-49.
Continuing the previous efforts of increased performability, the hyperbow also increased in wireless ability. An RF transmitter, on stage with the performer, sent the gathered sensor data to an offstage RF receiver connected to the computer via USB. Although the violin was still tethered to an external transmitting device, direct connection to the processing computer was no longer needed.

It is important to note that the New Generations Hyperstrings project not only involved technological updates, but also represented a significant shift in approach in working with sensor bow technology. Previous MIT projects involved very large and complex systems of performance and gesture analysis of an entire instrument setup, whereas Young’s initiative focused primarily on the bow. The subject of research was re-named from Hypercello or Hyperviolin to the Hyperbow. The electromagnetic field sensing frequencies used in the Hypercello, were re-used in the Hyperbow, allowing for compatibility with existing hardware developed at MIT. The addition of small LEDs indicating power and signal strengths provided a visual interface between performers and hardware. All of these advancements, though small, represent the specification of the bow as the most eligible and accessible method of gesture sensing hybridization.

Adaptions for Collaboration with Royal Academy of Music

Continuing with the goal of increasing expressive performability of gesture-

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sensing bow technology, Diana Young and the New Generation Hyperstrings team initiated collaboration with the Royal Academy of Music (RAM) in 2005. The goals of this collaboration were to help strengthen the role of the Hyperbow in performance by building repertoire and enabling performers. Placing the Hyperbow in the hands of unassociated performers and composers and educating them on its use could then establish the Hyperbow as a qualified instrument. Those involved from RAM included a handful of composers and cellists.

Although the original gesture-sensing bow developed at MIT was designed for use with a cello, the New Generations group had made significant changes and adaptations in its approach with the Hyperbow for violin. As a result, the Hyperbow had to be revised for use with acoustic cellos.

Figure 9. The New Generations hyperbow revised for acoustic cello.  

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The small revisions necessary included increased amplification of the electronic field positioning sensor to accommodate greater bridge distance, and the mounting of the receiving position sensor antenna to the underside of the tailpiece.

The collaborative nature of this project opened the door to many new ideas and solutions to previous obstacles. Taking the bow out of the lab and putting it into the hands of trained performers allowed for much more of a hands-on approach towards specifically desired elements of physical set up. This was most apparent in the repositioning of the receiving position sensor antenna. Performers were documented as preferring the antenna to be attached to the strings just under the bridge, much closer to the bow than before. The fine-tuning of this sensor for the sake of gestural accuracy in performance was a successful technological adaptation brought about by this collaboration.

Further Research

It is important to note that MIT Media Lab work with evolving gesture-sensing bows for the sake of performance effectively tapered off following the end of the RAM collaboration. Diana Young did continue to develop the hyperbow technology, but strongly in the direction of concentrated measurement and analysis.\textsuperscript{22} Although this new system was designed with performability in mind (mostly in terms of weight and balance of the bow), its laboratory setting took a few steps back in the evolution towards performance. Wireless capability from the violin to the computer

\textsuperscript{22} Young, “A Methodology for Investigation of Bowed String Performance,” 45.
for example, was not necessary with such a stationary setup. The increased data bandwidth needed for such detailed measurement required a direct cable connection from the electronics on the violin to the computer. An electric violin was also used in order to accommodate the needs of the measurement system. This eliminated one of the most important accomplishments of the previous hyperbow; increased accessibility by versatility of installation on any acoustic instrument.

The detail of measurement needed in this new setup did however facilitate a handful of positive advancements in sensor bow technology. A second PCB complete with accelerometers and gyroscopes was attached to the violin and gyroscopes were also added to the bow. The comparison between the two allowed for much more accurate calculation of bow position and movement. The previous electric field sensing system of the hyperbow was also upgraded to include four receiving antennas on the violin, further improving accuracy of bow position. The previous hyperbow achieved wireless communication of motion and downward force between the bow and the computer via RF. In this new measurement system, wireless communication between the bow and the violin PCB is instead achieved through the more standardized Bluetooth.

Although the goals of capturing the furthest limits of human performance with this measurement system have created a less practical performance setting, the published application of new technology has helped set the stage for further developments towards performance by others.
The Overtone Violin

The Overtone Violin was developed in 2004 by Dan Overholt in collaboration with the Center for Research in Electronic Art Technology (CREATE) and STEIM. It is a “radically augmented musical instrument” combining “both a traditional (electro-acoustic) violin, and a gestural computer music controller.” The instrument as a whole is an impressively complex collection of sensors and electronics built in to the body of an electric violin. An image of the instrument without the bow can be seen in Figure 11. For the sake of the thesis at hand, we will focus on the gesture sensing electronics built for the bow.

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The Overtone Violin includes two elements of bow gesture sensibility; movement via a dual axis accelerometer, and bow position via passive ultrasonic technology. The use of bow position measurement through passive ultrasound is similar to Jon Rose’s first MIDI bow prototype developed at STEIM. In this case, the receiving transducers were placed directly on the violin, improving accuracy in measuring minute gestures. The sonar emitting transducers, along with the dual-axis accelerometer, are sewn into a fingerless nylon glove worn on the bow hand of the performer. This creates both new opportunities and issues. Most notably, it frees the performer from dealing with an instrument specific, bulky, and sensor cluttered bow; any bow can be used. On the negative side, the glove’s embedded sensors communicate with the violin by a mini-XLR jack located on the right side of the instrument. The cable connecting the glove to the violin, combined with the general act of wearing a glove while playing, could be irritating to the performer.

Figure 11. The body and various input sensors of the Overtone Violin.²⁵

Similar to MIT’s hyperbow, Overholt sought a more wireless performance system. The various sensors throughout the violin are translated by an onboard microcontroller and then sent via RF transmitter to an offstage RF receiver. The receiver then converts the data to USB protocol to be received by the computer. An image of both the glove and RF receiver can be seen in Figure 12.

In *The Overtone Violin: A New Computer Music Instrument*, Overholt explains the benefits of USB data transfer:

“This makes the task of communicating with software such as SuperCollider, Max/MSP/Jitter, Pd, etc. much simpler, because these programs already have built-in support for game controllers through the HID (Human Interface Device) drivers. The use of USB has several advantages over MIDI, such as lower latency, bus-power (no need for batteries or a power adapter), and simply not having to carry around a MIDI interface.”

Figure 12. The USB RF receiver and nylon glove with sewn in sensors.

The Overtone Fiddle, presented at the 2011 International Conference on New Interfaces for Musical Expression (NIME), continues on the advancements of its

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predecessor, the Overtone Violin. With this new instrument, Overholt chose to pursue a new direction from fully electric violin, to an Actuated Acoustic Instrument. This new setup involves routing a series of electronic sensors and pickups wirelessly through an iPod, which then resonates an acoustic chamber, both of which are mounted to the body of a custom built violin. The instrument in its entirety is worthy of its own full discussion, however, with this new knowledge in redirection of research, we will again focus on changes in the gesture-sensing bow.

Part of Overholt’s redirection with the Overtone Fiddle was focused on the complete inclusion and improved accessibility of the instrument in the hands of the performer, from sensor input to sound production. With this priority in mind, the gesture-sensing bow interface was redesigned for wireless communication. To achieve this, a custom, lighter than average, carbon fiber bow was used to accommodate the added weight of a battery powered circuit board, a wireless transmitter, and an absolute orientation sensor. These electronics were then mounted on the frog of the bow, rather than attached to a glove as with the previous Overtone Violin. Although this new setup provided both a wireless relationship with the violin, and more accurate orientation measurement, it resulted in a loss of previous independence of sensor capability from choice of bow enjoyed by the glove approach of the Overtone Violin.

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Figure 13. Left, the custom carbon fiber bow of the Overtone Fiddle, and right, from top to bottom, a wireless transmitter, absolute orientation sensor, and battery powered circuit board.²⁹

The movement and position sensor capability of the Overtone Fiddle was revised from the dual-axis accelerometers and ultrasound of the Overtone Violin, to an absolute orientation sensor, cited as acquired from CH Robotics.³⁰ This device includes three-axis accelerometers, gyroscopes, and magnetometers. Combining the orientation sensor’s own cross-calculations of its internal sensors with the measured values of internal accelerometers and gyroscopes of the iPod mounted to the violin body, a measurement of bow speed and position can be calculated. This system of combining accelerometers and gyroscopes on both the bow and the instrument is

²⁹ Overholt, “The Overtone Fiddle,” 5.
previously found on Diana Young’s “playable measurement system for violin bowing”.  

Finally, it is also important to note how the Overtone Fiddle, similar to the New Generation Hyperstrings of MIT, represents a shift in approach from the very complex new vocabulary of sensory input of the Overtone Violin, to a much more accessible gesture sensing system focused on more familiar bowing gestures.

The Augmented Violin of IRCAM

With a strong history of gesture sensing technology research, specialists at IRCAM (Institut de Recherche et Coordination Acoustique/Musique) followed MIT’s footsteps in creating their own gesture-sensing bow. The project, named the Augmented Violin, evolved through three prototypes.

The first system, built in 2004 by Emmanuel Flety, was heavily inspired by the Hyperbow of MIT. Using similar sensor systems for bow position, placement, and accelerometers, the only real variances from previous projects occur in bow pressure measurement and data transfer.

The method developed by the team at IRCAM of measuring bow pressure from downward force involved the reinstatement of a sensor located directly beneath the index finder of the right hand. In Gesture Analysis of Bow Strokes Using an Augmented Violin, the author explains: “Emmanuel Flety chose to add a force sensing resistor (FSR) on the bow to measure the downward force of the forefinger onto the

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31 Young, “A Methodology for Investigation of Bowed String Performance”.
stick. This solution had already been implemented in the HyperCello project.”

Tod Machover had indeed used this method of sensing downward force with the hyperviolin, however, the MIT team had originally ruled out the specific use of a FSR with the hypercello stating, “The problem with these devices is that the relation between conductivity and pressure is both noisy and hysteretic.”

IRCAM confirmed this when analyzing the measurement capabilities of the various sensors by explaining how “the sensors are not perfect as they may not directly give access to the desired parameter, add noise and have a definite resolution.”

The use of this sensor placement brought back the dual-use of this sensor. Similar to the Hypercello, this gave the performer the ability to manipulate the sensor as a natural process of drawing the bow, or as an independent trigger.

The Augmented Violin project also made headway in the area of data transfer. Rather than receiving data via USB, as previously done with the hyperbow and the Overtone Violin, Flety designed a new Ethernet based digitization device called the *EtherSense*. Combining data via RF from the bow, and direct cable from the position sensor, this device created a much larger data transfer at faster speeds, allowing for a more frequent sampling of gesture data, therefore a more accurate measurement.

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33 Machover. Hyperinstruments: A Progress Report, 56.
Figure 14. The first version of the gesture-sensing Augmented Violin project developed at IRCAM\textsuperscript{36}

Figure 15. The position sensor antennae of the Augmented Violin\textsuperscript{37}

In a publication titled \textit{The Augmented Violin Project: Research, Composition and Performance Report}, the team at IRCAM presented the second prototype of their

\textsuperscript{36} Rasamimanana, “Gesture Analysis,” 8.
\textsuperscript{37} Rasamimanana, “Gesture Analysis,” 8.
gesture-sensing bow. The main purpose of this update was to help streamline the bow’s bulk of electronic sensors into something more accessible to performers. This included a smaller radio transmitter, repositioning of the batteries and the second accelerometer to the side of the frog, and an added foam cover to reduce negative contact with the instrument. The result was a decrease in thickness and weight and an increase in battery life. The repositioning of electronics without the foam buffer can be seen in Figure 16.

*Figure 16*. The second version of the gesture-sensing Augmented Violin project developed at IRCAM without foam padded housing.

The evolution of IRCAM’s gesture-sensing bow continues in their April 2012


publication *The Augmented String Quartet: Experiments and Gesture Following*.\(^{40}\) In this article a handful of performance oriented updates are described. An additional accelerometer was added, giving three dimensions of measurement, as well as a dual-axis gyroscope. A “bow force sensor,” a leaf spring type sensor detecting bow pressure by pressing on the bow hair close to the frog, was also added. This sensor, developed by Matthias Demoucron, is thoroughly described in *Measuring bow force in bowed string performance: Theory and implementation of a bow force sensor*.\(^{41}\) A photo of this specific sensor can be seen in Figure 17.

*Figure 17.* The “bow force sensor” developed for the third version of the Augmented Violin project. Seen here without foam housing.\(^{42}\)


\(^{42}\) Demoucron, “Measuring bow force in bowed string performance.”
This third version of the Augmented Violin bow unfortunately shed sensing capabilities of bow position and placement on the string. This in turn created issues in calculating lateral force. The process of drawing the bow while playing any string instrument creates distance between the location of the sensor itself, in this case at the frog of the bow, and the point at which the force is applied, where the bow hair makes contact with the string. This creates problems in detecting the lateral force exhibited on the bow in real time. In order for an accurate calculation of force, some variable relating to the contact of the bow with the string must be known.

In the making of the bow force sensor, Demoucron described two methods of measuring lateral force without using previous methods of measuring bow position; through motion capture technology, or by using a second force sensor at the tip and calculating the difference. In The Augmented String Quartet: Experiments and Gesture Following, neither of these methods was used, presumably for the sake of simplicity while experimenting in the artistic field. The authors explain how their current “setup could not provide the bow position,” so instead they “used the raw value of this ‘bow force sensor’ without calibration. This value is thus not an absolute measure of the bow force, but a value that increases with the actual bow force and decreases with the distance between the bow frog and bridge.” Even with some placement adjustments leading to decreased sensitivity, the team still found “the sensor remained sufficiently sensitive to observe bow force changes in many playing...

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styles."

Continuing the quest for better wireless capability, the developers of the third version of the augmented bow relied on the Zigbee wireless protocol. This allowed for a more accessible connection by various computers and software. It also provided a setting in which multiple bows assigned to different receivers on different channels could interact simultaneously. This option was not available within the previous setup of the Augmented Violin.45

Figure 18. The third version of the Augmented Violin project.46

Perhaps the most influential update with this version of the bow, seen in Figure 18, is the relocation of the wireless emitter to a housing worn as a strap around the wrist. This not only decreased unwanted weight of electronics on the bow, but also allowed for easy installation and extraction of the sensors. The authors are sure to point out that “with this design, the sensing system can be installed on any musician’s personal bow,”\(^{47}\) a major achievement in accessibility to the performer.

**The K-Bow**

Continuing on the research and developments of much of the above-mentioned technology, Keith McMillen and his team at Keith McMillen Instruments (KMI) in Berkeley, California, released the first commercially available gesture-sensing bow for string instruments in 2009, the K-bow. Production of the K-bow involved three years of collaborative development between a number of individuals in today’s world of music technology. A full list of acknowledged collaborators can be found in McMillen’s NIME conference paper, *Stage-Worthy Sensor Bows for Stringed Instruments*.\(^{48}\) The K-Bow’s production also involved a handful of creative advisors, including the previously mentioned Jon Rose.\(^{49}\)

The goal of Keith McMillen’s team was to create “reliable, practical stage-

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\(^{49}\) Rose, "Bow Wow," 64-65.
worthy sensor bows for the string family." To that end, they have not only created the most adept gesture-sensing bow to date, but a full suite of software to accompany it. The K-bow’s gesture sensing capability includes many of the previous forms of sensors discussed in previous projects. This includes three-dimensional motion of the frog via accelerometers, horizontal and vertical bow placement, hair tension, bow grip, and bow tilt. A graphic representation of the various elements measured can be seen in Figure 19.

![Graphic representation of the variables measured by the K-bow.](image)

*Figure 19. Graphic representation of the variables measured by the K-bow.*

Most notable about the K-bow, is not so much the advancements of individual gesture sensors; many previous projects have used the same technologies, but rather their finely detailed application towards a streamlined product. The evolution of gesture-sensing bow technology takes a strong turn towards performer and composer

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50 McMillen “Stage-Worthy Sensor Bows for Stringed Instruments,” 1.

accessibility with the K-bow. The advancements and differences that are present will be discussed below within this new frame of application towards a more accessible product.

The most visually noticeable aspect of the K-bow is the oddly shaped frog, which houses a handful of sensors and electronics. Within the black plastic housing lies a set of accelerometers oriented for three-dimensional measurement. The familiarity of three-dimensional accelerometer technology in today’s mobile device world, and its standardization in gesture-sensing bow technology, are apparent through the description provided in the K-bow’s patent. The accelerometers are only defined as far as they “may be any of a wide variety of commercially available MEMS accelerometers.”

Jon Rose’s description of the K-bow also highlights this by saying, “there is the expected x, y and z axis accelerometer in the frog of the bow.”

A system designed to sense bow hair tension, or lateral force, is also primarily housed within the frog of the K-bow. This sensor marks a revival of directly sensing the hair of the bow, the last example being Jon Rose’s makeshift implementation of a MIDI keyboard pressure pad. Following Rose, Machover abandoned the idea of direct bow hair measurement partly due to complications of rehairing the bow. McMillen decided to revisit the issue, but not without difficulties. In an interview conducted by Andrew Benson of Cycling ’74, McMillen mentions a “month-long

52 Keith McMillen et al., “Sensor Bow for Stringed Instruments,”
53 Rose, “K-bow Bow Wow,” 64.
54 Keith McMillen et al., “Sensor Bow for Stringed Instruments,”
research project on how to glue horse hair to titanium.” This impressive technological hurdle does however come with a price to the consumer. Due to the direct adhesive of the bow hair to the tension sensor, the bow cannot be traditionally rehaired, and must instead be sent back to KMI for what would normally be routine maintenance to any local luthier. The hair of the K-bow is secured between two small L-brackets partially protruding from the frog towards the tip. Within the frog, a force-sensing resistor (FSR) is sandwiched between the inner vertical tip-facing side of the lower L-bracket, and an additional surrounding bracket firmly secured to the interior PCB. Pressure applied to the bow hair presses the lower L-bracket into the surrounding bracket, the force of which is then measured by the FSR. A photo of the exposed electronics within the frog, seen in Figure 20, offers a glimpse of this complex sensor.

Unfortunately, as described with the third version of IRCAM’s Augmented Violin bow, a single sensor at the frog of the bow is not sufficient enough to provide a consistent measurement of lateral force as the bow is drawn. In the case of the K-bow, measurements of bow position and distance could have been used to further calculate a more accurate measurement of lateral force, however, from first hand experience with the K-bow, this does not seem to be the case. It is not known yet whether a more accurate measurement of lateral force could be obtained with further calculation. It may be of interest to note however, that similar to IRCAM’s

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Augmented Bow, an exactly accurate measurement of lateral force is not necessarily needed for practical artistic application.

*Figure 20.* The exposed electronics housed within the frog of the K-bow.  

Just above and forward of the frog lies the K-bow’s grip pressure sensor. Impressively camouflaged, the grip pressure sensor looks and feels similar to any standard bow grip. Again, the KMI team returned to previously unfavorable technology, choosing to use a carefully layered system of flexible conductive material and piezoresistive felt. With a successful hair tension sensor in place, there was no need to use the grip pressure sensor to measure downward force on the bow as previously implemented by MIT with the hyperbow. The focus of the grip pressure sensor was therefor primarily trigger based, although its sensitivity allows for a range in measurement. The insulated sensitivity of conductive layers, combined with additional calibration through the accompanying software, allows for a smooth,  

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quantifiable measurement of grip pressure. A cross section drawing of this layered system can be seen in Figure 21.

![Cross-section diagram of the K-bow’s grip sensor.]

Figure 21. A cross section diagram of the K-bow’s grip sensor.  

Similar to Diana Young’s “playable measurement system for violin bowing”, a second PCB is attached to the underside of the instrument’s fingerboard. A photo of this fingerboard attachment can be seen in Figure 22. This attachment assists in measuring vertical and horizontal bow position, and the tilt of the bow in relation to the fingerboard as the performer crosses strings. To achieve these measurements, the fingerboard attachment acts primarily as a reference beacon, supporting an RF transmitter and four IR LEDs. Embedded within the stick of the bow are two loop antennas set to receive the RF signal from the emitter. The vertical measurement of the bow between the bridge and the end of the fingerboard is derived from the signal strength by proximity to the RF transmitter. This process of measuring bow position

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was first used by MIT with the hypercello, but the transmit and receive rolls were
later reversed, resulting in a bulky frog with added battery weight. By returning the
bow to the receiving end of RF transmissions, the majority of the weight and power
consumption of the K-bow are neatly tucked under the fingerboard.

The design of the PCB fingerboard attachment does prevent its installation on
certain electric instruments that do not have fingerboards extending from the neck,
but rather are flush with the body of the instrument. Although this is a limitation to
the versatility of its use overall, it does further represent the standardization of the use
of gesture-sensing bow technology with acoustic instruments.

Figure 22. The K-bow PCB fingerboard attachment.59

59 Keith McMillen et all, Keith McMillen et all, K-Bow Reference Manual, 2009,
http://www.keithmcmillen.com/downloads/k-bow/k-bow%20downloads/K-
Bow_Attaching_the_Emitter.pdf
In regards to horizontal bow position, the K-bow uses an infrared-based system of measurement. Recalling Rose’s earlier communications with Chris Chaffe, a similar form of measurement had previously been implemented using Don Buchla’s Lightning. The K-bow receives the IR signals via an IR photodetector located just below the bow hair on the tip-facing side of the frog. The CPU inside of the frog then calculates the distance from the IR LEDs to the IR photodetector. A more thorough explanation of this process can be found in the K-Bow’s patent.

Both the double loop antennas and the IR LEDs have a secondary function. The protruding IR LEDs are positioned in pairs with one facing vertically and one horizontally. Additionally, the frequency of the RF transmission is synchronized with the alternating stimulus of the IR LEDs. Because of this, the CPU aboard the frog can determine which LEDs are vertical and which are horizontal. With this knowledge, the angle of the bow as it crosses the strings can be calculated. This gestural measurement has not yet been implemented in this way. The only previous system measuring bow tilt in respect to the instrument would be the dual six degree of inertial measurement units of Diana Young’s “playable measurement system for violin bowing”.

Recalling the earlier hyperbow prototypes, much effort was spent on creating an accessible user interface. A small element of this was the inclusion of an LED to signify battery life. With the K-bow, LEDs are used on both PCBs in similar fashion.

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60 Rose, “K-Bow Bow Wow”, pg 62.
Additionally, three LEDs, each a different color, are fixed to the bow stick just beyond the bow grip sensor and in view of the performer. When interacting with a computer, these LEDs can be programmed in a variety of ways to offer a strong visual feedback to the performer.

To counter the ever-present issue of weight and balance, the stick of the K-bow is made from a custom designed carbon graphite material. As a result, the stick is much lighter than the average bow, and feels almost hallow at close inspection. When applied as usual to an instrument, the weight and balance of the K-bow has been found to be surprisingly appropriate for performance.

The K-bow uses Bluetooth wireless technology to communicate with a computer. The standardization of Bluetooth technology in almost every laptop on the market today has made the K-bow one of the most accessible applications of gesture-sensing bow technology. The inclusive packaged design of Bluetooth communication has also identified the K-bow as the first truly wireless sensor bow. Similar to Diana Young’s latest measurement system, there is also a Bluetooth connection between the two PCBs. In the case of the K-bow however, Bluetooth communication is purely for power conservation, allowing the fingerboard emitter to power down automatically when not detecting the presence of a bow.

In addition to the various advancements in packaging, custom sensors, and wireless communication, the K-bow also presented a breakthrough in accompanying software. With the exception of Jon Rose’s “headless chicken” type MIDI bow, the majority of, if not all, previous sensor bow endeavors have involved custom computer
software to manage gesture data. With the K-bow’s stage set in the commercial consumer’s world, the next evolutionary step of a straightforward, yet versatile GUI was needed. Built in Max/MSP, K-Apps provides sensor calibration, sensor mapping, and MIDI or OSC routing, as well as a variety of more specific tools such as customized gestural triggers. The K-Apps software highlights the leap forward in computerized music technology that has become available in the last decade. The simple lack of processing power provided by the computers used in previous projects has been a large reason why a commercially available sensor bow was not previously available. Increased processing capabilities, combined with the standardization of OSC and software such as Max/MSP, allowed for the complexity and versatility of the software needed to justify its survival on the commercial market.

**Conclusion**

This chapter presented an overview of gesture-sensing bow controllers that have most significantly influenced the evolution of gesture-sensing technology applied to string instrument performance. Within these selections we find a number of similarities in technological advances and developmental choices that have helped shape the overall evolution. One such similarity is the repeated focus on the bow as the primary gestural interface. Each subject mentioned here, even those on the technologically conservative end, focused further on gestural elements of the bow, and often removed gesture sensors not related to the bow, as their project evolved.

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Jon Rose moved from stage-wide ultrasound to accelerometers. The complex hypercello evolved into the hyperbow. Additionally, the general advancement of the technologies used to measure bowing gestures, allowed for a more detailed application to the subtleties of the bow. This in turn provided more opportunity to apply gesture-sensing technology to more familiar acoustic instruments, presenting a more accessible bridge between technology and tradition.

The prioritization of the bow as the primary expressive voice, combined with increasing computer processing power, miniaturization of gesture-sensing electronics, and wireless technology, have led to a standardization of measured gestures, regardless of their technical acquisition. This communal understanding of usable parameters is promising for future gesture-sensing bow virtuosity. As the technology continues to evolve, the focus becomes less about how gestures are measured and more about how they are artistically applied.
CHAPTER 3

PERFORMANCE APPLICATION

The evolution of gesture-sensing technology and its physical application to string instruments has in turn shaped the creative and performance practice of those involved. As with most music technologies, the creative process is continuously dependent on the physical state of the technology at the time of its implementation. Throughout its evolution, the musical application of gesture-sensing technology to string instruments has thrived within the limitations of its various physical states, producing a body of work demonstrating a versatile role unparalleled by any other digital interface for string instruments. To highlight this versatility, the following chapter will examine the artistic application of works in both solo and chamber music settings, exploring the influence of technical limitations and their progressive application in performance.

Developing The Hypersolo Voice

The Improvisations of Jon Rose

The early experiments of Jon Rose provide a clear example of effective musical application within limitations of gestural measurement and physical clumsiness of technology at that time. Most of Rose's work lies in the realm of improvisation, which allowed him to more readily experiment with boundaries of technical limitations and artistic philosophy. Regarding gestural measurement
limitations, Rose has expressed how the earlier MIDI bow influenced his performance style:

I developed a technique that could handle the system’s specific difficulties—mainly weight and balance of bows and cables. It was quite a mind-body split, as the bow, which was the engine of the violin, was also driving the computer system. If I reacted to what the computer did by playing something on the violin, then I automatically changed the state of the bow and its real world input via bow sensors to computer. It was the musical equivalent to Heisenberg’s uncertainty principle: By identifying and entering the moment, you changed it.¹

Rose embraced the overall uncertainty of his MIDI bow. Without any visual feedback included in the first MIDI bow, he was forced to memorize the rotation of MIDI presets by ear, and eventually went so far as to randomize the selection. As he states:

From an improvisational aesthetic, the unexpected is often desired and seized upon. In my early bows, I set my MIDI note-on outcomes from bow pressure in a way that I couldn’t predict, but at the same time could feel a sense of pitched shapes and tonalities and where they might morph to. Through the bow it was possible to become aware of what might be described in chaos theory as the attractor sensibility.²

As discussed in Chapter 2, Rose chose to replace his utilization of ultrasound with accelerometers. Although this provided a more accurate measurement of smaller, more subtle motions of the bow, it also eliminated the possibility provided by ultrasound sensors of manipulating sound by physical placement within a performance space. This change is clearly seen in videos of Rose’s music. Before the

² Ibid.
switch to accelerometer, his performance was much more theatrical, using his 
vanishing placement within a staging area to manipulate the MIDI accompaniment.³

After abandoning the ultrasound sensing system, his performances become more stationary (although still quite active), instead focusing on smaller bow gestures.⁴

This transition did not come without technical problems. In K-Bow Bow Wow, Rose described his performance adjustments when switching to accelerometer:

“Computers just do not 'get' theatrical moments, and as in Murphy’s Law, if there is a chance of misreading a moment, computers will. An accelerometer does not know or care … the meaning of a movement is not necessarily decoded into sound.”⁵

In addition to the physical limitations of the technology, Rose was quite focused on self-imposed artistic limitations. The first MIDI bows were purposefully limited to one channel of MIDI to provide a balanced presence between the violin itself and its digital accompaniment. This allowed for a more natural musical connection between gesture input and the resulting sound. In his words, “the continuous control of any contrapuntal lines… still rests with the business of playing the violin.”⁶ In K-Bow Bow Wow, Rose describes holding to this artistic philosophy against the inclinations of software programmers:

The argument went something like this. Most programmers were

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⁵ Rose “K-Bow Bow Wow” 63.
looking for a simple gesture leading to a complex result, often bearing no relationship in scale to the original input. I was happy to have some heavy lifting done by smart programming but not at the expense of scale—the system had to reflect skill, energy, physical human limitations, time spent and the fact that only one performer was the originator of the music; the potential for artist to morph into an all-powerful Nietzsche-style Übermensch was not useful.7

Rose’s experiments in improvisation helped open the doors for future projects and experiments utilizing similar technology. Additionally, his self-imposed limitations highlighted helpful boundaries in artistic application for future artists and composers. An album showcasing a variety of Rose’s Hyperstrings work, including the MIDI bow, is currently distributed by the independent ReR Megacorp label.8

The Hyperstring Works of Tod Machover

In contrast to the improvisatory artistic process of Jon Rose, Tod Machover and the MIT Media Lab primarily approached gesture-sensing technology with a clear end-product in mind. Often these goals were very complex ideas, utilizing very complex systems of measurement and computer processing. Throughout most of these projects, the MIT team was fortunate to have the artistic collaboration of well-known performers such as Yo-Yo Ma, Ani Kavafian, and Joshua Bell. This collaboration helped to insure the high level of articulated virtuosity needed for such complex instrument systems and the success of public exposure.

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Hyperstring Trilogy

The *Hyperstring Trilogy* is a series of three works composed by Tod Machover for early Hyperstring technology. Though written and presented individually over a three-year period, these pieces were envisioned as one large work inspired by the emotional drama of Dante’s Divine Comedy. Machover describes this compositional exploration as the “loss and gain, pain and recovery, despair and hope and, in passing, what is lost and gained by technology.”\(^9\) The staggered compositional approach and public exposure of the trilogy provides a unique insight into Machover’s artistic application of Hyperstring technology.

The first piece, *Begin Again Again…*, was written in 1990 for the newly designed Hypercello at MIT media labs. The MIT development team was fortunate to have the artistic collaboration of Yo-Yo Ma, who was instrumental in establishing boundaries of possibility in gesture sensing capability. Yo-Yo Ma premiered the piece in 1991 at the Tanglewood Festival, marking one of the first major performances of Hyperstring technology.

Overall, the MIT team took a very calculated approach in artistically applying as many gestures as possible. By using a complex system of software to classify very specific gestures and bow strokes, and then observing combinations of these classifiers during performance, Machover was able to use the performers movements both to trigger sections of the piece and as a live manipulation of sound.

In describing the musical mapping of the piece, Machover is quick to point out its “live” compositional form. Though some sections of the piece involved pre-recorded sounds and triggers via bow gestures, it was very important that these were actively manipulated and engaged by the performer rather than passively exploited. This priority preserved the role of the performer as the musical interpreter of the composers work, and helped insure the validation of gesture-sensing bow technology to the musical world at large.

Contrary to Rose’s self limitations and careful balance, Machover pursued the newfound abilities of the Hypercello to their furthest extent in Begin Again Again.... When describing the “sonic world” of the Hypercello in relation to the form of the piece, Machover is clear to point out the intentional chaotic progression:

“These sounds are designed to create a continuum from single cello notes, to superimposed cello “drone” sounds that can imitate pseudo-cello timbres (harmonic or inharmonic), to complexes of noise that are so dense that the individual cello elements are hardly perceptible. These sound complexes allow for a musical expression that can move from single line to saturated texture, all based on a solo instrument.”

In one section of the piece, the cellist assumes control over balancing the sound of the cello itself with the computer output. In Machover’s own performance of the piece, the output of the cello itself was eliminated, temporarily redefining his hypercello as strictly a control instrument to external sound. Rose also explored the idea of using his MIDI bow as an independent music controller, but primarily separate from the violin, or with non-traditional objects. As previously discussed,
when working with a traditional violin, Rose was quite particular in regards to balance. Machover explains his intentional overpowering of the cellist by gesture manipulated computerized sound as a musical metaphor of the artistic deliberations involved in creating such an instrument.

*Begin Again Again...* is a piece about building an instrument, and it takes as its actual subject the delight in finding the many ways of extending a traditional instrument, the difficulty in containing this explosion of musical layers, the discipline and choice needed to refine this multitude of possibilities into a new and meaningful unity, and the beautiful and tenuous fragility, and expressive possibility, of the new instrument once it exists. The piece explores the implications of turning a monophonic instrument (the cello) into a polyphonic one (the orchestra and beyond).  

The second piece of the trilogy, *Song of Penance*, was commissioned by Betty Freeman and premiered in 1992 by Kim Kashkashian and the Los Angeles Philharmonic New Music Group. The piece is scored for hyperviola, recorded voice, and 17 instruments. In writing the piece, Machover collaborated with poet Rose Moss to shape the text of a “mini-libretto”. Recordings of this text, sung by soprano Karol Bennett, were then prepared and stored in a similar computer system to the Hypercello, to be called up and controlled by the hyperviola in performance.  

As mentioned in Chapter 2, the hyperviola instrument is essentially a smaller replica of the hypercello system. Although many of the same systems of bow measurement and analysis are used, the new setting and instrumentation in *Song of*  

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Penance allowed for a contrast in artistic application. The accompanying chamber ensemble freed the solo instrument from the responsibility of controlling such an immensely layered texture as with Begin Again Again.... This provided the melodic flexibility needed in order for the hyperviola to effectively control and phrase the recorded vocal line. This new responsibility in musical role, combined with the blending of a more dense instrumentation, led to what Machover described as a “less extroverted” presence of the solo instrument.\textsuperscript{12} The shift in musical presence refocused the role of gesture-sensing technology towards a more balanced and controlled expression.

The final piece of the Hyperstring Trilogy, \textit{Forever and Ever}, was commissioned and premiered by the St. Paul Chamber Orchestra with Ani Kavafian on solo hyperviolin in September of 1993. Advancements and modifications in Hyperstring technology applied to the violin discussed in Chapter 2 influenced its application in performance.\textsuperscript{13} While the main focus was towards a wireless bow, the reconstruction of the Hyperstring technology allowed for more sensitivity in measuring subtle gestures, making it “easier for the hyperviolinist to control the computer extensions through delicate timbral variation.”\textsuperscript{14} Machover describes how “the soloist is probably most free in \textit{Forever and Ever} to forget about the technology and just play, with the computer part following in a seemingly organic way.”\textsuperscript{15} This is

\begin{thebibliography}{9}
\bibitem{13} Paradiso, "Musical Applications of Electric Field Sensing," 78.
\bibitem{15} Ibid.
\end{thebibliography}
contrasting to Yo-Yo Ma’s experience with the earlier hypercello system. In an article titled “Taming the Hypercello”, Ma explains the prominent dilemma of working with, and sometimes against the electronic half of the instrument.

“You have to make sure that you end up projecting to the hypercello what is possible, what it can understand… I have to make sure that certain signals are magnified. You can't be too subtle. I exaggerate what I do. I have to, to minimize the chance of error.”

Machover applies this new freedom of subtle control of the hyperviolin in what he describes as “at once the most and least conventional” way. Primarily set in a traditional fast-slow-fast form, the piece moves from a concerto setting between the soloist and orchestra, to a more unified melodic voice. The contrast between these two settings is most apparent between the first and final, Intro and Coda, movements. In the beginning, the Hyperviolin takes a more traditional instrumental role as a soloist, showcasing the new subtleties of electronic manipulation within small cadenzas of the middle movements. By the end of the piece, the hyper side of the instrument takes a new form, melding more easily with the chamber accompaniment, extending itself as a larger instrument in combination.

The Hyperstring Trilogy provides a clear view into the early experimentation in artistic application of gesture-sensing bow technology. Within three years of writing, Machover explored a variety of possible functions of his hyperinstruments as the technology developed; hyper-solo, solo against chamber, and unified instrument as a whole. This exploration provided an important platform for future artistic

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application of gesture-sensing bow technology by expanding the possibilities of instrumentation and musical role. In combination with this broadening of the palette, the more subtle system of the Hyperviolin began a process of focusing on the bow as the most expressive force of hyperinstrument technology. The refinement of the gesture-sensing technology allowed for a shift from gesture controlled, trigger-based composition of external electronics, towards live manipulation of the instrument’s sound.

Toy Symphony

Tod Machover’s premier of the Toy Symphony production in February of 2002 provided the public debut of the hyperbow with Diana Young’s initiation of the New Generation of Hyperstring Technology. Performers Joshua Bell and Cora Venus Lunny both participated in touring performances of the work, which combined hyperbow technology with full orchestra, children’s choir, and various musical “toys” developed by the Opera of the Future group at MIT media labs.\(^\text{17}\)

The Toy Symphony project focused primarily on the accessibility of music composition and involvement with a performance community of all ages and musical experience. The massive amount of technology used, combined with the focus of public accessibility towards music as a whole, somewhat overshadowed the use of the hyperbow. Compositionally, the hyperbow technology was most often used to bridge

the gap between orchestra and new electronic instruments. This resulted in an ambiguous ambassadorial role between traditional string performance and new musical “toys”.

Although the new hyperbow did not hold the technological spotlight of previous Hyperstrings projects at MIT, this new role actually highlights an important era of gesture-sensing bow technology application as a whole. By moving from the complex instrument of the Hyperviolin, to a more conventional and publically available electronic violin, the New Generation Hyperstrings showed how external advancements in instrumental string technology are making it easier for the artistic application of gesture-sensing bow technology. The Toy Symphony project is therefore a transitional state in the redefinition of the performance application and musical role of gesture-sensing bow technology.

MIT’s Collaboration with The Royal Academy of Music

In 2005 the hyperbow was brought back into the spotlight through a collaboration between MIT and the Royal Academy of Music. This collaboration showcased a new element of synthesis with acoustic instruments. Although no major technical changes were made to the gesture-sensing process of previous hyperbow models, the physical adaptation of the hyperbow for use with an acoustic cello helped open accessibility of the technology to the music composition community. Additionally, advancements in related technology of amplifying acoustic string
instruments and digital sound processing helped in advancing the accessibility of gesture-sensing bow technology to composers and performers.

*Gaia Sketches* by Patrick Nunn

The most notable and well-documented composition produced by this collaboration was Patrick Nunn’s *Gaia Sketches*.18 As a composer exploring audience and performer interaction of electro-acoustic music, Nunn took particular consideration towards causal relationships of performance gesture to sound production. Limiting each gesture mapping to individual filters and effects of live acoustic sound, Nunn created an intuitive performance environment easily implemented by performers of traditional technique.19 To heighten audience perception of this intuitive control, *Gaia Sketches* calls for a four channel sound system surrounding the audience. The gestural manipulation of the entire performance space, rather than an abstraction of the instrument alone, provided a more organic fusion between technology and traditional performance.

**Hyperchamber Music**

The increase in processing power of personal computers provided a multitude of new opportunities in the artistic application of gesture-sensing technology to string

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instruments. The most enticing situations involved the use of multiple gesture-sensing devices or their interaction with other digital instruments and devices.

The Augmented String Quartet

With the successful articulation of solo hyperinstruments, many experimentalists turned to the possibility of applying their newfound abilities using multiple gesture-sensing bows. The rich history in repertoire and musical influence of the string quartet provided a perfect proving ground. The string quartet not only created a technical challenge, but also held a strong precedent in musical expressivity.

The first record of any such attempt at applying gesture-sensing technology to the string quartet dates back to the MIT hyperinstruments project. In 1995, after completing the Hyperstring Trilogy, Tod Machover had planned a collaboration with the Kronos Quartet involving “technology which would allow any acoustic string instrument to become a ‘hyperstring.’”20 This collaboration never came to fruition however, most likely due to lack of developmental funding, technical limitations, or a change in artistic interest. In any case, the technology continued to advance and other groups approached the setting of the string quartet in the future.

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See also: Elaine Schmidt, "Composer fuses technology, music with dynamic results," The Milwaukee Sentinel, March 17, 1995, 28.
In 2005 composer Florence Baschet began working with a research team at IRCAM studying instrumental gesture in music. This collaborative endeavor gave birth to the third version of IRCAM’s augmented bow, which was much more accessible to the average performer as discussed here in Chapter 2. In combination with these advancements in hardware, the research team also focused on adapting another of IRCAM’s projects, the “gesture follower” system, to the multiple gestures of a string quartet. This gesture recognition software allowed for a variety of new artistic possibilities never before explored. The result was a piece premiered by the Danel Quartet in 2008 titled *StreicherKreis*.

In composing *StreicherKreis*, Baschet explored gesture manipulation of live sound by both the individual performers and by the group as a whole. At certain moments in the piece, members of the quartet were able to control manipulation of their own individual sound, while at other times they would be in control of the resulting sound of another member of the quartet. This added a new dimension of ensemble communication that was embraced with ease and excitement by the Danel Quartet while working along side the IRCAM research team.

The gesture follower provided new opportunities in ensemble coordination with electronic media as well. With all of the performers gestures being inclusively monitored, what would previously be a fixed media track to be followed could now be an intuitive electroacoustic accompaniment reactive to gestures of the entire quartet. This was achieved by pre-recording a gestural template of the piece into the
gesture follower, which would then be used to determine when to enable or disable effects and processes or to manipulate playback time of an accompaniment when compared to gestures in live performance. The mathematical process behind this function is described in detail in the research team’s publication\textit{The Augmented String Quartet: Experiments and Gesture Following}.

The application of this setup was documented as being quite successful, both to the quartet and to the composer. The use of software such as the gesture follower offers exciting new creative applications for gesture-sensing technology in ensemble performance.

\textbf{Douglas Quin’s Polar Suite}

In November of 2009, the K-bow had its string quartet debut premiering a piece commissioned by the world-renowned Kronos Quartet and written by composer and sound designer Douglas Quin. In a similar setting to the performance experiments of IRCAM and MIT, this collaborative production involved input from members of Kronos Quartet and the software development team at Keith McMillen Instruments.

In composing \textit{Polar Suite}, Quin drew from his recent soundscape recordings of Antarctica, most noticeably the sounds of seals and windstorms. The measured placement of the K-bow in relation to the instrument was then set to control digital processing of these sounds. The subtle control of this sonic manipulation was particularly effective when paired with the timbral palette of the vertical axis (sul ponticello to sul tasto, or bridge to fingerboard placement). In the later half of the
piece, the score instructed the performers to remove their bows from the string while still maintaining certain bowing gestures just above. This allowed for control in manipulating the processed soundscapes without the acoustic instruments sounding, creating an impressive perceptual connection between string quartet performance gestures and electroacoustic sound.

The members of Kronos Quartet were all very positive about working with the K-bows. First violinist and Kronos Quartet founder David Harrington was quoted as saying:

“"This is an opportunity to essentially relearn our instruments and to transform how we approach live performance. Polar Suite is a very different kind of string quartet and an extraordinary sonic adventure—thanks in large part to the K-bow and what is now possible.""21

Kronos Quartet's embrace of gesture-sensing bows through this commission represents a professional setting unlike previous collaborations. Not only is Kronos dedicated to impressive musicality in performing new works, but they are also focused on maintaining repeatable repertoire that can be taken on tour. Both of these factors were discussed by Quin, Kronos, and McMillen during the collaborative composition of the piece.22

The successful performance of *Polar Suite* was made possible in large part by technological advances in miniaturized electronics and the performance oriented design of the K-bow. Fifteen years after the first attempt with MIT, Kronos Quartet was able to effectively and musically apply gesture-sensing technology to the string quartet.
CHAPTER 4

CURRENT CHALLENGES

The previous chapters of this thesis have provided a selective history of promising and well-documented forms of gesture-sensing bow technology applied in performance. This final chapter will discuss issues this technology faces at the time of this writing, and offer some insights on how to further develop its accessibility towards future use in performance.

Repeatable Repertoire

The issue of repeatable repertoire has plagued music technology for decades. Composers and performers are reluctant to invest in technologies that will become outdated and possibly unusable, as has been the case with much sophisticated music technology over time. Many individuals involved with developing technology for the bow have directly addressed this issue. In an interview for Fanfare Magazine, Machover describes his struggle:

Pieces that I made from the ’80s to the mid ’90s were often stymied by each software change, since in those days there was little compatibility between operating system versions. Each version upgrade would be a complete change; you’d write something in 1987 and by 1989 you couldn’t run it anymore. … There’s no question some of these earlier pieces would now need to be updated in order to be performable today. It’s a challenge to raise money to do these projects in the first place, but very few people are interested in putting money
into updating pieces.¹

In *Composing for Hyperbow: A Collaboration Between MIT and the Royal Academy of Music*, Diana Young states: “If the Hyperbow is ever to achieve the unqualified status of a real music instrument, it must not only provide wonderful new sonic possibilities, but must also be associated with a significant repertoire.”² A large reason for the MIT/RAM collaboration was to help build such a repertoire. The documentation of successful repeated performances of the pieces born from this collaboration can be seen as a successful reach towards that goal.³ Keith McMillen has also attempted to inspire growth in repertoire by equipping string quartets at major universities with gesture-sensing K-Bows. In *The Next Music - MAPPS Using Technology to Extend Virtuosity for a 21st Century Music*, Keith compares the acceptance of technology such as gesture-sensing bows to the evolution of composing for now established instruments such as the modern piano over the harpsichord.⁴

Although both of these projects greatly helped in breaking down barriers of accessibility to this technology, they highlighted a major issue in the composition community's perception of gesture-sensing technology for the bow: Prohibitive

dependency on specific hardware. This dependency on hardware becomes less of an issue as related technologies and software develop. Tod Machover, while looking back at his Hypertriology, has noted how "Things these days (since OS X) are so much more stable and compatible over a period of years… With laptops being so full-featured, the processing power needed to run these setups is available anywhere." Promoting repertoire from the standpoint of specific hardware undermines the benefits this technology has to offer; the standardization of effective performance gestures regardless of their acquisition, and the idiomatic nature of this interface to the performer. The hardware itself is not the main objective; it’s the artistic application of performance gestures already inherent to traditional performance technique. The specific hardware by which these gestures are measured is as secondary to the composer as the types of strings or specific measurements of the acoustic instrument with which it is paired. Thus, it is in the best interest of those progressing this technology towards repeatable performance to anchor their writing in time-proven software such as Max, keeping the calibration and application of performance gestures as inclusive as possible.

The Role of the Performer

For the most part, educators of the creative arts have continued to recognize the ever-increasing role of technology in music. In particular, institutions of higher education have integrated music technology into their curriculum by offering courses

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5 Carson Cooman, "Hypercollaborations: An Interview with Tod Machover."
and degree programs in sound production and related software. Unfortunately, much of this progressive education has been isolated to the fields of composition and audio recording, leaving the instrumental performance community largely unaware of the creative benefits in working with new digital interfaces.

Gesture-sensing technology and its varied artistic applications offer string instrumentalists new avenues in exploring creative expression in performance. As demonstrated in this thesis, the current state of gesture-sensing bow technology has more potential for compatibility with traditional practice than any other form of performable technology, since it unobtrusively interacts with the already familiar vocabulary of performance gestures. The technology surrounding gesture-sensing bows, its commercial availability, and the standardization of measured gestures, have all reached a point in which gesture-sensing bows can be embraced by the instrumental performance community and included in standard curriculum. This would involve basic training for performers in digital sound production, and proficiency in software related to gesture tracking and calibration. Considering the growing prevalence of gesture-oriented technology around us today (phones, tablets, gaming systems) and the positive response by performers of previous experiments, the modern-day string instrumentalist will easily be able to engage this increasing responsibility to become proficient in these performance tools as they become a foundation for new music.
Future Technology and Research

The application of gesture-sensing technology to string instrument performance has come a long way from the early experiments of Jon Rose and Tod Machover. Although this technology has become much more accessible and relevant to the modern string instrumentalist, there is still work that could be done to simplify or remove the barriers between musician and computer.

At the present time, most gesture-sensing technologies are making large advances in optical motion tracking. Devices developed in the entertainment and gaming industry, such as the recently released Kinect for Microsoft's Xbox One, are becoming increasingly accurate in measuring detailed and message-specific gestures.\(^6\) As optical-tracking technologies continue to advance, they will eventually eliminate the need for certain types of hardware physically attached to the bow. This will advance gesture-sensing technology applied to string instruments in a number of ways: First, it will reduce the burden of cost on the performer - the less bow-specific hardware needed, the lower the cost and the greater the accessibility. Although the commercial availability of the K-Bow has been a huge step forward in accessibility, the current cost of such a device is unfortunately a deterrent to current musicians of standard curriculum. Secondly, the elimination of bow-specific hardware will give more flexibility to composers who wish to work with this technology. By utilizing

more versatile optical tracking systems to acquire gesture data, the concern of hardware obsolescence is reduced. As previously discussed, there is a much greater opportunity for composers to create repeatable repertoire when dependency on specific hardware is not an issue. Anchoring the compositional approach in more long-term compatible software systems will help unify different forms of gesture-sensing hardware, which could potentially bring pieces written for earlier hardware systems forward into performance today.

With the complex and subtle control variables that are possible using gesture-sensing technology, it also may be necessary to standardize a notation suitable for conveying such detail. From my perspective as a performing cellist, I believe strongly that a performer’s freedom in the interpretation of a composition is what brings so much of the human element and value to live performance. Since much of how a string musician crafts an interpretation is dependent on detailed decisions regarding bow placement and pressure, it could be argued that excessive instruction in bowing gesture could reduce the quality and value of string instrument performance. As a composer working with this technology, however, I have also felt the need for a more detailed language that can convey specific combinations of bowing gestures. This intricate balance of notating gesture in acoustic performance will take much more time and experience than the scope of this thesis, but I look forward to exploring this subject in the future.
I am excited to do my part as a performer, composer, scholar, and advocate, to ensure that gesture-sensing bow technologies continue to develop new avenues for creative expression – through innovative hardware, software, and lasting repertoire.
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