THE VBOW
AN EXPRESSIVE MUSICAL CONTROLLER
HAPTIC HUMAN-COMPUTER INTERFACE

A DISSERTATION

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DOCTOR OF PHILOSOPHY

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ABSTRACT

This dissertation describes the development of the vBow, a virtual violin bow controller. This interface was designed to accurately sense the component physical motions of a violinist's bowing gesture, while providing the performer with both the auditory feedback of the sound synthesis and the tactile sensations of the haptic feedback, produced by the system. Both the sound synthesis and haptic feedback are generated by software which uses the sensor readings, from the encoders on the vBow, as parameter data for a bowed string physical model, a friction model, and simulations of detents, elasticity, and barriers, produced by the motors on the vBow.

The vBow was designed around the component physical motions of the bowing gesture, with each encoder sensing the movement, and each servomotor producing the tactile feedback, that corresponds to the four main trajectories, or degrees of freedom, of the bowing gesture. On an acoustic violin, the manipulation of each of these four main trajectories of bowing contributes to the expression inflected in the tone of the violin. Similarly, with the vBow, maneuvering each of the four degrees of freedom generates data from each of the four encoders, which affect the parameters of the sound synthesis software, producing expressive variations in the timbre.

Just as the four component physical motions of bowing contribute to variations in the timbre produced by both an acoustic violin and the vBow, each degree of freedom also contributes to the tactile feedback of both systems. For an acoustic violin, each trajectory of motion produces the tactile feedback of vibration, friction, detents, or elasticity. On the vBow, each encoder is attached to a servomotor, which generates the same haptic feedback that corresponds to the bowing motion producing the encoder reading.

The encoders and servomotors used by the vBow were selected for their high resolution of sensing and wide range of force, to maximize the expressive potential of the instrument. Similarly, the sound synthesis and haptic feedback models were chosen because of their responsiveness and flexibility.

To elucidate the importance of expressive potential to the design of an instrument, the introduction chapter of this dissertation outlines the developmental history of the violin and bow. The evolution of the expressive possibilities of the violin bow is also illustrated through a survey of the development of bowing technique. This survey further serves to

demonstrate that it is the bow that provides the majority of the expressive variety in violin dynamics and timbre.

Furthermore, to show that the importance of expressive potential also applies to the development of computer music interfaces, the introduction chapter presents an overview of writings by computer musicians expounding the importance and difficulty of expressive interaction with computer music systems. Finally, to clarify the importance of haptic feedback to the expressive performance of an instrument, the introduction contains a discussion of research into measuring and simulating the tactile feedback of musical instruments.

Later, after a discussion of the motivation behind the project, in order to put the development of the vBow in a historical perspective, the background chapter of this dissertation contains an overview of the development of computer music interfaces. This developmental overview begins with the evolution of early systems, moves through the design of non-keyboard controllers, focusing primarily on violin and bow interfaces, and concludes with the production of haptic interfaces, specifically designed for computer music performance and research. At the heart of the development of these interfaces is the pursuit of an expressive gestural connection to the powerful and flexible sound synthesis possibilities of the computer.

Next comes a chapter that steps through the development of the vBow hardware, followed by a chapter discussing the design and implementation of the software for the vBow system. Within this chapter about the vBow software, violin tone production is studied, through an analysis of both treatises by reputed instructors of violin performance from throughout history, and papers by scientists researching the contribution of bowing parameters to violin tone production. These two perspectives on the effect of the bow on violin tone production, the musically practical and scientifically theoretical, are used as a springboard from which the developmental history of the bowed-string physical model, used in the vBow software, is discussed.

After this general discussion of the acoustic and electroacoustic production of an expressive violin timbre, each of the four specific bowing parameters, which correlate to the four kinds of motion provided by the vBow, are discussed in relation to how they contribute to the variation of violin timbre, both on an acoustic instrument and in the bowed-string physical model used by the vBow system software. In support of these discussions, passages are cited from texts, describing the affect of these four bowing parameters on violin tone production.

Similarly, each of the four kinds of haptic feedback produced by the vBow system software, which relate to the component physical motions of a bowing gesture, are discussed in this chapter. In addition to describing how the haptic effects are generated through the servomotors on the vBow by the system software, models previously developed by haptics researchers are discussed.

Finally, in the chapter covering future applications of the vBow, in addition to a general discussion of possible sound synthesis, haptic feedback, and compositional and performance applications for the interface, writings by experts on mapping strategies, or how the output of the interface can be connected to input parameters of the system software, are presented.

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CHAPTER 1
INTRODUCTION

The vBow is the product of research intent on developing an electronic musical instrument that expressively translates physical gesture into synthesis parameters, while providing useful haptic feedback to the performer.

To a composer and performer, expressivity of a musical controller is defined as the ability of the instrument to map performance gesture to sound synthesis parameters, with fine resolution in the sensing of physical gesture, and a broad range of response from the synthesis parameters. The interface is expressive if it amplifies the performance gesture, translating it into synthesis data that produces a wide range of dynamic and timbral effects.

The development of this correlation between finely resolved physical motion and maximized dynamic effect is apparent in the evolutionary history of the acoustic bowed-string instrument, culminating in the modern violin and bow.

History of the Violin

In Hyacinth Abele's text covering the history of the development of the violin (Abele 1905), the author begins by describing early bowed-string instruments such as ancient India's Ravanastron, a long thin two-stringed instrument made of wood, with boa skin stretched across for resonance, and gazelle gut for strings, stretched over a bridge, and played with a bow made from bamboo reed and a horse hair, which he describes as producing a "weak and dull, though pleasant" tone.

In a poetic account, in his book, *The Story of the Violin* (Stoeving 1904), Paul Stoeving writes that Tradition told him that the ancient king Ravana, from the island of Ceylon, invented this first bowed-string instrument, the Ravanastron, placing the origins of the violin and bow in Sri Lanka, five thousand years ago.

Stoeving also describes, in detail, the design of the Ravanastron, an instrument on exhibit at the British Museum:

> A small hollow cylinder of sycamore wood, open on one side, on the other covered with a piece of boa skin (the latter forming the sound-board), is traversed by a long rod of deal – flat on top and rounded underneath – which

> serves as neck and finger-board, and is slightly bent towards the end where the pegs are inserted. Two strings are fastened at the lower end and stretched over a tiny bridge, which rests on the sound-board, and is cut sloping on top. A bow made of bamboo – the hair roughly attached on one end with a knot, on the other with rush string – completes the outfit.

According to Stoeving's firsthand account, the tone of the Ravanastron is "soft, thin (a little muffled, as if muted), ethereal, suggestive, if you will, of thought rather than emotion."

In his book, *The Violin: History, Aesthetics, Manufacture, and Acoustics* (Leipp 1969), Emile Leipp includes an excellent photograph of a Ravanastron, that supports Abele's and Stoeving's descriptions.

Edmond van der Straeten, in his text, *The History of the Violin* (Van Der Straeten 1968), begins his chronicle of the development of bowed-string instruments with the Egyptian Lyre and Kithara, and Persian Rebab, each fostering a branching line of instruments. The author distinguishes between these lines of instruments according to the shape of their body: the Lyre, with its rounded back, evolving into the Crwth, the pear-shaped Rebab developing into the Rebec and Gigue, and the flat Kithara, with its front and back coupled with side-pieces, prefiguring the modern violin design.

According to van der Straeten's account, which draws heavily from a genealogical table illustrated by Kathleen Schlesinger in her book, *The Precursors of the Violin Family*, the history of the development of the modern violin design begins with the Egyptian Kithara, which developed into the Greek Cithara, and later with the Roman Cithara, which was also called the Fidicula or Rotta. This lineage continues with the Spanish Viguela or Vihuela, which influenced the French Vielle and Viole, and later the Italian Viola and Violina, which was a small Viol or Lyra da Braccio.

Abele continues his narrative by describing the ancient Arabic Rebab or Rebek, an oblong one- to three-stringed instrument, constructed from strips of wood and pieces of parchment, and used to accompany singing, and the early British Crouth, a bowed three- to six-stringed trapezoidal instrument with sound-holes cut in the face, and a bridge with one foot that extends through one of the sound-holes to the back, serving as a soundpost.

Walter Kolneder, in his *The Amadeus Book of the Violin: Construction, History, and Music* (Kolneder 1998), explains the function of the soundpost, to the design of the violin. Placed below the right foot of the bridge, the soundpost impedes the vibrations transmitted from the bridge, while transmitting the vibrations from the top of the body to the back. Although the importance of this design element is disputed, Kolneder states that “the precise placement of the soundpost strongly affects volume and especially timbre.” This being the case, the invention of the soundpost in the early Crouth is a significant contribution to the developmental history of the bowed-string instrument.

Stoeving also discusses the Rebab, as the first bowed-string instrument in Europe, brought to Spain by an Arabic invasion, in the eighth century, and prolific throughout Europe in the Middle Ages. He describes the instrument as “pear-shaped,” with two or three strings, and two crescent sound-holes.

Van der Straeten adds to our understanding of this kind of bowed-string instrument by describing the tone of the pear-shaped Rebec as “harsh and dry,” mentioning that it used to play dance music and “early relegated to fairs and taverns,” although there are records of it used by court musicians.

Stoeving also discusses the early British instrument, calling it a Crwth, and attributing its construction to the Welsh. According to his interpretation of a Latin poem composed by Bishop Venantius Fortunatus, this instrument, which was still performed by Welsh musicians up to the late eighteenth century, may have predated the introduction of the Rebab to Europe by as many as two hundred years.

William Sandys, in his text, *The History of the Violin* (Sandys 1864), also mentions the early British bowed-string instrument, calling it a bowed Rote or Crwth. Like Abele, Sandys discusses the three-stringed Crwth, describing the bow used to play the instrument as “clumsy,” and mentions the six-stringed version, with the bridge that also functions as a soundpost, providing the same illustration as Abele. In addition to these two versions of the Crwth, Sandys describes and includes an illustration of a five-string version, that did not include a neck or bridge, and was played with a short bow, which he likens to a modern bass bow. He also mentions and presents an illustration of another six-stringed version, with sound-holes similar in shape and position to the modern violin.

Leipp attributes the invention of this line of bowed-string instruments to the Scandinavians, who are said to have created the Crouth Trithant, a three-stringed instrument with a fingerboard. This Crouth of Scandinavian origin is thought to be the ancestor of the Welsh Crwth, which the author also describes.

Adding to what Stoeving and Sandys wrote about the six-string version of the Crwth, Leipp explains that this instrument had two bass strings, tuned to G2 and G3, that were plucked with the thumb of the left hand, and four strings, tuned to C4, C3, D3, and D4, that were bowed. He also clarifies that this early Crwth, which he illustrates with the same drawing as Abele and Sandys, had a curved bridge, so individual strings could be played separately.

Sandys next presents a four-stringed instrument, with no fingerboard or bridge, but with low crescent-shaped sound-holes, a wide tailpiece, and a shape generally similar to a modern violin, with a body that curves in at the sides. This instrument, attributed to Albinus, who lived until the early ninth century, is pictured with an ornate arched bow. A similar instrument, with two additional higher crescent sound-holes, is illustrated by the author, from a carving of the eleventh or twelfth century. This early bowed-string instrument was placed between the knees of its courtly performer, and played with a bow held underhand.

In his section explaining the dynamics of violin tone production, Kolneder explains the importance of the placement and shape of the sound-holes (or f-holes) to the volume and timbre of the tone produced.

> The violin’s body, vibrating in its entirety, transmits its vibrations to the air, both inside and outside of the instrument. The outside transmissions are most important by far for volume and timbre, but the air vibrating inside the violin, emerging through the f holes, increases volume. The placement of the f holes is of great importance. The shape of the f holes affects the combination of inside and outside air only slightly but has a far greater effect on the top’s vibration and hence on tone quality; if they are very elongated, the top’s middle portion becomes overly elastic in relation to the upper and lower portions, which disturbs the uniformity of sound. Placing the holes closely together will have the same effect.

Even with these early bowed-string instruments of the Middle Ages, instrument builders were aware of the importance of this design element, experimenting with the placement and shape of the sound-holes.

The same carved depiction, described by Sandys, is noted by Stoeving, as an example of a bowed-string instrument design that differed radically from that of the Rebab. According to the author, this predecessor to the viol had a shape like a guitar, with “a sonorous chest, consisting of a back and a belly and sides or ribs connecting them.”

These early bowed-string instruments, precursors to the viol, are interesting for the variety of design choices and experimental engineering they represent, presumably for the sake of improving their expressive potential.

Sandys places the introduction of the viol in the eighth or ninth century, with the oblong Lyra (which Stoeving presents in his discussion of the Rebab, pointing out the likeness in design), a one-stringed viol with a small bridge, and half-circle, centered sound-holes. This design, which Leipp states was common in the Middle Ages, incorporated a sound post that fit between the front and back of the body. A three-stringed version of this Lyra, tuned in fourths, is still used to perform popular Greek music, today.

Sandys presents a wide assortment of viols, with a history of development that continues until the sixteenth century, describing their shapes, number of strings, pattern and position of sound-holes, and inclusion or exclusion of a separate neck, fingerboard, bridge, and tailpiece.

One viol in particular, an Italian Fidel from the beginning of the sixteenth century, prefigures the design of the modern violin. According to the illustration and description from van der Straeten, the shape of the body, position of the crescent sound-holes, and design of the pegbox and pegs are similar in proportion to that of the modern violin.

Abele also continues his discussion of the developmental history of bowed-string instruments with descriptions of European viols, violins, and fiddles, with various shapes, numbers of strings, and playing positions depicted in sculptures, paintings, and writings since the eleventh century. Included is a description of a Great Fiddle and Little Fiddle, illustrated in Sebastian Virdung's *Musika getutscht* from 1511.

The Great Fiddle is shown as a large nine-stringed instrument, with high crescent sound-holes and generally the same shape as the modern violin, but a fretted finger-board and no bridge. With no bridge, the elliptical bow would have made contact with all strings simultaneously, a design choice that Abele attributes to a faulty illustration. The Little Fiddle is more similar in design to the Rebek than the Great Fiddle, with an oblong body, low sound-holes, no frets, and a bridge, but also contains a scroll similar in design and function to the modern violin. Both are shown with curved, wide bows.

Sandys also describes an instrument like the Little Fiddle illustrated in Sebastian Virdung's text, calling it a Gigue or German Geige. This pear-shaped instrument from the thirteenth and fourteenth century is described as having evolved from a design that included a neck extending from the same piece of wood as the body, to having a separate neck and rounder body. All gigues discussed had three strings and a tailpiece, but the two illustrated have different shaped sound-holes, cut in different places in the body, and one has a fingerboard, bridge, and pegs, like the little fiddle, while the other does not. Sandys gives credit to Martin Agricola for describing four sizes of the more complex gigue, the Discantus, Altus, Tenor, and Bassus, in the mid sixteenth century.

In van der Straeten's account, the author describes a small sixteenth-century Rebec or Gigue design, with the same oblong body as the Little Fiddle, in Germany called the Polnische kleine Geigen, or "Polish small fiddles," and in Italy named the Violette da arco senza tasti, or "small viols with a bow, without frets."

Leipp adds to the description of the Rebec, stating that the current version, still used in Greece, has a "smooth fingerboard," is tuned in fifths, and uses a bridge design that rests the right foot of the bridge on the top of the sound post.

But for van der Straeten, the true ancestor of the violin must have a three piece design, a flat front and back joined by ribs, like the Great Fiddle, precluding the two piece design, flat front and rounded back, of the Rebab, Rebec, and Little Fiddle. In support of this claim, the author presents several Lyra from the fifteenth and sixteenth century, that have the general shape and proportions of a modern violin. Of particular interest is a Lyra from 1580, made by Ventura di Franco Linarol in Venice. In addition to its shape and proportions, this Lyra da Braccio already had the arched front and back, flat ribs, and f-shaped sound holes associated with the modern violin design.

Sandys conjectures that the evolution of the shape of these bowed-string instruments was in response to a greater need for facility when bowing, and comfort when holding, these early Viols:

> Before the inward curvatures were introduced, the rounded sides must have interfered with anything like execution, and checked the action of the bow, which from the form of some of these instruments, must have struck several strings together. As increased execution, or the desire for it, occurred, the sides would be curved inwards to meet the necessity, and frets were

> afterwards introduced to guide the fingers. These curvatures would also facilitate the holding of the larger instruments between the knees.

Leipp agrees, stating, in relation to the design of the Viols of the Middle Ages, that "the difficulty of wielding the bow with instruments of this shape was soon to lead to the introduction of incurved sides in all bowed instruments."

Van der Straeten similarly speculates that the development of the neck of the violin was motivated by the need for greater facility by the player:

> The neck of the violin was, in the first stages of the instrument, still broad, short, and clumsy, reminiscent of the viol neck, and continued thus until the early part of the 17th century, when it was adapted to the needs of an advancing technique by a more suitable form.

Abele presents Michael Praetorius' brief description of the "Viole di gamba" and "Viole de bracio or brazzo" in his second volume of *Syntagma Musicum* from 1619, with an illustration that shows that the tenor gamba was a large ornate fretted instrument, with a shape, proportion, tailpiece, bridge, and sound-hole placement similar to modern stringed instruments. "Gamba," the Italian word for leg, and "bracio," for arm, described the playing position of these bowed-string instruments. But, despite Abele's judgment of these instruments as the violin in "its perfected form," he conjectures that they did not have the "noble tone-character" of the modern violin, because of their low tuning and poor quality strings.

As viols were used to double choral parts, different sizes of the instrument were needed, with varying numbers of strings. The larger of these viols, Stoeving explains, required corner blocks, an improvement over the previous design, to allow for greater tension on the body, which provided "freer transmission of the vibrations of the strings." The author also mentions the various viols unique to Italy, the most interesting in design being the Viola di bordone, a large bass viol, with six played strings and twenty-two metal sympathetic strings.

According to Abele, the development of bowed-string instruments continues with the work of various lute makers of the fifteenth and sixteenth century. His only description of the timbre of one of these instruments, a viol with an arched body built by Joan Kerlino, was that the tone was "soft, but dull."

The first documented description of the violin, as presented by Leipp in his text, comes from Philibert Jambe-de-Fer, in his *Epitome musical des tons, sons et accords des voix humaines, fleustes d'alleman, fleustes a neuf trois, violes et violons*, from 1556. In the section about the violin, Jambe-de-Fer contrasts the design of the violin with that of the viol, stating that it has only four strings tuned in fifths, a "smaller, flatter body," no frets, "is easier to tune," and "is commonly used for dancing."

Stoeving attributes the introduction of the modern violin design, with its distinctively contoured pattern, f-shaped sound-holes, and scroll, to Gasparo da Salo and Gaspar Duiffoprugcar. Although Gasparo da Salo has long believed to have crafted the first modern violins, Stoeving presents a disputed case for the credit to go to Duiffoprugcar, citing six extant examples of his violins from the early sixteenth century, with elaborately inlaid and painted backs.

Based on the measurements of different moulds on which violins were built, and from which the shape and size of these violins were determined, Leipp concludes that the design of the modern violin is based on the French model, supporting Duiffoprugcar as the originator. This mould is based on proportions that are derived from the length of the vibrating string. The length of the violin body is equal to the length of the vibrating string, the upper width is equal to half of this length, the bottom width is equal to five-eighths of this length, and the middle width, between the inner curves, is equal to a third of this length.

Da Salo's instruments, with their large proportioned design, are described by Stoeving as having a "large and even" tone, while he describes the violins of Da Salo's student, Giovanni Paolo Maggini, with their narrow sides and steep arching, as having "large and noble, slightly veiled" tone.

Overlapping dates of production with da Salo, Andrew Amati crafted violins of an original design, that produced an unique tone. His violins, smaller in size, were made with thinner pieces of wood, brought to a higher arch at the center of the body. Stoeving describes the tone produced by this new design of violin as "sweet, delicate, round, and mellow to a degree, but lacking in sonority, brilliancy, and carrying power." The tone of the violins constructed by Nicolaus Amati, Andrew's grandson, is described by Stoeving as the best of the Amatis and rivaling all other makers, and is attributed to Nicolaus' design choices: size and contour of pattern, quality and thickness of wood, and color and consistency of varnish.

While leading us through the work of violin makers like Gaspar da Salo and Johann Paul Maggini in Brescia, and Andreas, Hieronymus, Antonius, and Nicholas Amati, Antonio Stradivario, and Andreas, Joseph, Peter, and Joseph Antonius Guarnarius of Cremona, Abele also describes the changes in size and contour of the body, position of the sound-holes, shape of the finger-board and tailpiece, quality of the wood and color of varnish used, and the improved tone production of these instruments, each design choice contributing to a richer and deeper timbre.

Similarly, Abele chronicles the violin makers from this period in other regions of Italy, as well as describing developments of violin makers from France and Germany. Most notable are Nicholas Lupot of France, the maker of a violin, owned by virtuoso violinist, composer, and conductor Louis Spohr, that Abele describes as having a "full and powerful tone," and Jocob Stainer of Germany, whose violins produced a flute-like tone due to their arched bodies, a tone that Stoeving describes as "rich and full, and of a remarkable silvery purity of sweetness." Most interesting is the work of the French acoustician, Felix Savart, who experimented with violin tone production by constructing rectangular violins from flat boards, with straight sound-holes, and tested the vibrations of violin bodies, by replacing the face and back of the violin with parts made from different woods and of different thicknesses, and by changing the volume of air within the body by constructing a movable back.

A photograph of one of Savart's experiments, a trapezoidal violin body, with no arching of the front and back, and strait sound holes, appears in Leipp's book. In addition to Savart's experiments, this author presents work by other researchers who attempted to improve on the modern violin design. Included is the work of Richelme, who based his wide design on "full circular curves," producing a viola described by Leipp as having qualities "comparable to those of a normally good instrument." Also mentioned is Suleau, who used "undulated tables" or a wavy top and back, in the early nineteenth century, and Tolbecque, who cut oval sound holes in the ribs of his violin, at the beginning of the twentieth century.

Violin making reached its highest achievement in the late production of Antonio Stradivari, in the early eighteenth century. Within Stoeving's chronicle of the life and work of the apprentice to Nicolo Amati, the author describes the transformation of Stradivari's design from the Amati pattern, to a broader, flatter body, made from carefully refined thicknesses of wood, with an improved bridge.

Because the bridge transmits the vibration of the bowed string to the violin body, the design of the bridge and the strength and quality of wood used can have a great affect on the tone of the violin. Kolneder credits Stradivari for crafting the modern bridge, although he acknowledges Josephus Guarnarius del Gesù for improving the design. The author explains that the decorative design in the center of the bridge serves to "increase elasticity by reducing the amount of wood in the bridge without reducing its stability."

Sandys describes this period in the development of the violin, that of Stradivarius and Guarnerius, as the pinnacle of its design history. According to the author, despite the subsequent years of experimentation and structural alterations, "there has been no permanent or essential change since the latter part of the sixteenth century."

Another author, George Hart, in his book, *The Violin: Its Famous Makers and Their Imitators* (Hart 1978), agrees with Sandys' assertion. According to Hart, only two structural elements have been improved upon since the sixteenth century.

> The only difference between the Violin of the sixteenth century and that of the nineteenth lies in the arrangement of the sound-bar (which is now longer, in order to bear the increased pressure caused by the diapason being higher than in former times), and the comparatively longer neck, so ordered to obtain increased length of string.

In addition to chronicling the craft of violin makers from the Italian, French, German, and English schools, Hart devotes a chapter to a discussion of the varnish used by the Italian master violin makers, stipulating that its composition contributed not only to the visual beauty of the instruments, but also to the tone quality. As stated by the author, the fine oil varnishes used had a "soft and yielding nature," that, when dried, left the wood "mellowed and wrapped in an elastic covering which yields to the tone of the instrument and imparts to it much of its own softness."

History of the Bow

Like the violin, the bow has gone through considerable changes during the development of its design. While examining the origins of bowed-string instruments in the Ravanastron, Stoeving begins the discussion of the development of the bow, and sums up the importance of the bow to the expression of the violin, in his imaginative style:

> It is the bow first and the bow last, as every violinist knows; and yet the bow even – that magic wand in the had of a Paganini which opens wondrous worlds of sound – how easy an invention it really seems here, in its first crude form: the simple principle of producing sounds from strings by friction, that is all.

Abele's discussion of the development of the bow begins with that used to play the Rebek, bent like an archer's bow, with a piece of string or gut strung across. Continuing, Abele describes the bow of the thirteenth century as having a less curved shape, and incorporating a nut and head, suggesting the use of hair.

Van der Straeten also describes early bows as "not much more than the weapon from which they derived their name," providing an illustration of a crude symmetrical bow used in the eighth to sixteenth centuries. Next to this illustration is another, showing a more developed Crwth bow from the ninth century, also bent in a crude curve, but strung from the tip to a point above the part of the stick that was left as a handle.

The same author also describes and illustrates a bow from the twelfth century that contained a knob at the base of the stick, a design choice that appeared as a more elaborate notch in a fourteenth-century bow, also illustrated in the book. Most interesting is a bow from the thirteenth century that has the shape of a Baroque bow, with an angled head, and what appears to be a thin frog.

Sandys declares that bows used to perform on viols of the twelfth century were "like that of the double bass." He does cite, however, the same bow as van der Straeten, that resembles that used at the time of Arcangelo Corelli. This author attributes knowledge of this bow to a painting, from the late fourteenth century, depicting a heavenly ensemble, by Barnabas de Modena.

The most notable innovation in the design of the bow came in the fifteenth century, when a system, which van der Straeten calls a Crémaillère, was developed to allow for the hair to be tightened. The author illustrates both the crude fifteenth-century, and more elegant seventeenth-century versions of this device, in which a wire loop, attached to the frog of the bow, latched behind one of a row of metal teeth, that sat on top of the bow, at the end of the stick.

This wire loop and metal teeth system was later replaced with a screw that tightened the hair by drawing the frog back toward the end of the bow. This system, that is still used today, is first known to have been used for a Viol da Gamba bow shown in the *Harmonie Universelle* of 1634, by Marin Mersenne.

Also used in the seventeenth century was yet another system for tightening the hair of the bow, in which the hair was secured to the bottom of the stick with a plug, and then tightened by wedging the frog between the hair and the stick.

According to Abele, in the late seventeenth and early eighteenth centuries, Arcangelo Corelli and Antonio Vivaldi used a bow even less curved than that of the thirteenth century, with a sloping head, and a separate frog, secured by the same wire loop and metal teeth system described above. Because the violin music of the mid to late eighteenth centuries required a more agile bow, they were made from lighter wood, with a straight stick. Nicolas Pierre Tourte improved the design further, by crafting a head that allowed the hair to lay in a more regular swath, while his son, François Xavier Tourte, fixed the dimensions, balanced the weight, and broadened the width of hair on the violin bow.

Van der Straeten also attributes Tourte with the innovation of using the best Brazil wood, which the author calls Pernambuco, for all of his bows, and inventing, perhaps at the suggestion of Giovanni Battista Viotti, the slide and ferrule, which broaden and secure the hair at the bottom of the frog. The same innovation seems to have been simultaneously invented by an English bow maker named John Dodd.

The above discussion is meant to illustrate that, although some design choices of instrument builders were made for aesthetic reasons, most contributed to the expressive potential of the developing bowed-string instrument, culminating in the design of the modern violin. The vBow is an extension of this pursuit, to design an instrument that provides the performer with an amplification of their musical intent, through the translation of their physical gesture into the expressive manipulation of timbre. A similar study of evolving expressive potential can be made from the perspective of the performer, and in particular, the developmental history of violin bowing.

It is difficult to discern whether the demands, on the performer, of more expressive music lead to the development of advanced techniques, which in turn prompted changes in the design of the violin bow, or if performers and composers took advantage of the improvements of the instrument. Either way, there has been considerable evolution of bowing style and technique since the sixteenth century.

History of Bowing

In his article, *Differences Between 18th Century and Modern Violin Bowing* (Babitz, 1970), Sol Babitz discusses this evolution, starting with the eighteenth century. The bow from this period had a substantially different design from the modern bow. The early bow had much more curve to the stick, giving the hair much less elastic resistance than a modern bow. This pronounced curve results in a distance between the stick and the hair that is twice that of the modern bow, producing what Babitz describes as a "natural springiness."

Because of the inherent spring of this early bow design, the technique used by the performer was considerably different than that used with the modern bow. In addition to holding the bow further up the stick than the modern bow grip, Babitz instructs that the performer played each note with a dynamic swell and decay, because of the varying elasticity along the length of the bow.

> Because of this initial slackness or 'give' of the hair, the early bow does not produce its full tone at the first contact of the hair with the string, but only after some finger pressure has been exerted while starting the stroke. This application of pressure to the point where the hair will be sufficiently tensed to play a full tone causes a momentary softness, followed by a crescendo to the full tone at each stroke. By changing the finger-pressure it is possible to produce a variety of crescendi, ranging from the slow and gradual to the sudden and accented.

In contrast, the modern bow has a much thinner design, providing much less spring than the early curved model, resulting in what Babitz describes as a "clinging-to-the-string, even motion," when bowing. Because the elasticity of the modern bow is much more consistent along its length, there is no difficulty producing a strong tone from the start of the bow stroke at the frog, to the end at the tip. Consequently, there is no natural crescendo and decrescendo when using a modern bow. Because the modern bow imposes less of an inherent dynamic limitation on the performer, its design provides a greater expressive potential.

What is common between the modern and early violin bow is the primary contribution it plays and played in the execution of an expressive violin tone, even if what was considered appropriate expression has changed between stylistic periods. Babitz describes the bow of the eighteenth century as "the primary source of emotional expression," ideal for the singing and oratory effect of the Baroque Affektenlehre, or doctrine of the affections.

David Boyden discusses the developmental history of violin bowing further in his book, *The History of Violin Playing from its Origins to 1761* (Boyden 1975), starting with the violin and bow of the sixteenth century. Before writing about how the bow of the sixteenth century was held and drawn, Boyden describes the general design of this early bow.

> The length, weight, and shape of individual bows varied greatly, and the old bow in general differed from the modern bow in several important points of construction. The stick of the old bow curved outward and away from the hair, although the degree of curvature was an individual matter; and the hair was probably strung at fixed tension, not adjusted or adjustable by a screw as in later bows. Compared to the modern bow, the ribbon of hair on the old bow was narrower, and this combined with lower tension and the (generally) shorter length of the bow, made for a smaller volume of tone. The shape of the head and the nut of the old bow also differed from our bow today.

This author continues by speculating that the balance, which was very close to the frog, made it difficult to produce a strong articulation or tone, when bowing at the tip. This, along with the drastic arc of the stick and slack hair, allowed for an early bowing technique consisting of short halting strokes, articulating separated notes. This style of bowing, which Boyden describes as producing a feeling of "light and air" with "greater breath between the phrases," would have been appropriate for the dance music performed and the singing emulated by these early performers. According to Boyden, this design and early bowing technique contributed to the production of a "relaxed and smaller tone" on the violins of the sixteenth century.

Boyden contrasts the bow grip of the early violin, palm down, with the weight of the arm transferred to the bow, with that of the viol, palm up, with tension exerted on the hair with the second and third fingers. Because the lengths of bows varied, requiring more or less control, and the fixed hair tension of the time often required adjustment while playing, thumb position also differed between players. French players are depicted with their thumb under the hair, while Italian players are shown with their thumb between the stick and hair of the bow.

In a quote from Sylvestro de Ganassi's treatise, *Regola Rubertina,* dated 1542-3, Boyden reveals that timbral differences due to bow position were also considered in the sixteenth century.

> … the distance of the bow from the bridge is determined by the kind of effect and tone desired: well away from the bridge and near the fingerboard for sad effects; near the bridge for stronger and harsher sounds; and in between for normal playing.

Again concerned with the expression resulting from bowing technique, the treatise instructs the player to adapt their bow velocity to the style of music performed.

> Energetic bowing is recommended for lively pieces, and more relaxed bowing for music of greater expression …

But, despite the development of bowing technique to this basically expressive level, Boyden believes that, at the start of the seventeenth century, the violin represented an "undeveloped potential for personal expression throughout a wide range of diverse use." This unexplored expressive potential would begin to be charted through the seventeenth century, with the help of a refined bow design, and the development of an idiomatic style.

According to Boyden, aside from some decorative elements, the design of the violin was left unchanged during the early seventeenth century. Instead, improvements were made to the design of the bow. Relying on illustrations and descriptions from treatises such as Michael Praetorius' *Syntagma Musicum* and Marin Mersenne's *Harmonie Universelle*, the author describes how design elements of the bow were not standardized, early in the seventeenth century. For instance, short bows were used for dance music, while longer bows were used to perform sonatas.

Improvements to the design of the bow, during the seventeenth century, included lengthening the bow stick, and consequently the playable area of the hair; developing the screw and movable frog, for tightening the hair; making a distinct tip or head at the top of the bow stick, allowing for more bow control; and straightening and tapering the stick, making the bow lighter and more flexible.

As Boyden writes, these improvements to the design of the bow, were motivated by seventeenth century composers, from the areas of Europe known for violin making, such as Claudio Monteverdi, himself a string player, born in Cremona, and later working in Venice, who advanced the idiom of violin music, writing pieces that demanded greater technical skill.

> All these changes were ultimately caused by musical requirements, especially in Italy, where new instrumental forms like the sonata inspired bow makers

> to produce a longer bow capable of more subtle bow strokes, greater variety of tone, and an increased range of expression and dynamics.

Some examples of idiomatic violin effects, made possible by improvements of the bow's design in the seventeenth century, include tremolo, used by Monteverdi for his measured "stile concitato" or excited style, and, according to Boyden, unmeasured by Carlo Farina in his *Capriccio Stravagante*; and col legno, an effect where spiccato notes are played on the violin, with the stick of the bow. Also noteworthy are passages of sometimes slurred elaborately ornamental sixteenth and thirty-second notes, often including fast string crossings, which were called passaggi, and independent obbligato parts for the violin, accompanying the vocal parts in operas.

Other seventeenth-century composers continued to expand the technical demands placed on the violinist, including Italy's Arcangelo Corelli, who used bariolage, a rapidly alternating string-crossing effect, as well as sustained crescendo and diminuendo, in his many sonatas, and Germany's Heinrich von Biber and Johann Jakob Walther, whose variations included slurred staccato, arpeggiando across strings, and ondeggiando, an undulating slurred string-crossing.

In the eighteenth century, the bow, which Boyden entitles the "soul" of the violin, was perfected by François Tourte, attaining a standardized design that has not changed significantly, since. Some of the standardized design elements included setting the length of the violin bow to twenty-nine and a half inches, allowing for twenty-five and a half inches of playing surface; bending the stick into a concave curve, providing a stronger, more resistant response; crafting a larger, higher, and heavier tip or head, moving the balance point closer to the middle of the bow; and widening the hair, making it lie flat on the string.

Eighteenth-century composers, such as Antonio Vivaldi and Johann Sebastian Bach, took advantage of this improved, standardized bow design, by writing concertos and solo sonatas that required a powerful solo tone that could rise above the accompanimental orchestra, and more subtle control over timbre and dynamics. Some of these subtle bowing effects included smooth bow changes, expressive crescendi or diminuendi produced from variations in bow pressure, changes in bow speed to increase or decrease loudness, and more complex combinations of slurs and staccato markings, requiring a diversity of bow strokes. This diverse set of bow strokes included a variety of short, separated staccato effects, played both on and off the string.

The need for expressive potential in the design of musical instruments has now extended beyond acoustics to electroacoustics in the need for greater expression in the performance of computer music. In direct response, the vBow has been designed to accurately sense the bowing gesture with acute resolution, in order to expressively, physically manipulate the parameters of digital synthesis. The importance and difficulty of expressive performance of electroacoustic music has been discussed by a number of leaders in the computer music community.

Expression in Electroacoustic Music

In an article edited by Stephen Pope, Carlos Cerana, an Argentinean composer and researcher, asks the question, "could a music touched by machine touch us?" (Pope 1995). The concern Cerana raises in his essay is that electroacoustic compositions realized with or by a computer "have no relation with the body, that is, with the human way of connecting with the world." It may be difficult for an audience to connect with or derive expression from this category of electroacoustic composition, in which the computer is both the compositional tool and performer.

Chris Brown, a composer teaching at Mills College, shares in Cerana's concerns (Brown, Bischoff, and Perkis 1996). In an article entitled "Bringing Digital Music to Life," Brown states that the difficulty in composers realizing their pieces with software is that, in addition to having to build their own instruments, the instruments computer music programmers build are no longer physically performed. With the exclusion of a physical interface, the expression of this category of computer music no longer relies on the musicianship and technical skill of the performer, but rather on the sophistication of the programming.

> The composer has become an instrument builder, but the instruments are ethereal genies. … there is no implied relationship to the body; these instruments are concepts, … and so interface is arbitrary. … This may be the most limiting factor in the development of this instrumentation – a non-arbitrary physical interface provides the stability that allows a performer to develop a repertoire of intuitional responses to sound that is responsible for the liveliness of traditional instrumental performance. It isn't just that we need the technological means for controlling multiple simultaneous parameters of sound. We also need some physical reason for developing these means, which will allow the intelligence of the body to enter the music.

One obvious remedy for the artificial or disembodied nature of computer-generated music is to include a live performer in the composition. With the addition of a physical interface to the computer-music system, the composition again relies on the intuition of the player for the expression of the performance, a source to which the audience can relate.

But, this interaction between human performer and computer, as perceived by the audience, is a tricky consideration. In an overview of "ways the computer can participate in live performance," entitled "Who's Playing?: The Computer's Role in Musical Performance," Alan Belkin raises some concerns about how the perceived interaction between the performer and computer in an electroacoustic composition can affect the relationship between the performer and audience (Belkin 1991).

> This relationship, which is central to the concertgoer's expectations, and which indeed constitutes the main difference between live and recorded music, deserves serious consideration. When I go to a live concert I enter into communication with the performer, and through him, with the composer. If the performer becomes anonymous or seems disconnected from what I hear, I will find him irrelevant.

If the audience does not recognize the interaction between performer and computer music system, if there is no perceived correlation between performance gesture and musical result, then the experience of the audience is no more connected to or informed by physical performance than when listening to a piece for computer-generated sound.

Christiane ten Hoopen, while a student at the University of Amsterdam, wrote that this issue of "source identification" is "a crucial aspect in the comprehension of electroacoustic music" (Ten Hoopen 1992). Although Ten Hoopen does not seem concerned by the loss of a perceived "connection between sound and source," a phenomenon which he labels as "one of the innovative aspects of electroacoustic music," he describes this experience in contrast to the clear association between instrument or voice and musical production in "traditional Western art music," a relationship he states "has been challenged by contemporary music and destroyed by the electroacoustic medium."

> Listeners can be confronted with sounds of ambiguous provenance or sounds can exhibit plural sources. In certain cases we may even experience sounds which have no apparent linkage to sources by behaving or developing in such a way that listeners cannot think of a rational explanation of what their origins might have been.

Similarly, in a paper, entitled "Live and In Concert: Composer/Performer Views of Real-Time Performance Systems," Jon Appleton calls "the need to have the audience understand the musical parameters being controlled in performance," "a major issue faced by all performers of electroacoustic music," and quotes composer, Morton Subotnick as stating that "the audience does not know what the composer is controlling on an electronic instrument, so that the difference between live performance and a disk, or something that is going on in the background, is really not clear" (Appleton 1984).

So, the addition of a human performer does not assure that the audience will relate to the musical expression produced by the computer-music system. But, Belkin suggests that building an electroacoustic performance system, in which the function of the player is similar to that when performing acoustic compositions, namely "subtle control" of sound with "finely tuned physical gestures," could result in heightened electroacoustic musical expression, which he, like Brown, calls "liveliness." Belkin's proposed system, like the vBow, takes advantage of the training of the classical musician.

> The performer's ability to subtly control aspects of sound with finely tuned physical gestures, and to hear delicate nuances in the resulting music is cultivated from years of training. If this sensitivity and training are not to be wasted, the performer must be allowed to use his strengths in meaningful musical ways. The performer's gestures may be translated by the computer to affect novel aspects of the sound. If this is sensitively applied, the resulting performance can have a new vibrancy and liveliness.

In response to similar concerns about the "cause-and-effect relationship in live performance," composers and performers, Andrew Schloss and David Jaffe, developed an interactive performance system for their collaborative piece, *Wildlife* (Schloss and Jaffe 1993). Under an assumption that "one of the significant aspects of live performance (from the point of view of the audience) is virtuosity, and that there is a danger that perception of virtuosity may erode as new technologies are applied to musical performance," the duo created an interactive system, using a Mathews/Boie Radio Drum, Zeta violin, and computers, in which the two performers could control the musical output of the other's instrument, as well as that generated by the computer, in an improvisatory context.

Like Belkin and Ten Hoopen, Schloss and Jaffe were concerned that, while "real time music systems (like MAX and the Music Kit) have greatly increased the power of the player", they have, at the same time, "exacerbated the issues of clarity in performance."

> Controlling sound on the timbral level typically requires great skill, but it is usually very clear what the intention of the player is (e.g. vibrato or glissando) – there is little danger of the audience's losing site [*sic*] of the meaning of a performer's gesture. Unfortunately, most current controllers

> do not always fare well in this domain, primarily due to the influence of the keyboard-orientation of MIDI.

These authors name "the impoverishment of the MIDI specification" as a principal reason for the loss of virtuosity among players of new controllers. Not only does the use of some electronic controllers in the performance of electroacoustic music cause confusion for the audience, but also these instruments limit the expression of the player. Schloss and Jaffe cite the case of the MIDI wind controller, which is "vastly less powerful than real instruments in terms of nuance of control."

> Even though they may be connected to powerful synthesizers, they tend to be less expressive than their acoustic counterparts. In particular, they have limited refinement in their control of pitch, timbre, and dynamics.

Their solution to the challenge of preserving the tradition of virtuosity in the performance of electroacoustic music, made worse by the limited expressive potential of MIDI controllers, was to create a system, where "all materials are generated in direct response to the performers' actions," and the players were able to improvise their own part, while, at the same time, influencing the musical output of the other instruments and computers, with the MIDI output of their controllers.

In the same article by Appleton, mentioned previously, William Buxton also describes the limitations imposed on the performer by electronic musical instruments, although MIDI is not explicitly mentioned, in this early paper. The Canadian designer and researcher is quoted as saying that "a major problem of synthesizers to date, especially recently, is that they constrain the performer to expressing ideas through a limited set of gestures." He states that often "the medium of expression" of these synthesizers is "at odds with the musical idea." Because of this, in his instrument designs, he strives to "enhance our ability to capture physical gesture and map it to sonic gesture," a goal I share in the development of the vBow.

The expressive limitations imposed on the performer of MIDI instruments is elaborated upon by F. Richard Moore, in his landmark paper, "The Dysfunctions of MIDI" (Moore 1987). Like Schloss and Jaffe, Moore believes that the ability to subtly control musical expression is a vital characteristic of any performance system.

> We are acutely sensitive to the expressive aspects of sounds, whereby a performer is able to make a single note sound urgent or relaxed, eager or

> reluctant, hesitant or self-assured, perhaps happy, sad, elegant, lonely, joyous, regal, questioning, etc. The more a musical instrument allows such affects to be reflected in the sound spontaneously at the will of the performer, the more musically powerful that instrument will be.

This characteristic of an instrument, its ability to correlate "the variety of musically desirable sounds produced and the psychophysiological capabilities of a practiced performer," which I call expressive potential, Moore names "control intimacy."

Moore cites the violin as good example of an instrument "exhibiting large control intimacy," explaining that instruments like the violin "allow the performer to evoke a wide range of affective quality in the musical sound," by mapping "the microgestural movements of the performer's body" to sound producing parameters. Moreover, the author states that, to emulate the expressive potential of the acoustic violin with an electronic controller, these mappings must be consistent and timely, especially when dealing with "continuously variable control functions," such as vibrato or crescendo.

Controlling these varying synthesis parameters with MIDI is made difficult by the limited bandwidth, or amount of data that can be transmitted within a given time, of the protocol. The bandwidth of MIDI would be sufficient for transmitting the continuous data generated by vibrato changing the pitch of the violin string, but there would be no bandwidth left to represent any other "realtime performance control parameters." Because of this limitation, data is often "clipped" or rejected when the maximum bandwidth is exceeded, reducing the expression of the performance to a level that the MIDI protocol can transmit in time.

Furthermore, transmission of MIDI data from a controller is subject to delays and fluctuations in transmission time, limiting the subtle expressive control of the performer. Often, to compensate for this latency, "the information for complex events may be precomputed so that it may be stored inside the synthesizer and simply triggered when it is needed," limiting the expressive control of the performer over the sound synthesis output of the instrument. These are the very reasons that the vBow uses parallel data streams, from the encoders at the back of the servomotors, to the ServoToGo data acquisition card, instead of a serial MIDI stream, to transmit sensor data to parameters of the sound synthesis programming.

Despite these limitations of MIDI instruments, Moore makes a case for the development of controllers for the performance of computer music, based on the need for a physical interface to sound synthesis, stating that the "physical capabilities of human performers are simply too magnificent to be ignored altogether in any form of musicmaking." In addition, he acknowledges the importance of haptic feedback to instrumentalists, and seems to suggest the inclusion of force feedback in the design of musical controllers.

> For subtle musical control to be possible, an instrument must respond in consistent ways that are well matched to the psychophysiological capabilities of highly practiced performers. The performer must receive both aural and tactile feedback from a musical instrument in a consistent way – otherwise the instrumentalist has no hope of learning how to perform on it in a musical way.

The limitations, imposed on the performer by the MIDI protocol, also concern Simon Emmerson, from City University, in London (Emmerson 1991). According to the author, quantizing sensor data to fit within the range of MIDI pitch and velocity values and limiting sensor readings to the resolution of "discrete clocked time," impoverishes "the analysis/transduction process." Instead, Emmerson suggests that "high resolution data" be used, and that "controller-produced value ranges match the range of parameter values to be controlled."

Like Schloss and Jaffe, Appleton is concerned with the virtuosity or performance practice of electroacoustic music (Appleton 1986). In an article entitled "The Computer and Live Musical Performance," the composer discusses the importance of musical interpretation in a performance, stating that "perhaps the most crucial aspect of live performance is the unique character of the event itself," a quality that is lost when electroacoustic music is performed by a computer or played from a tape or CD. But, while he recognizes the importance of interpretation to the audience's enjoyment of a performance, he acknowledges that, because the gestures of electroacoustic are still new to us, the interpretation of electroacoustic music may be lost on us. His hopeful conjecture is that "as a repertoire develops a performance tradition will follow; a performance tradition in the widest sense of the word, encompassing both the performer's technique and the audience's understanding of same."

For Joel Chadabe, this new performance practice of electroacoustic music involves placing a performer in "an unusually challenging performing environment" (Chadabe 1983). The system that he describes is similar to that developed by Schloss and Jaffe, in which the performer and computer share control over the music generated.

> An interactive composing system operates as an intelligent instrument – intelligent in the sense that it responds to a performer in a complex, not entirely predictable way, adding information to what a performer specifies and providing cues to the performer for further actions. The performer, in other words, shares control of the music with information that is automatically generated by the computer, and that information contains unpredictable elements to which the performer reacts while performing. The computer responds to the performer and the performer reacts the computer, and the music takes its form through that mutually influential, interactive relationship.

But, in response to the same concerns expressed by Belkin and Ten Hoopen, Chadabe recommends that, in addition to being interesting, informative, new, and unexpected, the response of the electroacoustic performance system must be "recognizably related to the performer's actions," not for the sake of the audience's enjoyment, but to make the interaction meaningful for the performer. He likens this performance practice to a conversation, where both parties have shared control over the resulting expression.

Johannes Goebel takes issue with using the term "interaction" to describe a system "where one side is not alive" (Goebel 1988). For this researcher, the term is used optimistically to describe not the current state of interactivity, which he more accurately terms "man-machine reaction," but rather a future "realm of mutual, reciprocal action between two partners who act on the ground of equal potential."

This issue of "what do computers bring to live performance" as well as the reciprocal question of "what does live performance bring to computer music," is at the foundation of Guy Garnett's paper, "The Aesthetics of Interactive Computer Music" (Garnett 2001). For this composer and researcher, the importance of incorporating the use of computers into a piece of interactive electroacoustic music lies in the ability of the computer to extend the performance capabilities of the human. And furthermore, whether the computer is processing the signal from an acoustic instrument, using data from sensors added to an acoustic instrument to enhance the performance, or mapping sensor data directly to sound synthesis parameters, this extension of human performance represents, for Garnett, an essential aesthetic response to current technology.

> To make music with the technology of our time, and specifically the computer, poses a tremendous challenge for the artist. To address this challenge, in itself, will help keep music alive and significant. To address this challenge in a way that acknowledges, directly and deeply, the human production of that music brings together into a new art form the diverse

> elements of performance, with its millennia of history, and the age of the computer, with its bare decades of history.

Similarly, for this author, the importance of the inclusion of a human performer in the presentation of a piece of electroacoustic music lies in our ability to add "gestural nuance such as rubato, subtleties of phrasing and articulation, and dynamics" and interpretation to the work.

Composer and researcher, Cort Lippe also asks how the computer contributes to live performance, in his paper, "A Look at Performer/Machine Interaction Using Real-Time Systems" (Lippe 1996). The answer to his specific question, "can the computer have a unique function in a real-time concert situation?" appears to be no. According to the author, "the computer appears to be a useful tool for creating new sounds, transforming pre-existing sounds, and controlling algorithmic compositional structures," none of which exclusively require the functionality of the computer. In the case of the vBow, and similar sensor-based instruments, however, I would argue that the ability to program both how the instrument sounds and feels, can only be done with a computer, making its function in this interactive computer music context unique.

In support of Goebel's concern, Stephen Horenstein, from the Jerusalem Institute of Contemporary Music, writes in his paper, "Interactive Works: New Problems and Potentials," that this new electroacoustic performance practice requires "new physiological techniques" to produce "a spontaneous, expressive performance" (Horenstein 1995). Because the player must incorporate "foreign gestures into his technique vocabulary" to ensure that the computer tracks the performance, the "expressive realization" of the piece is inhibited.

> For the computer to track the performer's input properly, the performer is often required to execute exaggerated tonguing, forced extreme dynamic changes, slower unnatural speeds, minimized use of pitch bend nuance, and reduced timbre change. These necessary restrictions can easily detract from the performer's natural expressivity. The performer's comprised "adapting" to such restrictive environments is one of the unfortunate results of this process.

In order to adapt to the difficulties of this new performance practice, Horenstein envisions making these extended techniques a part of instrumentalist's training, to foster "the vital importance of the human performer and his innate creativity," in the performance of interactive electroacoustic pieces.

In her article, entitled “Performance Practice in Computer Music,” violinist and composer Mari Kimura addresses many of these issues faced by performers of electroacoustic music (Kimura 1995). Of particular interest is her discussion of problems encountered when performing interactive computer music. In two specific and in-depth case studies, the author outlines the difficulties she had with interactive performance systems for Robert Rowe’s piece, *Maritime*, and her own, *“U” (The Cormorant)*. In both cases, limitations in the technology interfered with her expressive interpretation of the piece.

For her piece, *“U”*, the violinist experienced difficulties when pitch-tracking an acoustic violin amplified with a microphone. Because the microphone amplified the upper harmonics of the violin, a problem that was exacerbated by the live acoustics of the hall, the pitch tracker was unable to accurately translate the notes of the violin into MIDI data. Since Kimura had programmed safeguards into the piece, such as triggering the computer-generated music with a particular series of pitches from the violin, the problems with pitch tracking had a devastating effect on the performance of the piece. In order to compensate for the limitations of the technologies used for the work, the composer had to reprogram the piece, often sacrificing her musical ideas for technological logistics.

The violinist’s problems, when performing Rowe’s *Maritime*, arose from the limitations of the Zeta MIDI violin used. Despite the capability to fine-tune the response of the system, Kimura found the level of control over pitch and dynamic “incomparable to that of the acoustic violin.” Furthermore, the limited capabilities of the pitch-to-MIDI converter required that she restrict the expression of her bowing gesture.

> …it is unfortunate that in playing Zeta violin, one of the most essential elements of string playing, the sensitive art of controlling the articulation, might have to be sacrificed to adjust to the capability of MIDI and pitch tracking. For string instruments, the bow is what creates articulation. It would be interesting to see more development in computerized bows, rather than motion sensors attached to the fingerboard or a bow arm.

Kimura describes additional problems with the pitch tracker, incorrectly identifying notes played on the violin, because of the “complicated harmonic structure” of the instrument, transposing the octave of low pitches, and being unable to track accented strokes.

According to Miller Puckette and Zack Settel, these complications, inflicted on the player by interactive computer music systems, may actually enhance their performance (Puckette and

Settel 1993). Citing Freud's theories about the conscious and unconscious mind, these authors believe that diversions such as crashing computers, errant pitch trackers, foot pedals for synchronizing the player with the computer, video monitors, flashing lights, or click tracks for keeping time, wearing homemade equipment, short cables limiting movement, and poor monitor levels, facilitates the influence of the unconscious mind on the performance, improving the expression of the piece.

> In diverting the performer's thoughts from the details of the violin part, to the agonizing question of whether the machine was following correctly (and whether it would work at all,) the presence of live electronics may actually have improved the violin playing.

Despite this possible psychological benefit realized from the challenge of performing with machines, Puckette and Settel acknowledge that new musical interfaces should "make sense" to the performer, taking advantage of the "years of training and experience" of the player. In addition, they recommend that, since "for controlling articulation, only physical feedback is fast enough," new musical controllers should provide force feedback.

Guy Garnett and Camille Goudeseune, at the University of Illinois at Urbana-Champaign, have approached the problem of ensuring that a new musical controller makes sense to the performer, not by developing a better instrument, but "by improving tools for understanding and designing the mappings between the physical interfaces and resultant sounds" (Garnett and Goudeseune 1999). Using an interface that included "an electric violin tracked continuously in pitch, amplitude, and full spatial position/orientation of bow and instrument body," which enabled "a trained violinist to feel relatively 'at home' with the instrument," the team worked to map physical gestures to sound synthesis, in ways that simplify "the performer's idea of the instrument and the sounds it produces without impoverishing the sonic output or overloading the attentive capacity of the performer." Taking advantage of the practiced technique of the violinist avoided the need for physical retraining, and clarifying the mapping between physical gesture and sound synthesis parameters prevented the need for cognitive retraining.

In order to keep these simplified mappings musically interesting, Garnett and Goudeseune used a "geometrical, numerical mapping," called "simplicial interpolation," to correlate gestures to sound. The result was an ability to map one control parameter to many sound synthesis parameters or many control parameters to one sound synthesis parameter.

One of David Wessel's ideas for future improvements in computer music technology, as expressed in his article, "Instruments That Learn, Refined Controllers, and Source Model Loudspeakers," is musical controllers that use "very small and unobtrusive musical instrument transducer systems," such as pressure sensors and accelerometers made from "microdynamic silicon structures with moving parts," that combine "high-performance sensors" with "on-chip circuits for the processing of the sensor data" (Wessel 1991). According to this composer and researcher, this new technology would allow for "new generations of alternate controllers," as well as "adapting traditional acoustic instruments to be effective controllers."

For Wessel, development of a refined musical controller from this technology would facilitate an improvement in the "control intimacy," or "tight coupling between gesture and instrumental response," of the instrument, something that this author considers "one of the critical missing elements" in current computer music technology.

> The use of traditional instruments as controllers shows promise, but there are still problems with pitch extraction, the keyboard bias of the MIDI specification and its bottleneck data rate, and the fact that it is still very difficult to readily outfit a musician's preferred instrument, be it a Stradivarius or a Gibson guitar, with the acoustic and positional gesture sensors that are required to make it a refined controller.

This coupling between gesture and feedback is also the subject of Marcelo Wanderley's paper, "Gestural Control of Music" (Wanderley 2001). Specifically, this researcher is concerned that "new computer-based musical instruments – consisting of gesturally controlled, real time computer-generated sound" be designed so that they "obtain similar levels of control subtlety as those available in acoustic instruments." In order to do so, the author suggests that electroacoustic musical instrument designers recognize their connection to the study of "human-computer interaction."

> Gestural control of computer generated sound can be seen as a highly specialized branch of human-computer interaction (HCI) involving the simultaneous control of multiple parameters, timing, rhythm, and user training

Wanderley divides the electroacoustic performance system into the "gestural controller" or instrument hardware, "sound generation unit" or synthesis software, and "mapping layer" or routing of performance gestures through controller outputs to synthesis parameters, a separation that is not possible for acoustic instruments. Each of these three components must be considered when designing a new electroacoustic instrument, or musical human-computer interface.

According to Wanderley, the musical controller should be designed with the gestures of the instrumentalist in mind. In the case of the vBow, the interface was designed around the four primary component gestures of bowing a violin string: lateral, rotational, vertical, and longitudinal motion.

Similarly, the author states that when studying performance gestures, in preparation for designing a musical controller, "it is also important to be aware of the existing feedback available to the performer, be it visual, auditory or tactile-kinesthetic." The vBow was designed to simulate the auditory and tactile-kinesthetic feedback expected by the player of an acoustic violin.

When choosing a mapping strategy for an electroacoustic musical controller, both the output of the controller and the parameters of the sound synthesis should be considered. How the instrument output is routed to the sound input will vary depending on what type of synthesis is used. The author states that "for the same gestural controller and synthesis algorithm, the choice of mapping strategy may be the determinant factor concerning the expressivity of the instrument." By changing mapping strategies of controller outputs to synthesis parameters from one-to-one, one-to-many, and many-to-one, while keeping the controller and synthesis parameters consistent, the researcher discovered that "different mappings did influence the expressivity obtained during the playing."

In his discussion, Wanderley mentions the obvious direct, one-to-one mapping strategy represented by routing the vBow sensor output to the parameters of a bowed-string physical model.

> For the case of physical models, the available variables are usually the input parameters of an instrument, such as blow pressure, bow velocity, etc. In a sense the mapping of gestures to the synthesis inputs is more evident, since the relation of these inputs to the algorithm already encompasses the multiple dependencies based on the physics of the particular instrument.

Because the vBow and bowed-string physical model were both designed around the composite gesture of bowing on a violin string, a direct mapping between sensor output and sound input was an obvious and convenient choice.

Finally, Wanderley weighs the pros and cons of using a physical model versus a signal model for the synthesis of an electroacoustic musical controller system. While physical models allow a "realistic simulation of a given acoustic instrument," they also present a "complexity" in real-time performance, an aspect of the bowed-string physical model that the vBow is designed to explore. Signal models, like additive synthesis simulations of instrumental timbres do not provide the "full behavior of the original instrument," but do offer the flexibility of "continuous transformations between different instruments," another interesting performance scenario that the vBow is equipped to investigate.

As Moore and Wanderley alluded to, instrumentalists respond to both aural and tactile feedback, when performing on their instrument. The usefulness of this haptic feedback can be evaluated by whether or not the kinesthetic response of the system assists with the playability of the instrument. Force feedback is useful if it provides the performer with cues that support the acoustic response of the instrument or sound synthesis output of the controller, so that the performance can be judged cross-modally by the player. The vBow has been designed to provide this haptic feedback to the performer, by simulating tactile cues, with the use of servomotors and cable systems. The importance of these cues, to musical performance, has been researched by scientists studying the interaction between the player and instrument.

Musical Haptics Research

Claude Cadoz, Leszek Lisowski, and Jean Loup Florens write about the importance of haptic feedback to an instrumentalist, in an article describing the development of their "modular feedback keyboard" (Cadoz, Lisowski, and Florens 1990).

> The standard gestural instrument-performer relationship is bidirectional. This indicates both a transmission … and a reception: at the very moment of the instrumental gesture, a tactilo-proprio-kinesthetic perception takes place. This in turn informs us of the nature of the object we are manipulating and how it behaves. It also provides us with manipulation possibilities and even signals the nature of the sound phenomenon itself.

This haptic relationship between performer and instrument has been scientifically studied, by a number of researchers. In their seminal study of tactile feedback from acoustic stringed instruments, Anders Askenfelt and Erik Jansson, at the Royal Institute of Technology in Stockholm, studied vibration levels in the violin, as well as the double bass, guitar, and piano, and finger forces on the bow, as well as the piano key (Askenfelt and

Jansson 1992). These scientists wondered if vibrations of stringed instruments are perceived by the player, and, if so, if they assist with performance. In addition to these pragmatic questions, Askenfelt and Jansson conjectured whether or not these vibrations add to the pleasure of playing, and speculated if players of electronic instruments are missing part of the performance experience.

> … a provoking question to ask is whether or not the vibrations can contribute to the excitement of playing. Could it be that the vibrations convey a feeling of a resonant and "living" body? If so, the design of modern instruments, which rely on electronic devices to generate sound, could possibly be improved. By supplying additional vibration to the player, not required for actual sound generation, the "vibratory quality" of the traditional instruments could be mimicked.

For their study, Askenfelt and Jansson placed miniature accelerometers on the top plate of the violin, just below the left f-hole, a position that corresponds to the maximum of the lowest mode of vibration, as well as on the back plate, where the shoulder makes contact with the violin, and on the chin rest and neck of the violin. They also measured vibrations on the bow, with accelerometers placed at the back of the frog, to measure longitudinal vibrations, and on the bottom of the frog, to measure transverse vibrations.

For the range of frequencies in which fingertips sense vibration, below 1000 Hz and strongest at 250 Hz, the researchers measured vibrations within a 20 dB range, from *pp* to *ff*. The measurements indicate that vibrations transferred from the chin rest to the chin, the back plate to the shoulder, and the neck to the hand, are perceptible throughout the frequency range, or while playing all strings of the violin, and vibrations transferred through the frog to the bow hand, can be detected for low frequencies, or while playing the bottom two strings of the violin.

In addition to the vibrations detected by the player, the kinesthetic forces produced by the interaction between the bow and strings, and fingers and strings, are sensed by the player, and may be used to assist with timing in performance. These forces, the vertical "bow force" of the bow pushing against the strings, and the lateral "drawing force" of the bow pulling the strings, were measured by Askenfelt and Jansson, who speculate that the initial resistance and release of the string, during a bow stroke, and the inertia of the bow and hand, during changes in bowing direction, may provide timing cues to the performer.

Two researchers at Stanford University's Center for Computer Research in Music and Acoustics (CCRMA), Chris Chafe and Sile O'Modhrain, have conducted a number of experiments on musical tactile feedback. By comparing recordings of his Celletto electronic cello, with readings from accelerometers attached to the nail of the index finger of the left hand, Chafe was able to analyze the tactile feedback cues received by the fingering hand of a cellist (Chafe 1993). When playing a natural harmonic, the index finger sensor registered subharmonic transients that were buried in the audio signal, amplified from the bridge transducer of the Celletto. Even though the resultant pitch of the natural harmonic was beyond the range of frequencies felt by the fingertip, "note onsets, bow direction changes, and abrupt stops" were sensed "as brief vibrations at the fingertip."

When playing a pitch that was in the range of frequencies felt by the fingertip, in this case 110 Hz., not only were the initial onset and a continuous vibration felt, but also, initial quasi-periodic transients at the frequency of 123 Hz., that were not sustained in the tone of the Celletto, were felt by the fingertip. The frequency of this vibration, one tone higher than the pitch of the played note, "corresponds to the string length between fingertip and bow," and is caused by "the bow hair sticking to the string immediately after a quasi-pizzicato." From these findings, Chafe deduced that "fingertip vibration can be used to gauge the time and length of articulation."

To apply his findings to a computer-music application, Chafe constructed a haptic transducer, constructed from a voice coil actuator and a strain gauge, attached to a flexible metal bar. The readings from the strain gauge were used as data for the lip tension parameter of a brass physical model, and the audio output from the physical model was used to drive the voice coil, vibrating the metal bar. With the haptic feedback of "bumps," corresponding to changes of an overblown harmonic, the user was able to play the brass physical model with more control than without the tactile cue.

O'Modhrain joined Chafe for a study planned to "exploit the sense of touch in music editing tasks" (Chafe and O'Modhrain 1996). Using a haptic mouse, called the Moose, the pair developed a system for displaying the "effort" of contrasting performances by two pianists, with force feedback. Musical effort, which was calculated from normalized velocity, actual rhythm, and nominal rhythm, was mapped to resistive force, producing a contoured virtual wall, with the haptic interface. This virtual wall displayed a large-scale contour, representing the long-term phrasing, and small-scale deviations, showing short-term expression. Coupled with a MIDI realization of the performances, the system allowed the user to navigate between the two performances, by moving between two resistive contour walls, mixing the recorded musical expression from the two players. The project was successful in reducing complex musical performance data into “one simplified, intuitive, musical dimension,” that could be experienced and manipulated in real-time.

O’Modhrain continued this research, with the development of a system, using the same haptic interface, that displayed the similarity between a performance, and eight other performances, by moving the haptic mouse, representing the new performance, within a space bordered by eight points, representing the recorded performances (O’Modhrain 1997). Based on ideas from Gestalt psychology, the system was meant to “create a new haptic interaction with a piece that has nothing to do with how it is played physically but instead tells us something else about its performance.”

Taking advantage of the established haptic relationship between performer and instrument, and the narrative element in listening to and remembering a performance, the system provides two modes of tactile feedback during the listening of a performance. The first mode moves the hand of the user, with the haptic interface, toward one of eight performances, based on similarities between the recorded performances and statistical analysis of the new performance. The second mode allows the user to navigate between the recorded performances, auditioning their expressive characteristics, by hearing the auditory playback on a MIDI piano, and feeling the relationships between the recorded and new performances, as connecting springs or grooves.

For the next study, O’Modhrain and Chafe used the Moose as a virtual Theremin, to test if adding haptic feedback improved the “playability” of the instrument (O’Modhrain and Chafe 2000a). By mapping the y axis of the haptic mouse and one of six force-feedback conditions to pitch space, and measuring the deviation from pitch in melodies performed on the Moose, the researchers were able to determine the effect of haptic feedback on pitch accuracy. Haptic feedback of viscous damping, and positive and negative constant force and spring were simulated by the Moose, and the sound of a Theremin was played through the computer speaker, while subjects performed the melodies by moving the haptic mouse, in unison with melodies played by the computer on a software synthesizer. The statistical analysis of performance data showed that haptic feedback improved playability, or pitch accuracy, by twenty-three percent. The force-feedback condition that most improved pitch accuracy was positive spring, in which resistive force increased with rising pitch.

In a similar study, the researchers used the same virtual Theremin system to test “how players internalize the dynamic behavior of a new musical instrument” (O’Modhrain and Chafe 2000b). Based on a hypothesis that subjects would adapt to the force-feedback conditions produced by the Moose, the study tested subjects playing a melody with and without haptic feedback, after they had trained on a series of other melodies with haptic feedback. Results from this study showed that although subjects took longer to adapt to the viscous damping than the positive spring force-feedback condition, training eliminated the predilection for the positive spring condition, shown by subjects in the previous study. The evidence from this study supports the theory of these researchers that “adding haptic feedback to interfaces for computer-based musical instruments improves the player’s ability to control these instruments.

The Moose has also been used by O’Modhrain and Chafe, along with Stefania Serafin and Julius Smith, to test the playability of a bowed-string physical model, with the addition of the haptic feedback of “the normal and friction forces present during bow-string interaction” (O’Modhrain et al. 2000). Mapping values from the encoders, for the x axis of the haptic mouse, to the lateral motion of a bow moving across a violin string in the bowed-string physical model, and the y axis, to the vertical motion of the bow pushing into the string, the Moose could be played like a short length of violin bow. With the addition of normal and frictional forces, calculated by the physical model, and produced by the haptic mouse, the user could feel, as well as hear, the output of the physical model. Like the previous studies, this experiment suggested that the addition of haptic feedback improved the playability of the bowed-string physical model.

Summary

The planning and construction of the vBow was motivated by the same considerations of musical expression as these developmental histories of the acoustic violin, violin bow, bowing technique, electroacoustic music, and musical haptics. As an instrument builder, I created a design and used equipment and materials that would maximize the expressive potential of the instrument. As a performer, I needed an instrument that would sense my bowing gesture with acute resolution, affording me the greatest dynamic and timbral range possible. As a computer musician, I wanted an interface that would expressively shape computer-generated sound according to my physical gesture. And, as a researcher, I built a haptic human-computer interface that provides the kinesthetic feedback upon which musicians rely. My design choices were further motivated by my experiences and expectations as a composer, performer, and researcher, and influenced by my observations of work by other computer musicians and instrument builders, as explained in the next two chapters.

CHAPTER 2
MOTIVATION

Composition

While studying electroacoustic music with Jonathan Berger and Jack Vees at Yale University's Center for Studies in Music Technology (CSMT), I wrote an interactive computer music piece, *Stasis*, for soprano, MIDI violin, computer, and sampler. The piece simply used the pitch output of the IVL Technologies VC-225 Violin MIDI Controller, which converted frequency and amplitude to MIDI pitch and velocity, for the Zeta RetroPak MIDI violin pickup, that was attached to an electric violin beautifully designed and expertly crafted by Eric Jensen, to trigger algorithms written in the Max graphical programming environment.

While soprano, Beryl Lee Heuermann and I performed the piece, violin notes would signal to the computer the beginning and ending of sections of the piece, starting and stopping the computer accompaniment. The rhythmic algorithms generated musical material using predetermined sequences of pitches, sometimes randomly choosing the length or speed of the musical phrase, while driving a sampler loaded with sound files of different consonant and vowel combinations sung by the soprano voice, convoluted and mixed with sustained and pizzicato samples of the violin.

The piece was both musically and technologically successful, partly because my expectations of and demands on the pitch-to-MIDI converter were limited, and also because the resulting interaction aesthetically matched the sparse texture and restricted musical material of the piece.

Later, I decided to write a composition that attempted to use the MIDI violin as an expressive controller, capable of converting fast tremolos and trills into streams of MIDI notes and velocities, that were harmonized into expansive chords impossible to play on the violin, by Max programming. The piece, *Strata*, for MIDI violin, computer, and computer-generated sound, was technologically a disaster, and consequently musically a failure.

Although the computer-generated sound, which was a study in the granular synthesis of male and female voices, swept seamlessly around the stereo field within a wide dynamic range, the MIDI streams generated by the electric violin stuttered within a limited and erratic dynamic range. In addition, loud percussive interruptions to the swelling undulant texture, played on the violin, were ineffectually delayed and shortened, and dynamically unpredictable. Because of latency in the transmission from pitch-to-MIDI converter, through Max programming running on a Macintosh IIci computer, to a SampleCell II sampler card, the interplay, between densely clustered, granulated computer-generated sound and the harmonized tremolos and trills generated by the MIDI violin, was lost. Furthermore, because of errors translating bowed dynamics into MIDI velocities, percussive and rhythmic elements of the violin part were missed.

From the frustration of this project came the idea to build a violin controller that could directly track the bowing gesture of the performer, no longer relying on the pitch-to-MIDI converter to translate the signal resulting from the bowing gesture. With a violin controller that could map the wide dynamic and expressive range of bowing technique to sound synthesis parameters, I would be able to write interactive computer music, without having to compromise musical expression for technical logistics.

Performance

Since I am a violinist, it is important that I use a controller that takes advantage of the years of training I have had as a violinist. I do not want to perform using a joystick or other alternative controller. Although such an interface may allow for several degrees of freedom, that can be mapped to multiple synthesis parameters, I have not spent several years studying how to expressively perform a joystick. I have learned how to use a violin bow to subtly vary my performance, producing a wide range of dynamics and types of musical expression.

To begin with, it should be understood what intricate and precise mechanics are involved when bowing, a gesture that requires a most flexible instrument and technique. Percival Hodgson, in his book, *Motion Study and Violin Bowing* (Hodgson 1958), approaches the study of bowing from two interesting and enlightening perspectives. By analyzing the mechanics of the performer's arm and hand, as well as the bow, the author presents the interconnected motions that comprise the bowing gesture.

Hodgson begins with the violinist's arm, describing it as a "system of levers," the hand hinged at the wrist, forearm attached to the elbow, and upper arm joined at the shoulder. Each lever is controlled by opposing muscle groups, that move the lever in opposite directions, and the component levers and muscles of this system are interdependent in the execution of the bowing gesture.

The upper arm allows for the "greatest freedom and range of action," due to the ball and socket joint at the shoulder. The two bones of the forearm provide for both a hinge-joint and pivot-joint at the elbow, allowing for the combination of lateral and rotary motion. And, the joint at the wrist permits both "flexed" and lateral motion, that is limited in range. Hodgson likens the function of the wrist and hand in this system of levers as "a set of extraordinarily adaptable springs," that, although not directing the overall motion, contribute to the total gesture.

> The arm as a whole forms a wonderful bowing machine, and without the supple adjustments of the smaller members the work could not be done.

Next, the author explains the mechanics of the bow, considering it another lever, extended from the system of levers comprised of the upper arm, forearm, and wrist and hand. This additional lever, which balances on top of the pivot-point of the thumb, exhibits complicated behavior, however, due to the variations of elasticity at the tip, middle, and frog of the bow. While applying force at the tip, the hair does not give, but the stick will flex. At the frog, the hair gives, but the stick remains rigid. And at the middle, both the hair and stick bend.

It is further explained that none of these levers act independently during the execution of a bowing gesture, but instead work in concert, each in varying degrees. For instance, when each of the four open strings of the violin is played in succession with a legato bow, the bow is both moving in a straight lateral motion, while at the same time rotating over the arch of the four strings strung taught over the arcing bridge. If then the same notes were played with a spiccato bow stroke, then vertical motion would be added to the geometry. Interestingly, Hodgson graphs these complicated bowing gestures, comprised of multiple kinds of motion, as curved-line patterns from the perspective of the hand, at the frog of the bow.

Having studied the violin since an early age, this complicated system of levers or composite motion has become second nature. Because I take for granted the intricate mechanics of the bowing gesture, and rely on it to vary the expression of my performance, it is important that the controller I design allow for the execution and tracking of these complex motions. This is why the vBow was conceived of as a system of sensors, each independently tracking the constituent movements of the bowing gesture, lateral, rotational, vertical, and longitudinal motion. The only movement not accounted for is the wrist rotation that allows for varying the width of bow hair used.

To appreciate the design choices made during the construction of the vBow, it is important to understand how these component movements are combined to produce and vary the tone of the violin. Both an explanation of bowing technique by virtuosi and an analysis of bowing parameters by researchers will be discussed in the subsequent chapter about the vBow software.

Synthesis

About the time that I started building the first version of the vBow, I learned of Stefania Serafin's work on the bowed-string physical model. Not only had she developed the model further, but she had implemented a Synthesis ToolKit (STK), as well as a Max/MSP object of the model. Because I was programming the vBow software in C++, and because the sensor output of the vBow hardware could be mapped directly to the parameters of the bowed-string physical model, using Serafin's STK version of the model was an obvious choice.

In addition, Serafin was working with Sile O'Modhrain, testing the playability of the physical model, by driving it with the output of the Moose. By simulating a short length of bow, with the puck of the Moose, the researchers were able to vary the bow velocity and force parameters of the bowed-string physical model with the x and y axis of the Moose. Although the experiment demonstrated that the model was expressive and responsive to controller interaction, the Moose only permitted a limited lateral and longitudinal motion, for simulating two of the three component movements of a short bow stroke.

The design of the vBow, directly sensing the lateral, vertical, and longitudinal motion of the bowing gesture, is an ideal interface for mapping controller output to the bow velocity, force, and position parameters of the bowed-string physical model. And, because the vBow allows for a full bow stroke, as well as a full range of motion for moving above and pushing into a virtual string, and moving toward the virtual bridge or fingerboard, it is an excellent instrument for testing the expressivity of the bowed-string physical model.

Furthermore, before starting work on the vBow, I experimented with a hybrid approach to additive synthesis, in which each partial of an analyzed instrumental timbre was resynthesized with not only a sine wave oscillator, but also a pair of oscillators for frequency modulation, a pulse train and resonant filter for subtractive synthesis, and a Karplus-Strong plucked-string physical model, for my piece, *Interpose*, for guitar and computer-generated sound. In addition to shaping each parameter of the particular synthesis type, such as the frequency and amplitude of the sine wave oscillator, the carrier and modulator frequency and amplitude, the formant filter center frequency, amplitude, and bandwidth, and the physical model frequency and amplitude, with a local envelope for each partial, all local envelopes could be further shaped by a global envelope, adjusting the amount the dynamic character of each partial contributed to the behavior of the synthesized timbre over time.

Although not yet implemented, the vBow will be an excellent controller for shaping both the local and global envelopes for this kind of hybrid additive synthesis. For instance, lateral motion could control the shape of the local amplitude envelope for each partial, while longitudinal motion could control the shape of the global amplitude envelope, boosting the amplitude or varying the sustain of the higher or lower partials. Furthermore, because there are two additional degrees of freedom available, rotational motion could control the fundamental, carrier, or center frequency, while vertical motion could control the spacing of the partials, modulator frequency, or bandwidth, simultaneously dynamically shaping multiple synthesis parameters. In the case of mapping longitudinal motion to modulator amplitude or resonant filter bandwidth, control of the timbre by the vBow could simulate an analogous interaction on the acoustic violin, increasing or decreasing brightness as the bow moves closer to or farther from the bridge.

Haptics

When I first discussed my ideas for a violin controller with Chris Chafe, he explained to me the findings of the research that he was conducting with Sile O'Modhrain, on the importance of haptic feedback to the playability of an instrument, and suggested that I consider integrating force feedback into my plans for a violin controller.

Convinced that incorporating haptic feedback into the design of the violin controller would enhance the performance experience and increase the versatility of the instrument, I, along with Chafe, O'Modhrain, and Serafin, met with Kenneth Salisbury at the Stanford Robotics Laboratory, for a tutorial on interface design. At the meeting, Salisbury outlined the use of servomotor and cable systems with encoders to sense motion and simulate force feedback.

On subsequent visits with Salisbury at the Stanford Robotics Laboratory and Weston Griffin at the Stanford Dextrous Manipulation Laboratory, I was fortunate enough to observe and interact with haptic interfaces under development, and it became clear that simulating force feedback would be an interesting and exciting field of research to pursue. Furthermore, as a subject of Chafe and O'Modhrain's experiments using the Moose to simulate musical haptics, it became evident that force feedback served an important function in my interaction with a musical controller.

CHAPTER 3
BACKGROUND

In Bruce Pennycook's survey of computer-music interfaces, the composer and researcher states that "attempts to design and implement new user interfaces for computer music applications have indeed required a fresh examination of the musical activities for which they are intended" (Pennycook 1985). This reanalysis of how the performer or composer interfaces with his musical instrument, whether it be an electroacoustic controller or computer programming, has been central to the development of computer music.

Producing a novel and effective approach to transducing the composer's intent or performer's gestures into computer-generated sound, while enabling the subtlety and range of musical expression that we expect from acoustic instruments, is no small matter. As the author writes, "unraveling these complex interrelationships of knowledge, experience, and gesture poses a formidable challenge."

But, throughout the considerable history of computer music interface design, from modeling expressive performance with software, to designing new electroacoustic controllers to track performance gesture, attempting this difficult task of imposing human expression on computer-generated sound has resulted in some ingenious and innovative designs.

Early Interactive Systems

Some of the earliest interactive computer music systems, Groove developed by Max Mathews at Bell Laboratories and A Computer Aid for Musical Composers designed at the National Research Council of Canada, provided a real-time interface to the production of computer-generated sound, along with a visual display of the music created (Pennycook 1985).

In 1968, Mathews, along with F. Richard Moore, developed a system for recording, in real-time, a performer's gestures, to control an analog sound-synthesis system (Mathews and Moore 1970; Roads 1980; Pennycook 1985). In Pennycook's overview of computer-music interfaces, Mathews is quoted as saying that "the desired relationship between the performer and the computer is not that between a player and his instrument, but rather that between the conductor and his orchestra," a perspective that is evident in the design of Groove.

The system used a DDP-224 computer, to create, store, edit, and reproduce up to fourteen function of time, for up to several hour, "at sufficiently high sampling rates to describe fast human reactions" or performance gestures, up to two hundred samples per second. Although these functions could have been used to control any machine, they were used to change the settings of the voltage-controlled oscillators and amplifiers of an analog synthesizer.

These functions could be created and edited in real-time, through the use of four "rotary potentiometers or knobs," one "3-dimensional linear wand shown projecting up from a square box" or joystick, a "specially-built keyboard input device" on which "each key has a potentiometer associated with it, so it may be set to any desired group of discrete input values," and a typewriter for inputting commands. The user received feedback of the fourteen output functions of the Groove system through two speakers and an oscilloscope, while interactively composing functions of time, a process which Roads calls "edited improvisations," in order to expressively shape the output of the synthesizer.

In the late seventies, William Buxton developed a similar system, called the Structured Sound Synthesis Project, with a team at the University of Toronto (Pennycook 1985). With this system, the user could control the output of a synthesizer "during playback of prepared musical events" with two sliders, a mouse, a touch sensitive pad, a keyboard, and "four variable-slope, straight line segments for control of output rates or amplitude contours" in the system software.

Another early interactive computer music system, comprised of "three processors working in parallel and connected together by a common bus," was developed at the Institut de Recherche et Coordination Acoustique/Musique (IRCAM) (De Loye 1982). These three components included a dedicated processor for computing audio, called the 4X, a computer, for loading programs and graphical display, and a control system, which dealt with controller input and feedback. Possible controllers for the system included sliders, buttons, potentiometers, joysticks, an alphanumeric display, an organ keyboard, and a clarinet controller.

Development of the 4X system continued through the eighties, with improvements in the hardware, the use of new computers, and the design of better software (Favreau et al. 1986). Most interesting was the creation of the MAX programming environment, by Miller

Puckette, as “an implementation of a set of real-time process scheduling and communication ideas aimed at making it possible to design elements of a system which can be combined quickly and without changing code,” on the 4X system.

Later, experience with the 4X system lead to the development of the IRCAM Musical Workstation, or IMW, (Lindemann et al. 1991). This new system, designed to facilitate the realization of “interactive musical composition and performance algorithms,” was built using “an Intel i869-based multiprocessor system interfaced to a NeXT host computer.” The MAX programming environment was again used for the IMW, as was the Faster Than Sound (FTS) toolbox, for musical event and signal processing, the Animal software system, a graphical representation of the FTS toolbox, the Signal Editor application, allowing “viewing and editing of audio signals,” and the Universal Recorder multitracking software.

All of these systems were a great improvement over the control procedure for the RCA Mark 1 and 2 synthesizers, built in the fifties (Manning 1993). For these early synthesizers, the user punched holes, in thirty six columns, into a fifteen-inch wide paper tape, with a keyboard like a manual typewriter. The holes on this tape, which were read by a system of spring-loaded brushes that “made electrical contact with the drum beneath,” determined the settings for the frequency, octave, timbre, envelope, and volume of the synthesizer, in two channels. No real-time control of the synthesis parameters was possible.

Non-Keyboard Controllers

Many interesting controllers, that are not based on transducing the interaction between a performer and a keyboard, have been designed for real-time control of sound-synthesis parameters and computer-music composition.

Max Mathews is a pioneer in the development of non-keyboard controllers, designing and building his Sequential Drum, which subsequently evolved into the Mechanical Baton or Daton, and later the Radio Drum or Radio Baton (Mathews 1989a, 1991, 2000; Boulanger and Mathews 1997; Boulanger 1990). Each of these instruments share the design elements of a sensor surface that interacts with one or two batons.

The Sequential Drum used “a grid of crossed wires underneath a drum head,” to sense where hitting the drum head shorted together “the two wires that crossed underneath that point,” and a small contact microphone “attached to a plate under the head,” to measure how hard the drum was hit, by the "size of the pulse" from the microphone. In the case of the Daton, the position and strength of the hit from a baton was calculated from the sensor readings of strain gauges in each corner of a square drum. And for the Radio Baton, a "complex array of receiving antennae" on the surface of the square drum reads the transmissions from two "small radio transmitters" inside the head of the batons, which allow the Radio Baton to sense the x, y, and z coordinates of the batons on or above the drum surface.

At MIT's Media Lab, Tod Machover and his team have been experimenting with combinations of existing musical controllers and innovative interface designs, under the project title of Hyperinstruments (Machover and Chung 1989; Machover 1992). Early Hyperinstruments were constructed from a combination of MIDI controllers, computers, MIDI synthesizers and samplers, and effects processors.

In their paper, "Hyperinstruments: Musically Intelligent and Interactive Performance and Creativity Systems," Machover and Chung explain the motivation behind their work.

> Hyperinstrument research is an attempt to develop musically intelligent and interactive performance and creativity systems. We believe that the combination of machine-augmented instrumental technique, knowledge-based performance monitoring, and intelligent music structure generation, will lead to a gradual redefinition of musical expression.

Machover's Hyperinstrument piece, *Towards the Center*, was scored for flute, clarinet, violin, cello, Yamaha KX88 and Kurzweil Midiboard keyboards, and Silicon Mallet, Octapad, and KAT percussion controllers, using the MIDI instruments to trigger programming written in Hyperlisp on a Macintosh II computer. The programming sent MIDI data to synthesizers and samplers, generating additional musical material, and Yamaha SPX-90 multi-effects processors, affecting the sound of the acoustic instruments. An earlier piece of the composers, *VALIS*, also used keyboard and percussion instruments to control the Hyperinstrument system, as the musical accompaniment for the opera.

In his next piece, *Bug-Mudra*, Machover used an Exos Dexterous Hand Master, a glove gesture controller developed by Beth Marcus, along with an acoustic and electric guitar, KAT percussion controller, three computers, and various MIDI synthesizers, drum machines, and mixers. The glove controller, "an aluminum 'skeleton' that fits onto the fingers with Velcro" that "uses sensors and magnets to measure the movements at each finger joint," was used to "conduct" the Hyperinstrument ensemble, influencing the musical output of the other instruments. More recent developments, at the Media Lab, in the design of Hyperinstruments, are discussed in the section below, about bow controllers.

Another system, comprised of MIDI controllers, a computer, and various synthesizers, samplers, and signal processors, was developed by Chabot, in order to reintroduce “a concern for body, gesture, and space” in electroacoustic music (Chabot 1990, 1985). The MIDI controllers for the system include a sonar system, built from a Polaroid kit by Pat Downes, that emits “a pulsed ultrasonic signal” and measures “the time it takes to reflect off of an obstacle and to return to the detector,” an “angular detector,” composed of “a pendulum moving in an oil bath,” that swings from minus forty-five to plus forty-five degrees, an Airdrum, designed by Pat Downes, that uses accelerometers on short sticks to track vertical, horizontal, and rotational motion, and an IVL Technology Pitchrider 2000 pitch detector. The output of these sensors was sent as MIDI data to software written in the preFORM Music Toolkit object-oriented programming language, which in turn controlled the synthesizers and audio equipment.

For their piece, *Futurity*, for performer-dancer and live electronics, Chabot and Joji Yuasa used one Airdrum held in the performer’s hand, another fastened to their foot, and the angular detector secured to their elbow. In addition, the performer moved within a space detected by the sonar system. Output from these interfaces was used to control a sampler, mixer with onboard effects, and 4-track tape recorder, which played, mixed, and processed “sampled spoken words and vocal sounds plus texts and prerecorded music on tape.”

Other interesting and innovative electroacoustic instrument designs include Dean Rubine and Paul McAvinney’s VideoHarp (Rubine and McAvinney 1990), and Serge de Laubier’s Meta-Instrument (De Laubier 1998). The VideoHarp, based on a design originally conceived for a “multiple finger touch-screen device,” uses a neon tube “focused by a lens system onto the surface of a 64 Kbit dynamic RAM,” which “optically tracks a performer’s fingertips.” Because light striking the DRAM causes a bit change from one to zero, the areas of the DRAM that are obscured by the shadow of the fingertips “retain their charge for several hundred milliseconds.” By optically tracking fingertip position, the VideoHarp allows for strumming or drumming gestures, that are “mapped to MIDI commands, which are sent to a synthesizer.”

The Meta-Instrument, developed by Laubier, along with Yvon Alopeau, Jean Loup Dierstein, and Dominique Brégeard, was designed as a controller to play musique concrète “in live concert performance," and as an interface to diffuse sound in octophonic space. The instrument, which can "simultaneously and independently control 32 continuous variables," is comprised of two contoured blocks, onto which are secured two rows of five Hall-effect sensors for the fingers, and two Hall-effects sensors for the thumb, of each hand. These contoured blocks are positioned at the end of swiveling handles, that can be moved vertically and horizontally up to 90 degrees, with the forearm, producing two more Hall-effect sensor values per arm. Additional values are produced by a foot pedal. All of these sensor values are translated into MIDI data, which is transmitted to Max programming, on a PowerBook computer.

Another novel instrument, the Metasaxophone, has been developed by Mathew Burtner (Burtner 2002; Burtner and Serafin 2002; Serafin et al. 2001). Conceptually, the Metasaxophone is two independent sensor systems, that the inventor calls the MIDI Saxophone and the Electric Saxophone. Both systems, attached to a single tenor saxophone, are meant to "put signal processing under direct expressive control of the performer."

The MIDI Saxophone is comprised of force sensing resistors, attached to six keys and two thumb rests on the instrument, which measure finger pressure, "five triggers located at different points on the horn," which function as momentary switches, and a two-axis accelerometer, secured to the bell, which tracks horizontal and vertical position of the saxophone. The output of each of these sensors is connected to a Basic Stamp microprocessor, attached to the saxophone, which translates sensor data into MIDI control messages. These MIDI messages are then used to "control digital signal processing and synthesis algorithms" in Max/MSP programming.

The Electric Saxophone uses up to three "condenser electret cartridges fitted to the ends of bendable tubing," which "can be placed independently at the desired location outside or inside the instrument," to amplify the tenor saxophone. The author describes a standard configuration, where one microphone is placed inside the bell, another is positioned outside the lower half of the saxophone, and the third is located at the neck, independently amplifying the low, high, and mid-range frequencies of the instrument. Because each of the microphones has a separate output, each can be processed separately or used as an independent control signal, again in Max/MSP programming.

For his piece, *Noisegate 67*, Burtner used the Metasaxophone as a "real-time, expressive noise controller." Pressure applied to the eight force sensing resistors was mapped to the amplitude of noise generators and filters, so that "by carefully controlling the finger pressure, the performer plays shifting bands of noise." In addition, the dynamic of the saxophone was used to vary the amplitude of the noise generator, while the output of the pressure sensors was used to change the filter parameters. Furthermore, the pressure sensors and triggers were used to change depth of modulation of the amplified saxophone signal, control delay line parameters, and trigger samples played by the computer.

For *S-Trance-S*, the composer used the Metasaxophone as a MIDI controller, to vary, in real time, parameters of the same bowed-string physical model, developed by Stefania Serafin, that is currently used for the sound synthesis of the vBow. In this case, output from six pressure sensors is mapped to the bow force, position, and velocity, frequency, inharmonicity, and noise parameters of the physical model. As the piece progresses, sensor outputs are remapped to additional physical models, so that the performer is controlling different parameters of up to four bowed-string models, simultaneously with the same key.

Despite an interest in other developments in the design of interfaces and controllers, this chapter will focus primarily on electroacoustic instruments that share with the vBow a construction based on transducing the gestures of a violinist's technique into computer-generated sound, or providing the performer with tactile-kinesthetic, in addition to audio, feedback.

Violins

In the chapter covering nonkeyboard controllers, in his book, *Synthesizer performance and real-time techniques* (Pressing, 1992), Jeff Pressing presents the problems involved with developing a violin controller, using commercially available synthesizer technology. The standard Musical Instrument Digital Interface (MIDI) protocol was designed for keyboard instruments that allow for a discrete set of pitches, while the violin is an instrument with a continuous pitch range. Furthermore, the author acknowledges, the MIDI protocol does not allow for "small variations in articulation and the dynamics of sustaining sounds" that are a fundamental part of the violinists musical expression.

These concerns aside, an electric violin can be used as a MIDI controller with the assistance of a pitch-to-MIDI converter, that translates the vibration of the violin string into the pitch and velocity numbers of a MIDI note message. Unfortunately, as Pressing explains, controllers that rely on pitch-to-MIDI conversion, to translate the output of an acoustic instrument into MIDI data, are prone to errors in pitch and dynamic, and delays in the response time of the system to the performer.

> … At the current time, all such controllers … have characteristic limitations. When played with traditional technique, they sometimes do not respond in sensible ways: Notes are bent that were not so intended; notes are missed or delayed; extra notes are triggered; notes sustain that were to have been damped, …

The MIDI violin system cited by Pressing includes a Zeta Music Systems electric violin and a pitch-to-MIDI converter, that allows for each string of the violin to be assigned its own MIDI channel. This instrument is badly reviewed and illustrated in an issue of the Computer Music Journal, from the Summer of1990 (Metlay 1990).

Several designs of electric violins, by various makers, are chronicled and beautifully illustrated in Hanno Graesser's book, *Electric Violin* (Graesser 1998). This author's account of the history of the amplified violin begins with an instrument, whose strings vibrated a bridge against a diaphragm attached to a metal horn, developed around 1900 by Augustus Stroh. This amplified violin was advertised to be as loud as four violins, and was used for recording sessions as late as the 1920s.

Subsequent amplified violins included the electric Giant Tone Radio Violin, invented by R. F. Starzl in 1927, with a "pickup which was attached at the f-hole of a normal violin," the Superviolon, developed by Paul Bizos, that "made it possible for an acoustic violin to play also in the range of a cello or bass," an electric violin, produced by Lloyd Loar in 1934, with a "minimal body" to avoid feedback, and the Electro Violin, sold by Rickenbacker in 1935, that used an electromagnetic pickup on a "stick like" Bakelite, aluminum, or wood body.

In 1936, John Dopyera, working for the National Dobro Corporation, invented the Vio-Electric, which jazz violinist Stuff Smith played. This electric violin, with a volume control "on the top plate below the right f-hole" was later called the Violectric, and played by jazz violinist Stéphane Grappelli, on a recording with Jean-Luc Ponty, in 1973. Later in the 1940s, Vega Electronics produced a "stick like" instrument, called the Vega Electric Violin, that Ray Perry played in Lionel Hampton's band. Jazz violinist Jean-Luc Ponty started playing electric violins, when he was given an instrument by inventor John Berry, of the

Barcus-Berry company, in 1969. Later, on his album from 1984, Ponty was the first to use the Zeta MIDI Jazz Violin, an instrument suggested to inventor Keith McMillen, by violinist Daniel Kobialka, in 1982.

In the second section of his book, Graesser features a wide assortment of electric violin designs, by modern makers. In addition to the excellent craftsmanship, variety of shapes, solid or hollow bodies, select woods, numbers of strings, and types of pickups, some of the instruments incorporate unique features in their design. Tucker Barrett produces an acrylic, as well as wood model, that increases the volume of the instrument, while Eric Jensen builds violins with tuners placed behind the bridge, to balance the weight of the instrument. The Phoenix electric violin, built by Ka Wong, of Heys Instrument, incorporates a preamplifier and wireless transmitter in the body of the instrument, while Eric Aceto's Aceto/Violect violin uses "voiced tone bars" and tuned air chambers. Nicholas Tipney and Midge Stalley, of Vector Instruments, build their V-1 Millennium electric violin with a carbon-graphite body, while Mark Wood offers a fretted version of his Viper "Flying-V" model.

One of the most unusual electronic violins doesn't amplify the vibrations of the strings, but rather uses an elaborate, automated electromechanical system to play an acoustic violin, while accompanying it with a mechanically-played piano, cello, or second violin. The Mills Violano-Virtuoso (Kitner and Reblitz 1984), introduced at the Alaska-Yukon-Pacific Exhibition in Seattle in 1909, uses four "rotating laminated celluloid bows," that bow at five different speeds, sixty-four steel "violin fingers," that rise from below to stop the strings, and a "tailpiece-shaking tremolo device," which alternately increases and releases string tension, adding vibrato to the violin tone. Later versions of this instrument include a "variable bow pressure device," that allows for a wider dynamic range, and "varieties of mechanisms used for bow staccato." All of these parameters are controlled by a punched-hole paper music roll, like a traditional player piano, read by brushes that make electrical contact with a roller beneath the paper, like the RCA Mark I and II synthesizer. The design of this instrument is especially interesting because of its capacity for expressive bowing: its ability to change bow velocity and force, and approach the string from above, for off-the-string bowing.

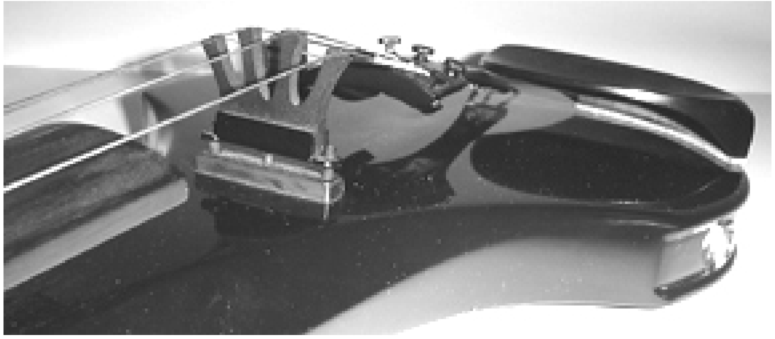
In the introduction to his book, Graesser lists various kinds of transducer systems, electromagnetic, electrodynamic, electrostatic, and piezoelectric, as pickup technologies used for electric violins. The electromagnetic pickup is similar to those used for electric guitars, whereas electrodynamic and electrostatic are based on microphone designs. The piezoelectric pickup uses piezoelectric sensors to track the vibrations of each string.

How these transducers are used to amplify the acoustic signal of a violin differs between manufacturers. Ashworth Electronics, L. R. Baggs, Barbera, and Barcus Berry all produce transducers embedded into maple bridges, while Fishman makes a transducer system that clips to a standard bridge. Stephan Kurmann manufactures a soundpost that is “part wood and part transducer,” and can be installed in any acoustic violin, replacing the standard soundpost. Schertler Audio Transducers makes an electrodynamic system, where the “’moving coil’ is stuck to the instruments top plate near the bridge,” and an electrostatic transducer that fits inside the notch in the side of a standard bridge. And, Zeta manufactures a piezoelectric transducer system, in which two piezoelectric elements sense the vibrations of each string, at the top of a bridge housing.

Another piezoelectric transducer bridge used by Zeta Music Systems, was invented by computer music pioneer, Max Mathews. In 1989, Mathews received a patent for his “bimorphic piezoelectric pickup device for stringed musical instruments” (Mathews 1989b), which solved some of the problems inherent in other kinds of piezoelectric pickups.

As explained in the patent document and an earlier paper about the invention (Mathews 1988), other piezoelectric violin bridges rely on a pressure-sensitive surface, that requires the string be bent over the element differently than is normally done by the bridge and tailpiece. According to Mathews, that bend “makes it awkward to mount the string on the instrument and causes some problems in tuning the string.” Additionally, pressure sensors are not optimal for sensing the strings’ response to bowing, because the elements sense fluctuating pressure, not vibration.

Mathews’ bridge solves these problems by using bend sensors, instead of pressure sensors, embedded in the bridge. The piezoelectric bender-elements extend within the independent support beams of the bridge, each of which support one of the violin strings. Because the support beams are separated by a notch, the vibrations of each string are isolated from one another, and restricted to only one of the piezoelectric sensors, making the bridge ideal for tuning the dynamics of the signal from each string, or using each output as a control signal.



photographed with permission from Max Mathews

Figure 1. Max Mathews’ piezoelectric bimorphic pickup bridge on a Zeta electric violin

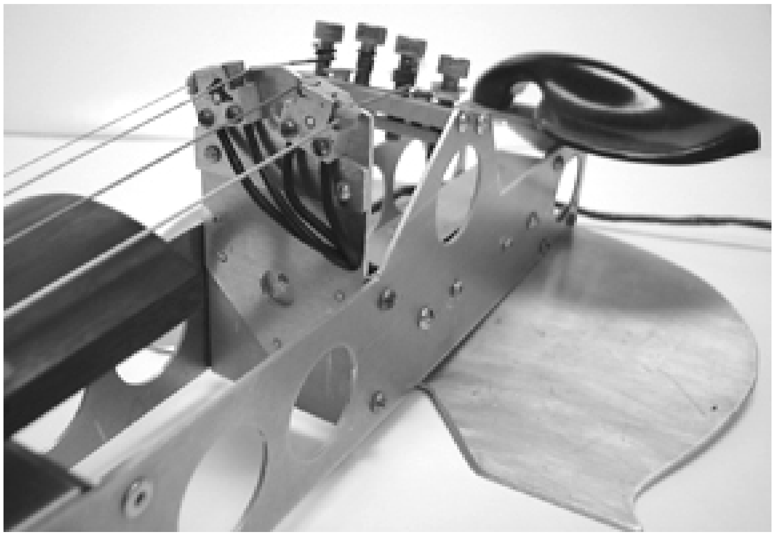
This piezoelectric bender-element bridge was preceded by other electric violin research conducted by Mathews. In an interview conducted by Curtis Roads (Roads 1980), the inventor describes his work with earlier electronic violins, experimenting with tuning the resonance of the instruments.

> … I’ve made a number of electronic violins. Some of them are closely related to normal violins, in that I’ve worked very carefully on the resonances of normal violins, and made electronic circuits which introduce these same resonances into the electronic violins. … It is possible to tune the resonances very accurately, and it is, of course, possible to have as much energy as you want in the sound. It also makes it possible to use some of the things we know about timbres to change completely the timbre of the violin. …

photographed with permission from Max Mathews

Figure 2. Max Mathews’ electronic violin

This research is further described by Mathews, in a paper published in the *Journal of the Violin Society of America* (Mathews 1984). In this article he describes a bridge design that uses four “ceramic crystal microphones” to convert string vibrations into electrical signals. The signals from these microphones are amplified and filtered independently, and played through four separate loudspeakers.



photographed with permission from Max Mathews

Figure 3. Ceramic crystal contact microphones on Max Mathews’ electronic violin bridge

In an experiment, testing the effect of applying a “singing formant” to the output of the electric violin, the output of each string was processed with a band-pass filter centered at 3000 Hz, with a 2000 Hz bandwidth. This signal, filtered through a “singing formant,” which simulated the technique used by male singers to project their voices, was then mixed with the direct signal from the pickup. Through comparison testing, it was determined that the tone of the electric violin was preferred, when filtered through a band-pass filter, centered at 3000 Hz or higher.

In related research, Mathews, along with Kohut, simulated the frequency response of an acoustic violin by playing an electric violin through twenty resonant circuits (Kohut and Mathews 1971). The frequencies of each of the resonant filters were set to the “17 prominent peaks on a Stradivarius response curve” and “three additional high-frequency resonances.” The bandwidth and attenuation of the individual filters were also tuned, and the output of the resonant circuits summed to simulate different frequency responses for the electric violin. This research is particularly interesting, as it may be useful toward the future development of a vBody, or virtual violin body resonator, to amplify the electroacoustic output of the vBow.

In an article about his piece, *Three Chapters from the Book of Dreams*, for electric violin and "real-time computer music workstation" (Boulanger 1986), Richard Boulanger recounts tuning "thirty to sixty resonances" with Mathew's early electric violin system.

> Not only was it possible to "tune" the instrument for any given performance space, but it was also possible to completely transform the violin's natural timbre. For example, by using a low-pass filter whose bandwidth increased with intensity, he was able to make his electronic violin produce a convincing brass sound; and by using a band-pass filter whose center frequency rose with amplitude, the electronic violin could be made to produce a voicelike "wah" sound.

Boulanger used both the multiple resonance filter and "singing formant" versions of the Mathews electric violin system in early versions of his piece, and later used the instrument as a real-time controller to trigger sampled violin tones, and as a sound source for various digital signal processors.

The Matthews electric violin was also used by Andrew Voelkel, to develop an "input processor-pitch detector" (Voelkel 1985). Voelkel's motivation for designing this "hybrid digital-analog pitch detector" for an electric violin was similar to my incentive for building the vBow, namely to develop a performance interface "for the control of realtime computer music systems." In his case, Voelkel designed a working prototype that detected the pitch and amplitude envelope of the output signal from the electric violin.

This pitch and amplitude detector was used by János Négyesy and Lee Ray, along with an electric violin, for their piece, *Zivatar* (Négyesy and Ray 1989). The electric violin was again a Mathews violin, but with a body sculpted by artist Michael Monfort. In this piece, the electric violin was used both as a sound source for signal processing and as a source of pitch and amplitude values to translate into MIDI pitch and velocity data. The amplified signals from the piezoelectric sensors on the bridge of the electric violin were processed with compression, delay, and reverb, whereas the MIDI data from the conversion of the electric violin signal were used to trigger a synthesizer and sampler. In the piece, the processed output of the electric violin was mixed with musical events triggered by the MIDI data, from the pitch-to-MIDI conversion.

Violinist and composer, David Jaffe, and percussionist and composer, Andrew Schloss, document their musical experiments, using a Zeta MIDI violin, in combination with a Mathews/Boie Radio Drum and two computers, in two papers (Jaffe and Schloss 1992, 1994). In their piece, *Wildlife*, the MIDI output of the violin system is used by the computer to “double the violin part with some synthetic sound” , as well as “make decisions based on what the violinist is playing.” Some of these musical decisions, determined by the output of the MIDI violin, include the pitches used for the percussionist’s improvisation and those used for the melodic material generated by the computer. Similarly, in the piece, a note from the MIDI violin can determine the root of an arpeggio performed by the percussionist or the chord played by the computer.

Composer, Daniel Weymouth has composed two virtuosic pieces for MIDI violin and interactive electronics. *This Time, This* and *Another Violin* both use the MIDI pitch and velocity data from the electric violin to trigger musical events generated by patches programmed in Max software. These computer-generated musical events are then transmitted as MIDI data to a synthesizer. In the case of *This Time, This* the computer generates musical material that both closely imitates the music performed by the violinist, and accompanies the performer with contrasting material, shaped by MIDI pitch bend messages. During *Another Violin*, the MIDI violin triggers computer-generated musical events with changes in dynamic, and in the case of a semi-improvised section, groups of three pitches.

An interesting recent development in the field of violin controllers has come from composer and violinist Daniel Truman, and engineer Perry Cook. In his dissertation, *Reinventing the Violin* (Trueman 1999), Truman describes the component parts of his violin controller: the R-Bow, a sensor bow that tracks bow force and acceleration, the Fangerbored, the combination of a linear position sensor, four force-sensing resistors, and a biaxial accelerometer, the Bonge, an array of bowed foam-covered wood pieces that move against force-sensing resistors, and a “12-channel spherical speaker array.” The Fangerbored tracks left-hand and right-hand fingering and overall motion, while the Bonge is used to sense bowing direction and what string is played. The speaker array, an extension of Truman and Cook’s NBody project, spatializes input audio, filtered through twelve frequency responses. When all of the parts are assembled, they comprise the BoSSA, or Bowed-Sensor-Speaker-Array, providing the player with “fourteen data points,” to be used as parameters for synthesis and interactive compositions.

Bows

Rather than amplifying the vibration of the violin string, or translating its signal into MIDI data, several researchers, like Truman and Cook, have designed controllers that sense the bowing gestures that produce the dynamic and timbral expression of the violin. These violin bow controllers sample bow pressure, acceleration, and proximity to the bridge, with sensors, using the data as parameters for sound synthesis.

An early precursor to the violin bow controller is described in a paper by Chandrasekhara Venkata Raman, a founding fellow of the Indian Academy of Sciences, entitled "Experiments with Mechanically-Played Violins" (Raman 1920-21). In his article, Raman details the design of a "mechanical player" that permitted "accurate measurements of the pressure and speed of bowing" and allowed for "the discrimination by ear of the effect of varying these factors." This device used an ordinary violin and bow, mounted to an apparatus that moved the violin back and forth, under the bow, with an electric motor.

The violin sat in a wooden cradle, attached to a brass slide, that moved along a cast-iron track. The impetus from the electric motor was transferred through two belts, to a conical pulley and driving wheel. The driving wheel, attached to one of two hubs, transferred the energy to a chain, strung between the two hubs, which moved the violin assembly, back and forth. The speed of the bowing motion could be controlled with a tachometer, attached to the electric motor.

The bow was attached to a wooden lathe, that allowed for adjustments to the amount of hair that touched the string. The pressure of the bow on the string was adjusted with weights, hung at the end of the wooden lathe, that balanced on an axis. This early bow controller allowed Raman to experiment with the interactions between variations of bow speed, pressure, and position, under controlled conditions.

Another mechanical bow was used by Bradley and Stewart, at the Department of Physics of the University of Western Ontario, for their study of violin frequency response curves, to compare results with those from bowing the string by hand, and exciting the string with an electromagnetic driver (Bradley and Stewart 1970). Their bow was constructed from synthetic bow hair sewn to a cloth belt, that was strung between two pulleys, and driven by a motor.

A research group studying KANSEI or sensory engineering, at Waseda University in Japan, recently designed a bowing machine, to test how bowing parameters combine to produce expressive timbres (Shibuya et al. 1996, 1997). Working under the hypothesis that understanding how humans adapt their motion to sensory input will lead to designing robots that move more like humans, these scientists studied "task planning" and "motion planning" in violinists, with the intent of building a robot that can change bow speed, force, and position, in response to changes in timbre, a subjective and qualitative, or KANSEI, musical parameter.

A servomotor controlled by a computer was used by the bowing machine, to vary bow speed, while the bow force and position were adjusted by moving the table that held the violin that was bowed. Additionally, bow force was measured by strain gauges attached to the bow hair. Each bowing parameter could be set to three values, and the combinations of these parameters were judged within six descriptive categories. From these judgments, models of the necessary combinations of bow speed, force, and position were constructed, for the production of each category of timbre.

An early bow controller was developed by the research team at the Association pour la Création et la Recherche sur les Outils d'Expression (ACROE) and the Laboratoire d'Informatique Fondamentale et d'Intelligence Artificielle (LIFIA), for use with their CORDIS-ANIMA real-time synthesis system (Florens et al. 1986). This instrument, one of two designed to allow a performer to interact with physical models, used "vertical force and transversal velocity sensors" to track the "transverse force exerted on the string" and the "sliding speed of the bow." Like the vBow, these sensor readings were used as data for parameters of a bowed-string physical model, mapping bow force and velocity to a "simulation of a vibrating string, associated to a bow friction mechanism."

Chris Chafe, at Stanford University's CCRMA, developed a sensor bow for use with his electric cello, the Celletto. This controller, as show on the cover of Volume 14, Number 4, of the *Computer Music Journal*, from 1990, used an accelerometer, attached to the screw at the end of a standard cello bow, to track bow acceleration, and a strain gauge, mounted at the middle of the stick of the bow, to sense bow force. The conditioned signal from each sensor was converted to MIDI and used to affect musical parameters in interactive computer music programming (Chafe 2003).

Like Chafe, Jon Rose constructed a bow controller, shown on his website, www.jonroseweb.com, in a picture from 1990, that used sensors attached to a violin bow, to track motion and pressure (Rose 2003). In his case, Rose used ultrasound to "measure the actual movements of the bow" and "a sensor, built into the bow itself, to measure continuously the hairpressure of the bow on the strings." According to the inventor, the design of this instrument was an attempt "to bring together the physicality and dynamics of improvised music (as played on a violin) with the quick change and virtual possibilities of computer music."

For his piece, The Hyperstring Project, dated 1999, Rose used "an accelerometer mounted on a bowing arm," rather than ultrasound, to measure the movement and speed of his bowing. The readings from this sensor, as well as from the aforementioned pressure sensor, were translated into MIDI data, which Rose used to improvise multilayered counterpoint.

photograph used with permission from Jon Rose

taken from www.jonroseweb.com

Figure 4. Jon Rose with his MIDI bow

Researchers at the MIT Media Laboratory, Joseph Paradiso and Neil Gershenfeld, developed a system for tracking bow position, laterally from frog to tip and longitudinally relative to the bridge, using electric field sensing (Paradiso and Gershenfeld 1997; Paradiso 1997). The Hypercello version of this system, on which Yo-Yo Ma performed Tod Machover's composition, *Begin Again Again…*, used an antenna, which broadcast a sine wave from behind the bridge, to a "bow electrode," comprised of a resistive strip affixed to a cello bow. The resultant currents, measured at each end of the resistive strip, were used to calculate lateral and longitudinal position of the bow. Lateral position, relative to the midpoint of the bow, could be derived from the normalized difference between these two currents, and longitudinal position of the bow, relative to the bridge antenna, could be figured from the inverse of the sum of the two currents.

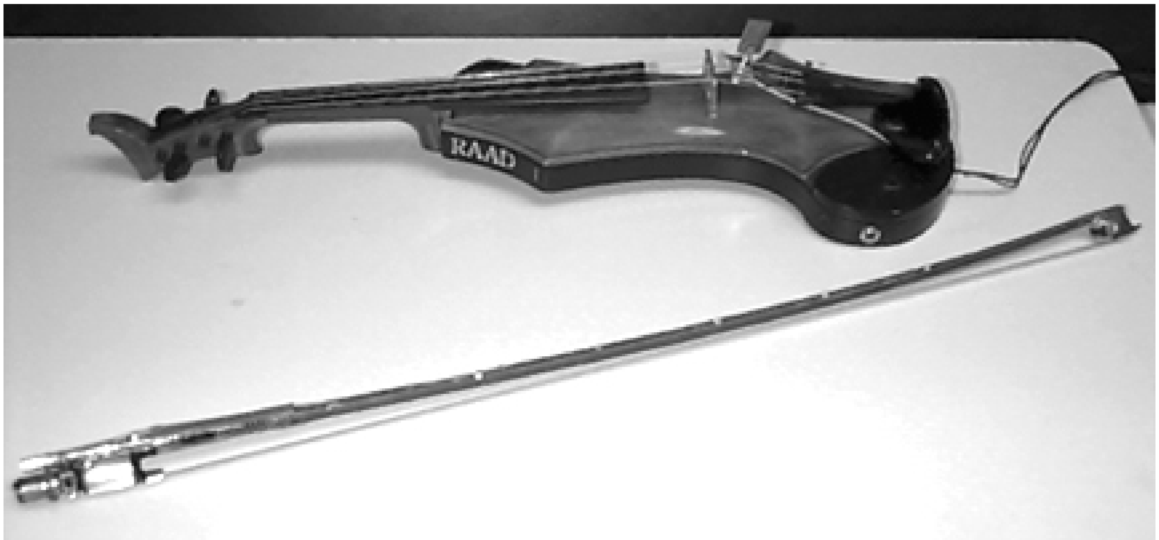
In addition to the electric field sensor, this system used a deformable capacitor, fastened at the frog of the bow, to track the force applied to the bow by the fingers of the right hand. Data from this pressure sensor, along with readings from the electric field sensor, and measurements, from other sensors, of wrist angle and finger position along the strings, were translated into MIDI commands, and used to control samplers and synthesizers. These MIDI-translated data streams were also used to control the consol that mixed the output of the four strings of the RAAD electric cello used, and the signal from a pickup attached to the top plate of the cello. A Hyperviola version of this system was used by Kim Kashkashian, for her performance of Machover's piece, *Song of Penance*.

A Hyperviolin version of this system was also developed, using the same electric field sensing technology, for another piece by Machover, *Forever and Ever*, which Ani Kevaffian performed with the St. Paul Chamber Orchestra. Because a cordless bow was necessary for the violin version of this system, the roles of the bow electrode and bridge antenna were reversed. The resistive strip on the bow was used as the transmitter, while the bridge antenna was the receiver.

The resistive strip, affixed to a violin bow, transmitted two frequencies, generated by oscillators connected at either end of the resistive strip. Two voltages, corresponding to the proportion of these two frequencies received by the bridge antenna, were used to calculate the lateral and longitudinal position of the bow, using the same formulas as those used for the Hypercello system.

A piezoresistive strip was used, instead of an elastic capacitor, to sense finger pressure on the Hyperviolin version of the bow controller. Pressure applied to this piezoresistor created a voltage, that varied with pressure, which was used to control the frequency of an oscillator.

The output of this oscillator was broadcast. from another antenna attached to the bow, to the bridge antenna. And, variations in the frequency of the signal received from the bow to the bridge antenna indicated changes in bow pressure.



photograph used with permission from Joseph Paradiso

Figure 5. Joseph Paradiso and Neil Gershenfeld's Hyperviolin

Diana Young, also working at the MIT Media Lab, has designed another violin bow controller, in the tradition of the Hyperinstruments developed for the performance of Machover's compositions, the Hyperbow (Young 2002). In addition to using the same electric field sensing technology as the Hyperviolin, to measure bow position, this interface also uses two two-axis accelerometers, one positioned orthogonal to the other, to track bow acceleration along three axes, and foil strain gauges, fastened along the length of the bow stick, to sense downward and lateral forces applied to the bow. These sensor readings were used to control effects, processing the signal output of the Jensen electric violin used, for Machover's recent piece, *Toy Symphony*.

This violin bow controller was also recently used to test the playability of a bowed-string physical model (Young and Serafin 2003). For this research, Young, working with Stefania Serafin, mapped data from the strain gauges of the Hyperbow to the bow force parameter of the physical model. By changing downward force, while keeping the other parameters fixed, the researchers were able to produce a tone that "sounded appropriate for the amount of pressure … applied to the bow." In addition to changing bow force with a static lateral position, Young and Serafin experimented with different bow strokes, finding that the effect of lateral motion on the downward force again produced "a satisfying interaction."

photograph used with permission from Diana Young

Figure 6. Diana Young's Hyperbow

As discussed earlier in this chapter, Dan Trueman and Perry Cook designed a bow controller, call the R-Bow, as part of their BoSSA violin controller (Trueman and Cook 1999, 2000). This interface tracks bow pressure, with force-sensing resistors "mounted on light, soft foam at two locations between the stick and the hair" of a standard violin bow, and bow position or motion for two degrees of freedom, with a two-axis accelerometer attached to the frog. For his composition, *Lobster Quadrille*, Trueman mapped the accelerometer of the R-Bow to a physical model of bamboo wind chimes, and the force-sensors to the vibrato of a bank of comb filters, which processed samples of spoken text.

photograph used with permission from Dan Trueman

Figure 7. Dan Trueman and Perry Cook's R-Bow

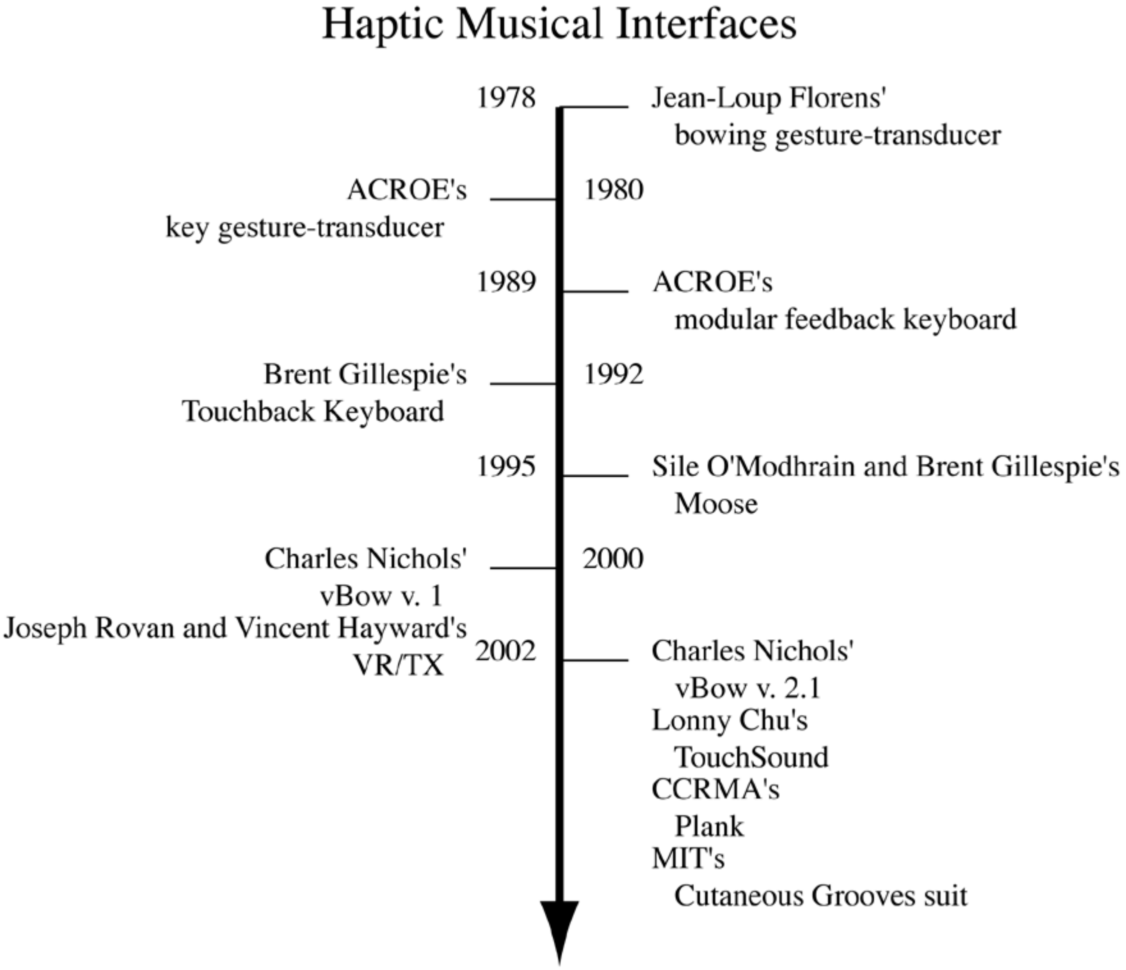


Figure 8. Haptic musical interfaces timeline

The research group, from ACROE, that designed the early bow interface, for use with their CORDIS-ANIMA real-time synthesis system, were also early developers of haptic musical controllers (Cadoz et al. 1982; Cadoz, Luciani, and Florens 1984; Florens et al. 1986; Cadoz, Lisowski, and Florens 1990). As early as 1978, Claude Cadoz and Jean-Loup Florens had designed a “gestural force-feedback transducer” that produced “a mechanical feedback force,” correlated with the sound and visual display of simulated instruments. As described earlier, in the section about bow interfaces, this “gesture-transducer” used a “force sensor with strain gauges” to track force applied to the stick, and an “inductive position sensor” to measure velocity. But, this device also used a servomotor to return the stick, mounted on a carriage, to its initial position. The force feedback of the servomotor, driving the cable system to return the stick, was moderated by electrodynamic clutches, controlled by a computer responding to the position sensor.

The second force-feedback interface, from the research group at ACROE, illustrated by a drawing in the paper from 1982, and in photographs in the papers from 1984 and 1990, consisted of a single haptic key. This gestural transducer contained "a force sensor with strain gauges, a displacement sensor with inductive effect …, and a torque motor." The strain gauges were positioned under the key, which was attached to an arm. Below the arm and just past the key hung a pivoting connecting rod. A cable, attached at either end of the connecting rod, wrapped around a rotating pulley, which was attached to a position sensor on one side, and a motor on the other. As the key was depressed, the strain gauges below the key read the pressure, and the position sensor read the rotation of the pulley, driven by the cable attached to the connecting rod, which was pushed downward by the arm that the key was attached to.

This haptic key, which served as a "force sensor with position-return" or a "position sensor with force-return," was used to physically interact with sound synthesis models of plucked strings and maracas. With the string model, the key was used as a plectrum, to pluck the two simulated strings, producing a "mechanical feedback" of "the reaction of the strings to the gestual [*sic*] action." For the model of maracas, the key was used to shake the simulated "resonant cavity" filled with "particles," generating the haptic feedback of the inertia of the instrument and "the hit of particles on the surfaces."

The "modular feedback keyboard," shown in drawings in the paper from 1990, and in two photographs on the cover of the *Computer Music Journal*, Volume 14, Number 2, represents the third haptic musical interface designed by the group from ACROE. The caption for these photographs, on the inside cover of the journal, succinctly describes the configuration of components and a possible use for this haptic keyboard.

> The keys are mounted on bars connected to the coils of the so-called sliced motor, whereby the position can be accurately sensed and a variable force can be applied to the key. This allows control programs to produce the arbitrary force-versus-position function on the keys, simulating, for example, the differences among pianos, harpsichords, and clavichords.

This "sliced motor," a patented device consisting of a "single magnetic polarization circuit," along with a position sensor, comprises a single "sensor-motor module," that has the thickness of about one piano key. Any number of these sensor-motor modules can be grouped together, to form a keyboard, and because the resting height of each key can be set independently by the control software, any configuration of white and black keys is possible.

This modular feedback keyboard, which measures key displacement, while producing programmable force feedback, has been used by the group from ACROE, to control their CORDIS-ANIMA "real-time music synthesis system."

Another haptic keyboard, the Touchback Keyboard, was developed by Brent Gillespie, as a part of his doctoral studies at Stanford University's CCRMA (Gillespie 1992a, 1992b, 1994, 1996). The design of this instrument was meant to provide "various touch responses, such as those of a harpsichord, organ, or grand piano" for the player, and "reestablish the touch relationship between performer and instrument" in electronic keyboards. An early version of this controller consisted of a keyboard of eight large keys, each of which contained an optical encoder, to measure position, a strain gauge, to track pressure, and a tachometer, to sense force and estimate acceleration, along with the strain gauge reading. Each key was also connected to a motor, extracted from a large disk drive, which was driven by an independent amplifier, to produce the haptic feedback.

This version of the Touchback Keyboard was developed in conjunction with an experimental device that Gillespie used to mechanically play a single key action from a grand piano, in order to record its motion. The device consisted of a large linear motor coupled to the piano key through a loop of cable and three pulleys, and was used to move the key with a specific force and trajectory, while strain gauges measured force between the cable and the piano key, and encoders sensed the motion of the key. At the same time, high-speed video was used to track the motion of "retro-reflective patches," attached to the piano key action. The data from the digitized video were compared with computer-animated simulations, to determine the accuracy of the grand piano action model.

Gillespie's later version of a haptic keyboard controller is an instrument designed to recreate "the mechanical impedance of the grand piano in a synthesizer keyboard." Each key of this keyboard extends into and pivots within an assembly, and inside the assembly, the interior end of the key is attached to a capstan. A cable runs around the capstan secured to the key, and wraps around a pulley, attached to the shaft of a servomotor, fastened at the end of the assembly. One of these keys, a prototype of the complete design, was also fitted with a strain gauge, to sense force applied to the key. Seven of these key assemblies were stacked at 45° angles, to allow room for the servomotors, which alone provide the haptic simulation of the piano action to the seven keys of the Touchback Keyboard.

Gillespie also worked with Sile O'Modhrain, another research scientist at CCRMA, on a haptic interface, called the Moose (O'Modhrain and Gillespie 1995a, 1995b). This interface was designed to "provide access for blind sound engineers to the graphics-based computer interfaces currently found in digital sound studios." The hardware for this interface consists of a centered "puck or manipulandum" attached on two contiguous sides to two linear motors with two pairs of flexures, made from foot-long strips of spring steel. As the user moves the puck, the flexures move the linear motor, and the position of the motors is read by linear position encoders. At the same time, the motors are controlled by voltages from an I/O card in a PC, producing force feedback to the manipulandum.

As an early proof of concept, O'Modhrain and Gillespie programmed "virtual springs, textures, and buttons" into the system software, providing haptic navigation of the Windows operating system, with the Moose. Holding the puck, the user could move around the graphical user interface, feeling the borders around buttons and detents in checkboxes.

O'Modhrain has used the Moose as the apparatus for a number of experiments in musical performance (O'Modhrain 2000). In two of these experiments, testing how subjects use haptic feedback to judge pitch space, the Moose was used as a virtual Theremin, producing the audio output of a sine wave, which varied in pitch according to movement of the haptic interface, in the y axis. Pitch accuracy was judged, as subjects matched pitch, on the virtual Theremin, to a series of melodies, played by the computer on a MIDI software synthesizer. At the same time, six kinds of haptic feedback were generated by the computer, producing force feedback on the manipulandum of the Moose, in relation to movement within the pitch space, or y axis. For the simulation of viscous damping, the force exerted on the user varied with the velocity of the movement of the manipulandum. For the simulations of constant positive and negative feedback, force was applied in the same or opposite direction, as the motion of the manipulandum. For the simulations of positive and negative spring, force increased or decreased with increasing pitch. And, for the sixth condition, no force feedback was simulated.

In another experiment, testing whether or not the haptic feedback of friction facilitated the playing of a bowed-string physical model, O'Modhrain used the Moose as a virtual violin bow interface, simulating the sound and force feedback of drawing a short length of bow over a violin string (O'Modhrain et al. 2000). The two degrees of freedom of the Moose interface were mapped, through MIDI, to the bow velocity and force parameters of bowed-string physical model sound synthesis. The friction model of the interaction between the bow hair and violin string were calculated by the bowed-string physical model, and used to drive the haptic feedback of the Moose, along with a simulation of the normal force, usually produced by bow pressure applied to the string.

photograph used with permission from Sile O'Modhrain

Figure 9. Sile O'Modhrain and Brent Gillespie's Moose

Similar research on the interaction between a haptic interface and a bowed-string physical model has continued at ACROE, with the work of Florens and Cyrille Henry (Florens and Henry 2001). Recently, they have been working with a "two axis joystick," used to track the lateral motion and pressure of the bowing gesture, and an "electro-dynamic multi-axis actuator," that transmits the force feedback of the "main pulsed components of the bowing force" to the players hand. This composite controller is interfaced, through a "visco-elastic link," to programming of a bow mass model, which is in turn linked, with a non-linear friction interaction, to a string model.

Most recently, O'Modhrain has been working with a group at the MIT Media Lab, including Eric Gunther and Glorianna Davenport, while herself at the Media Lab Europe, to develop "a system that facilitates the composition and perception of intricate, musically structured spatio-temporal patterns of vibration on the surface of the body" (Gunther, Davenport, and O'Modhrain 2002). This system, for the realization of "tactile composition," is comprised of "a full-body vibrotactile stimulator comprised of thirteen transducers worn against the body." The coil-based transducers used were selected because of their ability to output a variety of waveforms and transmit vibrations through clothing. The thirteen transducers, distributed across the body, receive independent audio signals from ProTools digital audio multitracking software, through a multichannel audio interface. A real-time "tactile sampler" has also been designed in the Max/MSP graphical programming environment for MIDI and digital audio applications. This system was used to present a concert, entitled Cutaneous Grooves, of tactile compositions, to audiences of ten participants at a time.

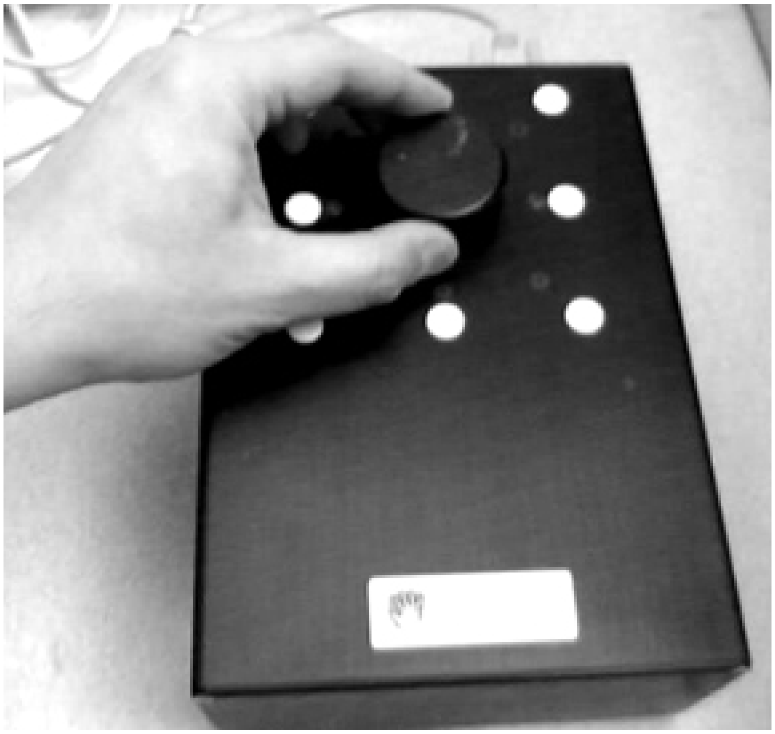
photograph used with permission from Eric Gunther

Figure 10. Eric Gunther in the Cutaneous Grooves vibrotactile suit

A colleague of O'Modhrain, Lonny Chu, has designed a variety of haptic systems for musical applications. One early design, a "force-feedback based MIDI controller," used a motor with an encoder, controlled and read by an I/O card in a PC, to generate MIDI information and produce haptic feedback (Chu 1996).

Another proposed design, by Chu, is a multi-modal "immersive, real-time performance environment," called MusiCloth, which is meant to make the computer "as accessible and as controllable to a skilled performer as an acoustic instrument" (Chu 1999). The conceptual model for MusiCloth is "a hanging tapestry or curtain that produces sound when touched," and provides the haptic feedback of "a variety of resiliency" and "different textures along its surface." The prototype for MusiCloth, a computer-animated simulation of the tapestry in the form of a "polygonal mesh," produced audio feedback by sending MIDI data to a synthesizer, and visual feedback by generating graphics on a computer screen. Both of these modes of feedback responded to interaction by the user, with a computer mouse, but Chu imagines using a six-degree-of-freedom controller, or glove interface, to manipulate the tapestry, and receive haptic cues.

The most fully realized design, by Chu, is a system developed around a haptic knob constructed by the Immersion Corporation, for editing sound in digital audio software (Chu 2002a, 2002b). The design of this system, called TouchSound, is based on the premise that "the inclusion of haptic feedback will improve user performance in basic sound editing tasks," such as finding the onset of a sound with the assistance of the haptic simulation of a detent. The haptic knob, which provides direct manipulation of recorded sound, analogous to moving a reel of magnetic tape across a playback head, helps the user navigate through digital audio, by providing haptic cues, such as pops, textures, and springs, to signify beats and changes in or slope of amplitude.



photograph used with permission from Lonny Chu

Figure 11. Immersion Corporation's haptic knob used for Lonny Chu's TouchSound

Other researchers have suggested designs for, or built prototypes of, additional haptic musical controllers. Bert Bongers, at the Royal Conservatory in the Netherlands, has proposed a haptic glove interface, that uses Muscle Wire, a proprietary material that "shortens in length when electricity is supplied," to provide resistance to flexing fingers, and Tactors, plates that "transform an electric signal into a haptic cue," to supply force feedback to fingertips, in relation to the music generated by this controller (Bongers 1994).

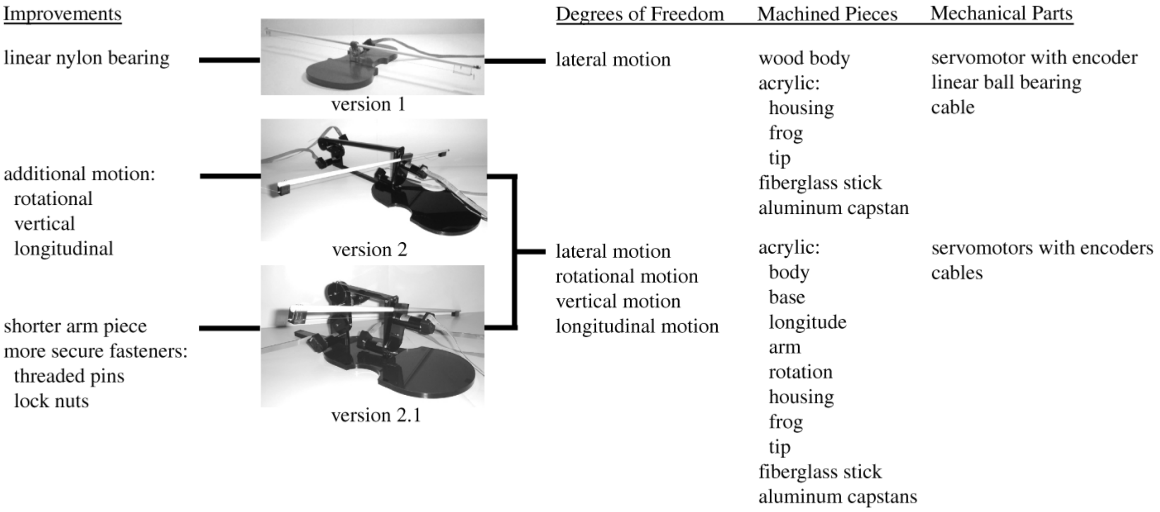
Another haptic musical controller system, the VR/TX, designed by Joseph Rovan and Vincent Hayward, in collaboration with percussionist Mark Goldstein, began as "an attempt to incorporate feedback into a custom glove controller" (Rovan and Hayward 2000). Three versions of a coil and magnet transducer were constructed, one ring-mounted, another mounted to the glove controller, and the other "embedded in a surface on which a performer can stand." These transducers were driven by audio signals, or "tactile sounds," generated by programming in Max/MSP software, which responded to the output from a Dimension Beam infrared controller, adding tactile feedback to an open-air performance interface.

A team at CCRMA, including Bill Verplank, Michael Gurevich, and Max Mathews, have designed the prototype of a haptic interface, called The Plank, which provides "one axis of force-feedback with limited range of motion" (Verplank, Gurevich, and Mathews 2002). This controller, made from the voice-coil motor of an old computer disk drive, has been used to experiment with haptic effects, such as simulating the slope of a terrain with positive and negative forces, and will be used to interact with "scanned synthesis," by directly manipulating the shape of an audio waveform.

Like these violin and bow controllers, the vBow has been constructed to transduce the bowing gesture of a violinist into sound synthesis parameters, by tracking the lateral, rotational, vertical, and longitudinal motion of a bow stroke with encoder sensors. And, like these haptic musical interfaces, the vBow was built to provide the performer with tactile-kinesthetic feedback, by simulating vibration, friction, detents, elasticity, and barriers with servomotor and cable systems. What is unique to the vBow is its ability to simultaneously simulate four independent haptic cues, mapped to four diverse yet interdependent bowing motions, with a four degree of freedom human-computer interface, built specifically to meet the performance needs of a violinist.

CHAPTER 4
VBOW HARDWARE

Construction



Improvements		Degrees of Freedom	Machined Pieces	Mechanical Parts
linear nylon bearing	version 1	lateral motion	wood body acrylic: housing frog tip fiberglass stick aluminum capstan	servomotor with encoder linear ball bearing cable
additional motion: rotational vertical longitudinal	version 2	lateral motion rotational motion vertical motion longitudinal motion	acrylic: body base longitude arm rotation housing frog tip fiberglass stick aluminum capstans	servomotors with encoders cables
shorter arm piece more secure fasteners: threaded pins lock nuts	version 2.1			

Figure 12. Construction synopsis

Version 1

The first version of the vBow was designed around a single servomotor with digital encoder and cable system, which sensed one degree of freedom of the bowing gesture of a violinist, and provided the haptic feedback of a randomly varied vibration (Nichols 2000).

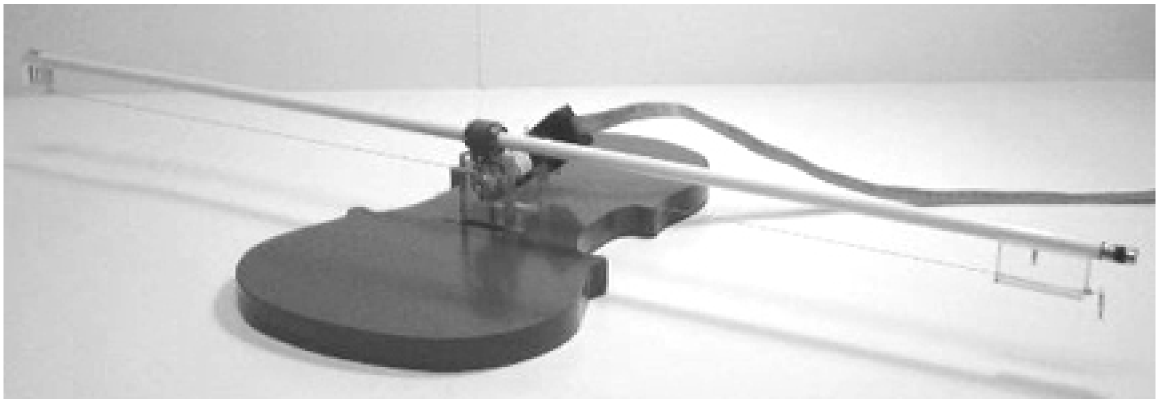


Figure 13. The vBow, version 1

The servomotor, a Maxon Precision Motors RE Ø25 series servomotor, was selected for its stall torque and operating range, so it would withstand the force of a normal bow stroke (Askenfelt 1989), while providing haptic feedback. At the back of the servomotor is attached a digital encoder that reads one thousand transitions per revolution from five hundred slots in two channels, providing a resolution of two thousand counts per revolution.

The single servomotor was attached to an acrylic housing with two screws that fit through holes drilled through the depth of the housing, and screwed into threaded holes in the front base of the cylinder of the servomotor.

An aluminum capstan, attached to the shaft of the servomotor with a set screw, fit through a third, larger hole, drilled through the depth of the acrylic housing. The capstan was turned on a lathe from an aluminum rod, to the diameter of the hole in the housing, and was further machined with a groove for the cable, and a threaded hole for the set screw.

Figure 14. Servomotor with encoder and capstan

Also attached to the housing was a linear bearing through which the stick of the vBow passed. The linear bearing was secured to the housing with a strip of metal that wrapped over the top of the bearing, and was fastened to the housing with a screw and nut. The screw passed through a hole at one end of the metal strip, through a fourth hole drilled through the depth of the housing, and through another hole at the other end of the metal strip, and was terminated with a nut. A strip of craft foam, attached to the inside arc of the metal strip, helped hold the linear bearing tightly against the housing.

The linear bearing was further stabilized with two clips that fit into grooves cut into the outer wall of the bearing, and snuggly straddled the walls of two shelves cut into both sides of the top of the housing.

Two Berg Manufacturing linear bearings were tested for the design of the first version of the vBow. The first was a mechanical linear bearing, with four rows of double-layered ball bearings evenly spaced along its interior wall. Because the ball bearings produced mechanical vibrations in the system, another linear bearing was tested.

The second linear bearing used was made of self-lubricating molybdenum disulfide filled nylon, rather than ball bearings. This linear bearing provided a smooth linear travel through the bore, like the first linear bearing used, but without the additional vibration.

The housing rested inside a notch that was cut into the top of a wooden, violin-shaped body, and was secured to the body with two wood screws. The screws fit through holes drilled through the feet of the housing, and screwed into holes drilled into the floor of the notch in the body.

The housing was originally designed in SolidWorks computer aided design software and laser cut from quarter-inch acrylic, but because the linear bearing could not be fastened securely to such a narrow housing, it was later machined by hand on a mill from half-inch thick, clear acrylic.

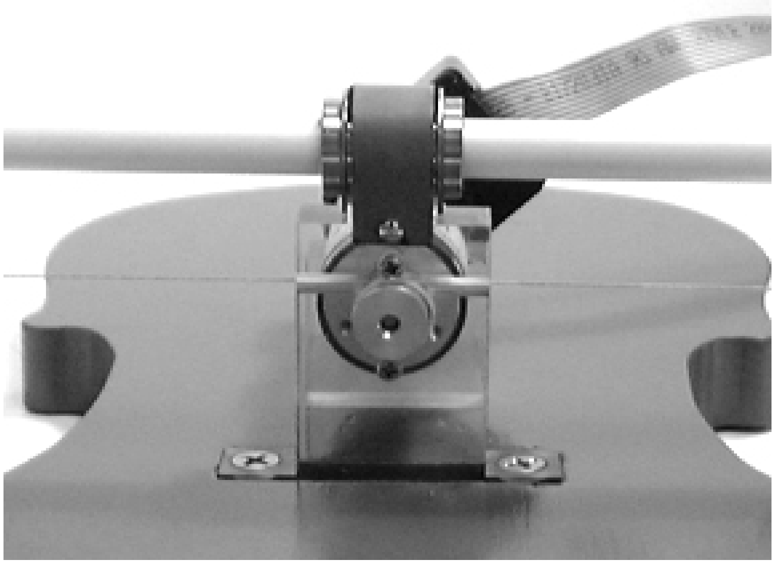


Figure 15. Acrylic housing with servomotor and linear bearing

The stick that passed through the linear bearing was cut from a fiberglass rod. At either end of the stick was fastened an acrylic tip and frog, with a groove cut along the top edges to fit over the diameter of the stick. A cable guide hole was drilled through the length of both the tip and frog, at the same distance from the groove, in which the fiberglass stick rests, as the height between the stick and the hair of a violin bow.

A Sava Industries 1x7, nylon-coated, stainless steel cable, terminated at either end of the tip and frog cable guide holes with a stainless steel ball and shank, passed through a cable guide hole drilled through the width of the acrylic housing. The cable guide hole was drilled through the housing at the height of the contact point between the hair of a violin bow and a violin string, just beside the bridge.

The cable wrapped once around the aluminum capstan within a groove cut into the exterior wall of the capstan. The surface of the groove was cut at the height of the center of the cable guide hole, so that the cable traveled smoothly through the housing, in direct line with the surface of the capstan.

A standard eyelet and screw, used to tighten the hair of a violin bow, was used as the cable tensioner for the vBow. The threads of the eyelet screwed into a hole drilled into the bottom of the groove cut along the top edge of the frog, at approximately the same distance from the back edge as the screw hole of the frog of a violin bow. The screw fit through a hole drilled into the end of the fiberglass stick and through the top of the eyelet, which fit into a notch cut into the bottom edge of the fiberglass stick. As the screw was turned, the eyelet traveled along the threads of the screw, pulling the frog toward the end of the bow and tightening the attached cable.

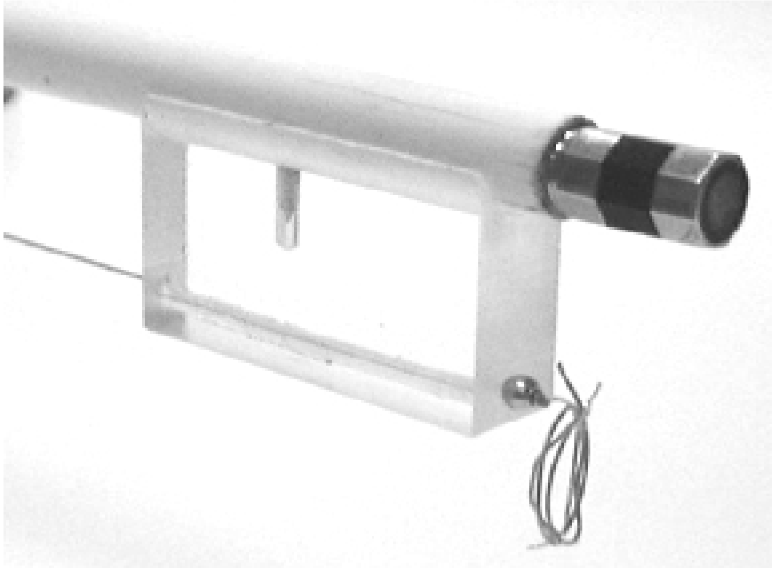


Figure 16. Fiberglass stick and acrylic frog with eyelet and screw, cable, and ball and shank

As the fiberglass stick of the vBow moved through the linear bearing, the cable, terminated at the frog and tip attached at the ends of the fiberglass stick, moved in parallel through the cable guide hole of the housing, spinning the capstan and the shaft of the servomotor. As the servomotor shaft spun, the digital encoder sensed the lateral motion of the bowing gesture.

Control software then engaged the motor, spinning its shaft and the attached capstan, in turn spooling the cable wound around the capstan, and moving the frog, tip, and attached fiberglass stick.

Version 2

The second version of the vBow incorporated the design of the first version into an interface that could sense three more degrees of freedom, and provide the haptic feedback associated with these additional kinds of bowing motion (Nichols 2001b).

Figure 17. The vBow, version 2

Because the laser used at the time could not cut half-inch thick acrylic, the pieces for this second version were laser cut in duplicate from quarter-inch thick acrylic, and the duplicate pieces glued together with acrylic epoxy, to make half-inch thick pieces.

The pieces were then fastened at the joints with stainless steel pins, which were secured with e-clips that fit into grooves cut into their circumference.

Version 2.1

Improvements were made to the design of the second version of the vBow, in order to improve the mechanical stability of the interface. Specifically, the arm was shortened, moving the base to the edge of the top arc of the violin body, allowing for the fingerboard to be shortened, and the pieces were joined with threaded stainless steel pins and lock nuts (Nichols 2002).

Figure 18. The vBow, version 2.1

All of the pieces were designed in Solid Edge computer aided design software, laser cut from half-inch acrylic, and further machined on a mill. The capstans were turned from an aluminum rod on a lathe, further machined with a mill, and threaded with a tap. The pins that join the acrylic pieces were cut from a stainless steel rod and threaded with a die.

Like the second version, this version incorporates the single servomotor from the first version, that sensed and provided haptic feedback for the lateral motion of the bowing gesture of a violinist, into a design that adds three additional servomotors with encoders, to sense and provide haptic feedback for rotational motion across, vertical motion above and into, and longitudinal motion along multiple virtual strings.

All of the servomotors are now secured to the acrylic pieces with three screws, which thread into holes arranged in an arc along the bottom half of the front base of the cylinder of the servomotor. This arrangement fastens the servomotors to the acrylic pieces more securely than the two screws used for the first version of the vBow.

In this design, the housing from the first version of the vBow is suspended above an acrylic violin-shaped body on an articulated arm. To each piece of the articulated arm is secured a servomotor or cable for each of the additional degrees of freedom of the interface.

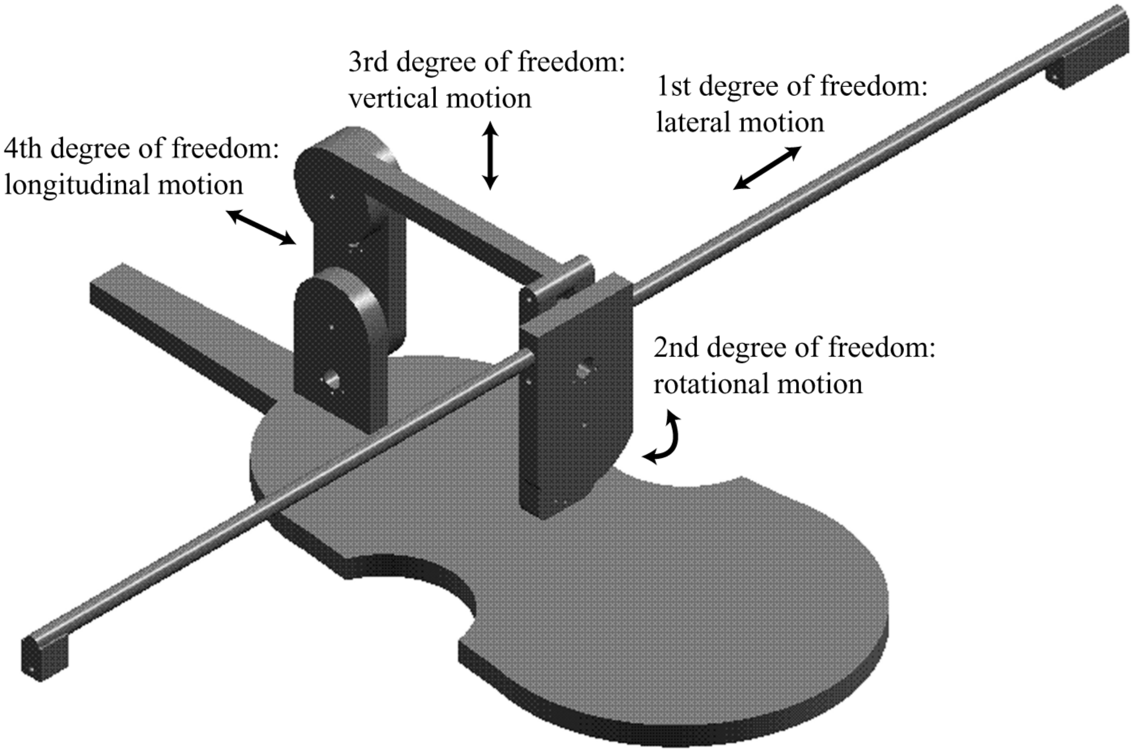


Figure 19. Degrees of freedom

The fiberglass stick from the first version is also used in this version, with a new tip and frog attached at either end. Like the first version, a cable guide hole is drilled through the length of the tip and frog, the tip is secured to the fiberglass stick with two screws, and the frog is attached with an eyelet and screw.

The housing from the first version has been modified, with a hole drilled through the width, at the diameter of the fiberglass stick, to replace the linear bearing of the first version. When the fiberglass stick is oiled, it passes smoothly through this hole, with little additional friction added to the system.

Like the first version, the fiberglass stick passes through the hole drilled through the housing piece, pulling the cable that is terminated at the ends of the tip and frog pieces. The cable, which is wrapped around the capstan, spins the shaft of the servomotor, which is secured to the housing piece. As the servomotor shaft spins, the digital encoder reads the shaft rotation, sensing lateral position, and sends the data through a ribbon cable to a connector on a circuit board.

Additionally, the housing piece has been redesigned to pivot against the rotation piece. The bottom edge of the housing piece is cut at a curve that is the inverse of the arc of a violin bridge. The housing piece is fastened to the rotation piece with a threaded pin and two lock nuts, that fit through holes drilled through the depth of both the housing and rotation piece. The hole in the housing piece is drilled at a point equidistant from the point of contact between the cable and the capstan for the first lateral degree of freedom, and the curved bottom edge of the housing piece. The result of this position for the pivot point, and the arc of the curved bottom edge, is that the vBow pivots in the same arc as a violin bow crossing violin strings.

Below the curved edge of the housing piece is a capstan attached to the shaft of the servomotor for the second rotational degree of freedom. This servomotor with encoder, which senses and provides haptic feedback for the motion of a violin bow crossing the strings of a violin, is secured to the bottom of the rotation piece with three screws that fit through holes drilled through its depth. The capstan fits through a fourth hole drilled through the depth of the rotation piece, and extends beyond the depth of the housing piece above.

Two screws tighten into threaded holes drilled and tapped into the bottom edge of the housing piece, at either end of the curve. A cable extends along the bottom curved edge, clamped tightly to the housing piece by the screws, and wraps around the capstan below.

As the housing piece pivots against the rotation piece, the curved edge rides along the capstan below, and the attached cable spins the capstan and the servomotor shaft. Like the servomotor with encoder of the first lateral degree of freedom, the encoder reads the shaft rotation, sensing rotational position, and sends the data through the ribbon cable to the connector on the circuit board.

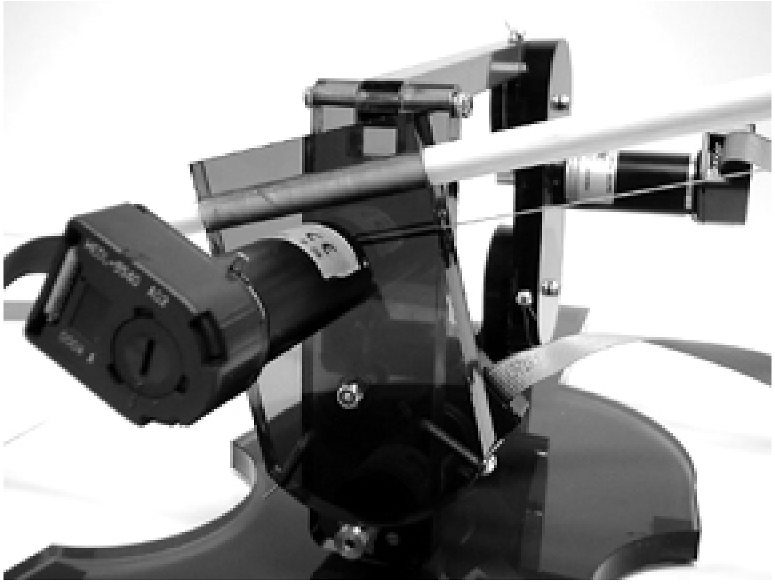


Figure 20. Rotational motion

The rotation piece is joined to an acrylic arm piece, with a threaded pin and two lock nuts. The far end of the arm piece fits into a slot, cut into the middle of the top edge of the rotation piece, to a depth that allows the rotation piece to swivel back and forth, without colliding with the arm piece.

The arm piece is joined at its other end to the longitude piece, with another threaded pin and two lock nuts. A cable wraps around the outer edge of this circular-shaped base of the arm piece, passing through a cable guide hole drilled through its height, at the point where the extension and circular-shaped base of the arm piece meet.

The cable is terminated at the top of the cable guide hole with a stainless steel ball and shank, and secured to the edge of the circular-shaped base, with a screw that tightens into a threaded hole drilled into the top edge of the arm piece. This cable wraps around the capstan attached to the servomotor and encoder that senses and provides haptic feedback for vertical motion of a violin bow lifting above and pushing into the strings of a violin.

This servomotor for the third vertical degree of freedom is secured to the longitude piece, with three screws that fit through holes drilled through the depth of the longitude piece. The capstan for this servomotor extends through a fourth hole drilled through the depth of the longitude piece, and extends past the depth of the circular-shaped base of the arm piece above.

As the arm is lifted or lowered, the circular-shaped base of the arm piece rides along the capstan below, and the attached cable spins the capstan and servomotor shaft. The encoder then reads the shaft rotations, sensing vertical position, and passes the data through its ribbon cable to the connector on the circuit board.

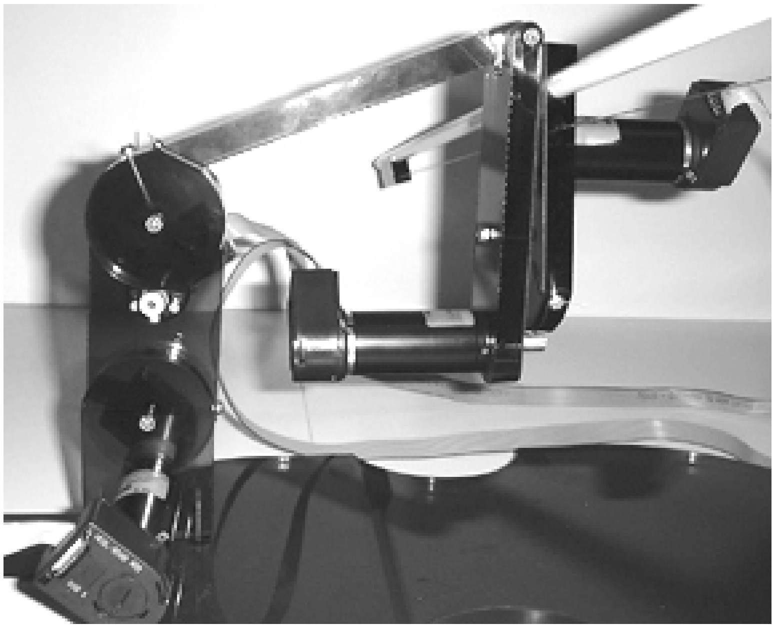


Figure 21. Vertical motion

The longitude piece pivots against both the arm piece and a base piece below, which is joined to the longitude piece with another threaded pin and two lock nuts. Like both the housing and arm piece, the curved bottom edge of the longitude piece rides along a capstan below, as the piece pivots.

Secured to the bottom edge of the longitude piece is a cable, clamped tightly by two screws, which tighten into threaded holes at either end of the curved edge. The cable wraps around the capstan below, which is attached to the servomotor with encoder that senses and provides haptic feedback for the longitudinal motion of a violin bow moving along the length of the violin string, toward and away from the bridge.

This servomotor is secured to the base piece with three screws that fit through holes drilled through the depth of the base piece, and the capstan fits through a fourth hole, extending beyond the depth of the longitudinal piece above.

As the longitude piece pivots, the cable fastened to its curved bottom edge spins the capstan attached to the shaft of the servomotor for the fourth longitudinal degree of freedom. The encoder at the back of the servomotor reads the shaft rotations, and senses the longitudinal position of the articulated arm, sending the data through its ribbon cable to the connector on the circuit board.

Figure 22. Longitudinal motion

The base piece is secured to a violin-shaped body piece, with two screws that pass through holes drilled through the height of the body piece, and tighten into threaded holes drilled up through the bottom edge, into the height of the base piece. The violin-shaped body piece provides a stable foundation for the vBow.

Version 2.2

At the suggestion of Kenneth Salisbury, two improvements have been made to the design of the vBow hardware, to counterbalance the load on the arm piece with a counterweight, and to mechanically stabilize the longitude piece with a spring.

The new arm piece, which now extends in both directions, was designed and laser cut from acrylic. This arm piece fastens to the longitude piece, like the old arm piece, with the same threaded pin and lock nuts, and again rides over the capstan attached to the motor fastened to the longitude piece. Because the new arm also extends away from the rest of the vBow assembly, a weight hung from the far end of the arm can now be used to counterbalance the mass of the acrylic and servomotors of the vBow. This counterbalance will allow for the player to move the vBow without supporting the weight of the mechanism, or relying on the servomotors to suspend the assembly.

In addition, another hole has been cut through the depth of the body piece, into which a threaded rod is inserted, and secured on either side of the body piece with lock nuts. Another hole has been cut through the depth of the longitude piece, in a bump that has been added to the piece on the side, next to the hole that is used to secure the rotation piece to the base piece with a threaded pin and lock nuts. Because the position of this bump is at the tangent point of the arc parallel to the edge of the piece, the tap into which the screw is inserted to secure the cable, has been moved further down the bottom arc of the piece. A spring can now be secured on one side to the threaded rod extending from the body piece and on the other side to the hole in the bump on the side of the longitude piece. Because the hole in the bump is at the tangent point equidistant to the top and bottom of the arc of motion, the spring will bring the longitude piece back to a vertical position from both motion closer to or further away from the player.

Figure 23: Improved acrylic arm, body, and longitude pieces

Electronics

Version 1

The electronics for the first version of the vBow were comprised of a Maxon Precision Motors linear servo amplifier, linear DC power supply, breakout board, servomotor disable switch, and power switch.

The servo amplifier was selected for its output power and voltage, and the power supply for its voltage output under load and current ripple.

The 10-contact socket connector at the end of the ribbon cable from the encoder, the 50-contact socket at the end of the ribbon cable plugged into the connector on the servo control and data acquisition card, and the connectors at the end of the wires soldered to the leads of the servomotor and secured by screws to the servo amplifier terminal block, plugged into the block and post headers on the breakout board. Under the breakout board, wires were soldered to the pins of the block and post headers, connecting the output and input from the encoder, servo control and data acquisition card, servomotors, and servo amplifier.

A Servo To Go servomotor and encoder I/O card, installed in a Pentium III computer, was used to read the three channels of encoder output and send control voltage for the servomotor to the servo amplifier. The card also supplied voltage to the encoder, and grounding for the servo amplifier and encoder.

The AC input to the power supply was connected to a switch, as was the output current from the servo amplifier to the servomotor. In the event of a problem with the control software, the disable switch could be used to cut the current sent from the servo control card, through the servo amplifier, to the servomotor.

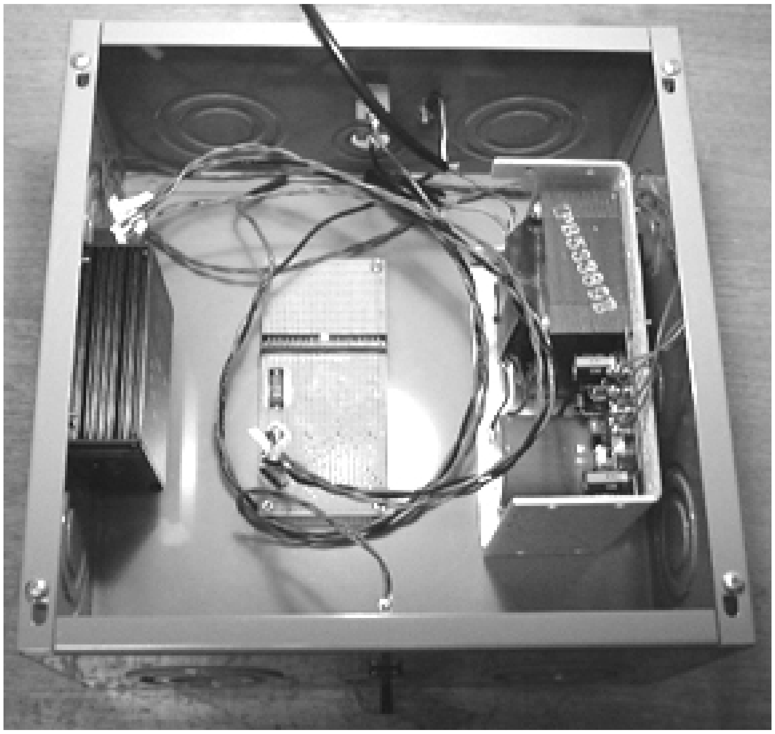


Figure 24. Electronics for the vBow, version 1

Version 2

The electronics for the current version of the vBow consist of four Advanced Motion Controls servo amplifiers and filter cards, a breakout board, two 4-pole servomotor disable switches, a power switch, and a power supply.

The servo amplifiers were selected for their output current and supply voltage range. The filter cards were necessary to increase the load inductance of the servomotors to match the output current from the servo amplifiers. The power supply was chosen for its output voltage and nominal output current.

Like the electronics for the first version of the vBow, the two servomotor disable switches cut the current from the servo amplifiers to the four servomotors, in the event of a problem with the control software. The power switch turns on and off the current from the power supply to the servo amplifiers.

The breakout board is assembled from a circuit board, one 50-contact and four 10-contact box headers, and two 8-position terminal blocks. The circuit board was designed in

Osmond printed circuit board design software, and manufactured by Alberta Printed Circuits.

The pins of the box headers and terminal blocks fit into holes drilled through the circuit board, and are soldered to the pads at the ends of the traces on the circuit board. The traces on the circuit board connect the pins of the box headers and terminal blocks, routing the input and output from the servo control and data acquisition card to the encoders and servo amplifiers.

The connectors at the ends of the 10-conductor ribbon cables attached to the encoders and the 50- conductor ribbon cable plugged into the servo control and data acquisition card plug into the box headers on the circuit board. The leads from the terminal blocks of the servo amplifiers are secured to the first terminal block on the circuit board. The second terminal bock serves as a junction at which the wires soldered to the leads of the servomotors and the wires from the servomotor disable switches are clamped together.

The servo amplifiers, filter cards, breakout board, and switches are mounted to four clear acrylic shelves, with screws and nuts, and are raised above the surface of the shelves by spacers, for ventilation and cooling. The shelves, separated by spacers, are stacked on four threaded rods, and secured with lock nuts at the top. The threaded rods pass through holes drilled through the thickness of the acrylic, in the four corners of the shelves, through the spacers, and are screwed to the base of the Advanced Motion Controls power supply, securing the assembly of electronics and shelves to the power supply.

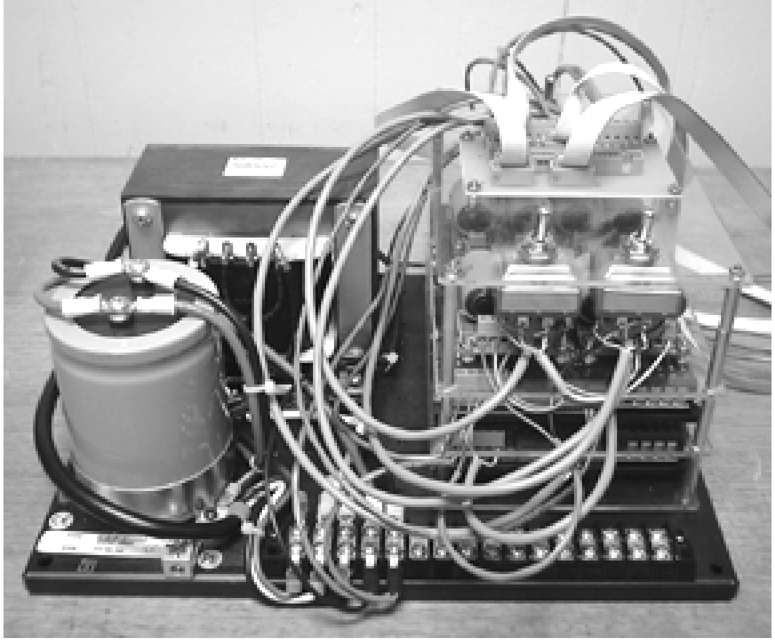


Figure 25. Electronics for the vBow, version 2.1

CHAPTER 5
VBOW SOFTWARE

Because the bowed-string physical model, used for sound synthesis in the vBow software, has been reverse-engineered from the interaction between the violin bow and string, it is important, when studying the developmental history of the physical model, to understand tone production from the perspective of the violinist. And, since the motivation behind the development of the bowed-string physical model is not only to produce a realistic sound, but also an expressively dynamic violin tone, through computer programming, it is valuable to learn how violinists control changes in the volume and timbre of the tone.

Many treatises by violin instructors outline the proper technique needed to produce a musically appropriate tone when bowing on a violin string, and in each explanation it is implicit that the expressive character of the violin relies on this interaction. Each author teaches the proper use of bow speed, pressure, and placement in relation to the bridge and fingerboard, to affect the volume and tone quality of the violin sound. Like the violin bow, the vBow relies on mapping lateral, vertical, and longitudinal motion to the parameters of bow velocity, force, and position, in the bowed string physical model, to expressively control the dynamics and timbre of the violin tone.

Performance Practice

Working chronologically through these monographs, this survey will start with the writings of Francesco Geminiani, the Italian violin virtuoso and composer, who wrote several sonatas, concertos, and treatises in the eighteenth century, and who studied with Antonio Vivaldi and Alessandro Scarlatti (Sadie 1980). In his violin treatise, *The Art of Playing on the Violin* (Geminiani 1751), the author instructs that "the tone of the violin principally depends upon the right management of the bow." After instructing how to properly hold, position, and draw the bow on the string, Geminiani explains that the management of crescendi and diminuendi relies on the player increasing and decreasing bow force, by pressing on the bow with the forefinger. He also states that bow velocity must be kept constant to produce a good tone.

> One of the principal Beauties of the Violin is the swelling or encreasing [*sic*] and softening the Sound; which is done by pressing the Bow upon the Strings with the Fore-finger more or less. … And lastly, particular Care must be taken to draw the Bow smooth from one End to the other without

> any Interruption or stopping in the Middle. For on this principally, and the keeping it always parallel with the Bridge, and pressing it only with the Fore-finger upon the Strings with Discretion, depends the fine Tone of the Instrument.

Later in the text, Geminiani briefly mentions the effect of bow position, instructing that "drawing the bow nearer to the bridge" while adding vibrato, "may express majesty, dignity, etc.."

Leopold Mozart, the accomplished violinist, organist, composer, and theorist, and father and teacher of Wolfgang Amadeus Mozart (Sadie 1980), continues the instruction, in his book, *A Treatise on the Fundamental Principles of Violin Playing* (Mozart 1951), published in 1756. In it, after an overview of bowed-string instruments, including an explanation of their design and construction, a brief history of music and musical instruments, and a concise music theory tutorial, he instructs the reader how best to hold the violin and use the bow.

While explaining how to place and draw the bow on the violin strings, Mozart first casually describes the interaction of bow velocity, force, and position, by instructing the player to "draw a long, uninterrupted, soft, and flowing stroke," not with a "quick stroke which scarce touches the string," but "solidly," with the bow "on a part of the string not too far from the bridge."

Mozart continues, in a chapter about bow control, by instructing how to produce a "pure tone" with the bow. He first warns against using a slow bow velocity, weak bow force, and bow position close to the bridge, describing the resultant tone.

> For what can be more insipid than the playing of one who has not confidence to attach the violin boldly, but scares touches the strings with the bow … ; and makes so artificial and whispering a sound right up against the bridge of the violin that only the hissing of a note here and there is heard …

Rather, he instructs that the player should vary bow velocity according to the desired dynamic, writing that "the stroke in soft tone must be drawn very slowly; when increasing the tone somewhat quicker; and in the final loud tone very quickly." Earlier in the chapter, Mozart coaches that the violinist should regulate bow force to control the volume of the violin sound, increasing the tone "by means of an imperceptible increase of pressure," and moderating it "by relaxing the pressure of the bow." He also teaches that the performer should change bow position in relation to the dynamic, placing the bow "a little farther from the bridge" for soft passages, and "nearer to the bridge" for a "loud tone."

Like the authors of these two treatises from the eighteenth century, Pierre Baillot, the French violinist and composer, who represents the last of those trained in the Classical Paris school of violin playing (Sadie 1980), reflects the development of violin virtuosity from his century, in his treatise *The Art of the Violin* (Baillot 1991), written in 1834. Like Geminiani and Mozart, this author begins with the basics of holding the violin and bow, and explains the fundamentals of tone production, but Baillot goes beyond these rudiments, explaining further musically expressive uses for bow velocity, force, and position.

The first of these extensions to the basic use of bowing parameters, discussed by Baillot, is the use of bow position, in combination with bow force and velocity, to produce variations in timbre.

> The positions of the bow very near the bridge and very near the fingerboard produce two opposite effects. The first is designated by the words sul ponticello, tout contre le chevalet (on the bridge); by drawing the bow with hardly any pressure, the violinist obtains a whistling and nasal sound; it is used for certain contrasts. The other effect is indicated by the words sul la [*sic*] tastiera, sur la touche (on the fingerboard); by slightly lengthening the bow stroke, the violinist produces sweet and flute-like sounds.

In a chapter devoted to bow control and tone production, the author explains how each of the three divisions of the bow length possesses an inherent elastic resistance and weight distribution, which contributes to the strength of the tone produced in each section. Bowing at the frog generates the strongest tone, due to the great elastic resistance and weight of the hand at this section, so can be used to produce accents and initiate long powerful strokes. The middle of the bow, or what Baillot calls "the center of expression," allows for "strength tempered by sweetness," because of the balance and increase in elasticity in this section. At the tip, the bow has no elasticity and little weight, which is conducive to producing a soft tone or short accents. The author continues the chapter with exercises meant to facilitate the production of musically appropriate tone at each of these three bow sections, with the aid of suitable bow velocity and force.

Baillot also explicitly discusses the use of slow and fast bow strokes, while controlling bow pressure, for the execution of several musical examples, with the proper tone. He describes the tone generated by a slowly drawn bow as "consisting of a profound and concentrated sentiment," and that of a quickly drawn bow as "sweeps of passion."

The author goes so far as to present recipes of varying degrees of bow velocity and pressure, to produce the now standard, named bow strokes, sorted into three categories. In the category of "bow strokes produced with the bow on the string," he describes détaché, the basic bow stroke, martelé, a more separated stroke at the tip, and staccato, an "articulated détaché." For "bow strokes produced using the elasticity of the bow," he explains light détaché, the basic stroke with less bow pressure and some bounce, perlé, a faster light détaché using very little bow in the middle, spiccato, a bouncing stroke at one point in the middle of the bow, and ricochet, a slurred spiccato. And, of "sustained bow strokes," he details détaché with pressure, a stroke used for tremolando and accents, and flautando, a "détaché with very light pressure." Baillot advises the violinist to use combinations of these bow strokes to express the "character of a particular passage," in order to "perform the passage with all the composer's intentions down to the smallest detail."

In addition to describing the bowing technique required for virtuosic special effects like arpeggio and bariolage, Baillot also explains the fast speed and heavy pressure required for the saccade stroke, a bowing used to accent the first of slurred groups of pitches, and the undulating bow pressure necessary for portato, a stroke used for slurred repeated notes.

The Austro-Hungarian violinist and composer, Joseph Joachim, who studied with Joseph Böhm, and worked closely with Felix Mendelssohn, Franz Liszt, and Johannes Brahms (Sadie 1980), also discusses the interaction between bow force, velocity, and position, for the production of an expressive tone, in his treatise, *Violin School* (Joachim 1905).

> … the pupil should clearly understand that the pressure exerted on the bow must always be in correct proportion to the speed at which it is travelling across the strings. Too much pressure with a slowly drawn bow produces a disagreeable, rasping, tone; on the other hand, too light a contact with the strings, both in quick and in slow bow-strokes, brings out a sound which can only be described as "wheezy". The pupil must therefore take great pains not to let his tone become harsh and scrapy when playing forte, nor thin and threadbare when playing piano. His first attempts at using expression will show him that tone increases as the bow comes nearer the bridge, and decreases as it approaches the finger-board.

This author continues by describing the heavy pressure and fast velocity required for the martelé stroke, and the vertical elasticity and lateral velocity needed to execute the spiccato bowing.

Leopold Auer, the Hungarian violinist and teacher, who studied with Jacob Dont and Joseph Joachim, and succeeded Henryk Wieniawski as professor of violin at the St Petersburg Conservatory, teaching Efrem Zimbalist and Jascha Heifetz (Sadie 1980), represents the Russian school of violin playing, in his treatise, *Violin Playing As I Teach It* (Auer 1921).

In his treatise, Auer focuses on the interaction of pressure from and movement of the wrist with the bow, to produce the bow force and velocity required to execute various kinds of bow strokes, and generate an "agreeable tone." As examples, he cites the technique of virtuosi violinists of his day, and the musical results of their skill.

But, Auer acknowledges that the complexity of the mechanics of the bowing gesture exceeds the capacity of analytical description.

> To describe in exact detail just how the bow should be held, just how the pressure of the fingers should be adjusted, and which finger – at a given moment – should stress its pressure upon the stick, and just how to set about beginning to use the wrist – the central point round which everything relating to tone production turns – all this presents a task of well-nigh insurmountable difficulty.

Ivan Galamian, the American-Iranian violinist who taught numerous virtuosi, including Itzhak Perlman, Pinchas Zukerman, and Jaime Laredo, at both the Curtis Institute of Music and the Juilliard School, represents a combination of the teachings of the Russian and French schools of violin technique (Sadie 1980).

In his book, *Principles of Violin Playing and Teaching* (Galamian 1978), he reinforces what has been written in previous treatises concerning the importance of the interaction between bow velocity, force, and position for tone production. Galamian explicitly describes this interaction as a series of instructions. For instance, to produce a good tone, an increase or decrease in pressure, with constant bow position, requires an increase or decrease of velocity, and an increase or decrease in pressure, with constant bow velocity, or a decrease or increase in velocity, with constant bow pressure, requires that the bow move toward the bridge or fingerboard, respectively.

Galamian continues by describing the interaction of these three parameters, in the context of specific musical circumstances. For example, if a rhythmic pattern requires changing bow velocity, pressure must be adjusted to compensate for the variation in dynamic. Similarly, to keep a constant dynamic within a long, slow stroke, pressure must be adjusted to keep the tone even, because of the naturally varying amount of force along the length of bow. Finally, when changing between the strings of the violin, or shifting positions, bow position must be modified to compensate for the varying thicknesses of the strings, and increasing or decreasing resultant tension.

The author also advises that bow velocity and force can be used to produce contrasting tones at identical dynamic levels, and should be used in combination to produce a "wide range of sound-character and timbre." Furthermore, Galamian explains how various proportions of bow velocity and force can be used to effect different styles of attack and smooth bow changes.

Bowed-String Physical Model

A bowed-string physical model, developed as a C++ object by Stefania Serafin, has been used for the synthesis software for both the first and current version of the vBow (Nichols 2001a; Serafin et al. 2001). This physical model was written using objects from the Synthesis Toolkit, a collection of signal processing and synthesis classes, written in C++, by Perry Cook and Gary Scavone (Cook and Scavone 1999).

Serafin's improvements to and programming of the bowed-string physical model represents recent work in a long history of development, with contributions from several research scientists. In addition to designing and implementing physical models, a number of these researchers devoted their work to the study and measurement of bowing parameters, such as bow velocity, pressure, and position.

Bowing Parameter Measurement

One such scientist, Chandrasekhara Venkata Raman, using a bowing machine, that is described in the previous section on bow controllers, measured the minimum bow force needed, in relation to changes in bow position, velocity, pitch, and muted pitch, to "elicit a full steady tone with pronounced fundamental" (Raman 1920-21). As the graphs illustrated in his paper show, the researcher found that "the bowing pressure necessary within the ordinary musical range of bowing varies inversely as the square of the distance of the bow from the bridge," and "that for very small bowing speeds, the bowing pressure necessary tends to a finite minimum value, and the increase of bowing pressure with speed is at first rather slow, but later becomes more rapid." The results further show that increased bow force is needed for bands of frequencies around the resonances of the violin, and when playing with a mute, bow force must be increased for lower frequencies and decreased for higher frequencies.

Fifty years later, John Bradley conducted a study of violin frequency response curves, with his colleague Stewart, using another bowing machine (Bradley and Stewart 1970). Bradley presented some of the results of this study in a later paper, with a graph of the "overall relative sound pressure levels," produced by machine-bowing the D string of a violin (Bradley 1976). The lines of the graph, each representing "three different initial bow forces of 115, 155, and 175 gram-force," show that although the change in force produced little change in sound pressure, change in pitch caused widely varying sound pressure levels for each constant force.

Bradley also showed that, with fixed bow position, sound pressure increases proportionally with bow velocity, producing a maximum level of 20 dB, and with a change in bow position, an additional increase of 18 dB, for a total sound pressure level of 38 dB, is possible.

In the mid-eighties, Anders Askenfelt measured transverse position and normal force of the bow, using a system of sensors connected to independent Wheatstone bridges (Askenfelt 1986). To measure "momentary transverse bow position," the researcher inserted a "thin resistance wire," in the hair of the bow, which was divided into two pieces by its contact with the short-circuited strings. When the bow was moved, "a voltage was generated proportional to the distance from the midpoint of the bow," through the electrical bridge. Bow velocity then could be calculated "from the slope of the bow position curve."

To sense bow force, two "thin strips of phosphor bronze" were glued to the hair of the bow at the tip and frog, and strain gauges, which were connected to another Wheatstone bridge, were fastened to these metal strips. When a force was applied to the bow, "the metal strips bent and the bridge generated a voltage representing the bow force."

In addition to using these sensors to measure bow transverse position and force, Askenfelt placed an accelerometer on the top of the violin, to read the "top plate acceleration" and the fundamental frequency of the note played.

From these measurements, the scientist found the normal bow force to be typically in the range of 0.5 to 1.5 N, with the minimum force required to produce a steady state tone measured at 0.1 N, same as the usual variation in force during a sustaining bow stroke. Velocity was calculated to be normally within the range of 0.1 to 1 m/s, with the lowest velocity measured at 0.04 m/s and the highest at 3 m/s. In concurrence with Bradley's measurements, Askenfelt found the maximum string vibration to have "a dynamic range of 38 dB," while the top plate vibrated at up to 30 dB.

The author continues to explain that different values were measured for various bow strokes. For instance, when bowing legato, velocity was 0.4 m/s, covering the entire length of the bow, for detaché bowing, velocity was 0.5 m/s, using less bow, and when playing staccato, velocity was 0.8 m/s, with short strokes. The bow force for all of these strokes was approximately 1 N, but varied during the bow stroke, especially before and after changes in direction.

Similarly, for sforzando bowing on and off the string, bow velocity was measured at 1.0 m/s and 1.8 m/s, with 1 N of force for both strokes. Force and acceleration simultaneously increased continuously from 0.1 to 0.3 m/s and 0.1 to 2 N, during a crescendo, while a moderate bow force with a "slow initial velocity followed by an acceleration towards the termination" was seen for spiccato notes, and bow velocity and force varied continuously during the crescendo and diminuendo of saltellato bowing.

In a companion piece to the previous paper, Askenfelt described an addition to the system for measuring bowing parameters, which tracks bow position in relation to the bridge, or what the author calls "bow-bridge distance" (Askenfelt 1989). Using a third Wheatstone bridge, the string was used as a resistance wire, divided by the wire inserted between the hairs of the bow. The ratio between resistances of the two divided parts of the string now determined the position of the bow in relation to the bridge.

The system was used to measure bowing parameters of two violinists, while playing whole notes, detaché on the open G string, at three dynamic levels. The results showed that the distance between the bow and bridge decreased from 40 to 20 mm, bow velocity remained between 0.2 and 0.3 m/s, and bow forced increase from 0.5 to 2 N, as dynamic level increased from piano to forte. Furthermore, bow-bridge distance measurements varied by about 10 or 20 mm, velocity varied by more than 0.1 m/s, and although force varied little, the difference increased with the rising dynamic level.

When asked to play sul tasto, the violinists' bow-bridge distance was measured at 55 to 60 mm, and for sul ponticello, 1 to 4 mm, in contrast to the usual 25 to 35 mm, with as little as 2 mm of variation during a steady bow stroke. For a crescendo starting up-bow, bow-bridge distance shortened from 35 mm to about half the length, bow velocity increased to 0.3 m/s, and force increased to 2.5 N, for a dynamic rise of 20 dB. For a down-bow crescendo, bow-bridge distance and bow velocity increased even more, resulting in a dynamic rise of 25 dB.

Summing up the findings of both papers, Askenfelt charts the minimum, maximum, and average values for these three bowing parameters. Minimum bow-bridge difference was measured at 1 mm, while the maximum was 60 mm, and the range for usual bow-bridge difference was found to be between 10 and 50 mm. For bow velocity, a minimum value of 0.04 m/s was observed, while the maximum was 3 m/s, with a usual range of between 0.2 and 1 m/s. The scientist assessed the minimum bow force to be as small as 0.15 N, with a maximum of 3 N, although as high as 6 N is possible at the frog, with a usual range of 0.5 to 2 N, a measurement that was used to choose the servomotors for the vBow.

As Askenfelt states at the end of his paper, the results of this study quantifiably confirm the interdependency of bowing parameters for producing and expressively changing the dynamic or timbre of the violin.

> The registrations of the bowing patterns have illustrated the high complexity in the coordination of the bowing parameters in performing a given task. In principle, the player has a wide choice of combinations of bow-bridge distance, bow velocity, and bow force for producing a given dynamic level and tone quality. The dynamic level and tone quality may even be independently controlled to a considerable degree. However, the duration of the notes, the character of the bowing pattern and the succeeding evolution in dynamic level, all put demands on the combination of parameters. These demands do not always converge into one optimal combination.

A few years later, Robert Schumacher measured bowing parameters using a bowing machine, in order to assess the "probable validity of the friction curve model of the force between bow hair and string in bowed string motion" (Schumacher 1994). Primarily interested in "the maximum bow force for Helmholtz oscillations, and the frequency shift as a function of bow force," or what has been called the "flattening effect," the scientist varied bow force, measured in grams force (gmf), while keeping bow speed at 5 and 10 cm/s, and bow position, or the proportion of the string divided by the bow, at 0.05 and 0.1, for eleven kinds of strings, from a variety of makers.

The results show that the maximum bow force for a bow speed of 5 cm/s and position of 0.1 ranges between 12 and 32 gmf, for the eleven strings, while the maximum force for a speed of 10 cm/s and position of 0.1 varies between 12 and 29 gmf. For a bow position of 0.05, the maximum bow force increased to between 25 and 57 gmf for a bow speed of 5 cm/s, and to between 23 and 49 gmf for a speed of 10 cm/s. The maximum flattening was measured at between 0.82 and 3.7 percent for the four categories. In conclusion, the author states that "there seems to be no particular correlation between flattening and any parameters of the strings, or between flattening and the relevant parameter of bowing," which is bow speed divided by position.

In preparation for developing a violin-playing robot, a team at Waseda University in Tokyo measured a violinist's arm motion, with a "3D-Video Tracker System," which followed markers attached to the player's body with CCD cameras, joint angle of the fingers, with "flexible goniometers," and bow force, with strain gauges secured to the hair of the bow at the tip and frog (Shibuya and Sugano 1997). Arm motion, finger angle, and bow force data were acquired while professional violinists, students, and "inexperienced persons" played a down-bow and up-bow on the A string, with three different bow forces and velocities.

From the measurements taken, the team generalized that there was little difference in the movement of joints of the shoulder, elbow, and wrist between the professional, student, and novice violinist, although they observed that while the professional violinist's wrist joint torque decreased along with bow force, there was no such correlation for the novice player. Furthermore, the researchers determined that the forefinger controls "transverse direction of the bow by holding the stick," while the other three fingers control "horizontal direction of the bow by picking up and pulling down the frog."

Bowed-String Physical Model Development

As early as the beginning of the sixties, John Schelleng was describing the violin as a circuit, in which the contact between the bow and string is "a constant-velocity generator," the string is "a lossless transmission line," and the lengths of string on either side of the point of contact between the bow and string form a "series resonant circuit," with "positive mechanical reactance" on one side and negative on the other (Schelleng 1963).

Almost a decade later, Schelleng presented another circuit for calculating minimum and maximum bow force, in which the bow "delivers power" into a "pure resistance," both the short length of string between the bow and bridge and the long section of string between the bow and finger or nut are represented as a reactance, and "bridge impedance is represented by a high reactance," "in parallel with a high resistance," which represents "all sinks of vibrational power referred to the end of the string at the bridge" (Schelleng 1973). In addition, the author represented the bowed string as "hypothetical single-mode balanced transmission lines," in which bow velocity is divided into bow slipping, string translational, and string rotational velocities, each contributing more or less to the overall motion, depending on the state of the other two lines. For instance, if "all string motion is blocked," all motion is contributed by the bow slipping velocity, but if the bow is stuck, "bow motion appears as string translation and rotation."

A few years earlier, Mathews and Kohut measured "the velocity of a bowed violin string," by assessing the changes in a voltage at the ends of a string, when a magnet was placed at different points along its length (Mathews and Kohut 1973). According to the advice of Rose, "the voltage at the endpoints will measure the velocity of the string at the position of the magnet." With these measurements, the team was able to show that "the violin string motion is essentially as predicted by the Helmholtz theory with certain exceptions." Explainable cases in which this ideal triangular waveform is not produced occur when the bow is played with "too light a bow pressure" or "when the bow position is far from the bridge."

Lothar Cremer's paper from the early seventies begins with a tutorial on Helmholtz' theory, describing the motion of a bowed-string as "a triangle with connection of the supports of the string as the base and a constant top angle whose apex propagates to and fro inside two enveloping parabolae, changing its sign with direction of propagation" (Cremer 1972). The author continues to explain that change in the string velocity and consequently sound pressure is proportional to bow velocity and inversely proportional to bow distance from the bridge.

But, Cremer points out, Helmholtz did not consider how "the frictional force between bow and string," caused by bow pressure, affects the motion of the vibrating string. And, the author explains, bow pressure is indeed an important component of the bowing gesture, so its effect on the motion of the bowed-string must be considered. According to the researcher, "changes in bow pressure actually modify the shape of the string motion at the bow," causing a rounding of the corners of the Helmholtz motion.

In a later paper, discussing his investigations into the cause of the "long transient duration of the fundamental tone" of a violin, Cremer states that when a violinist "starts a new note by accelerating the string at the bowing-point from rest to a special bow velocity it takes time to get the periodic Helmholtz motion" (Cremer 1982). Additionally, he describes a "static deformation" in the triangular motion, caused by the "mean friction force at the bow." The interaction of this bow force on the Helmholtz motion of a string that is plucked before the bow is placed, produces triangular waves whose amplitudes "decrease from period to period." The same interaction in the case of a bowed string, results in a motion that repeats the "half period of sliding but in the opposite direction and sequence."

Later in the paper, Cremer presents a "signal flow diagram of the simulation of transients at a bowed string on a computer," with and without the interference of torsional waves, and sites McIntyre and Woodhouse's computer simulations of bowed-string transients. At the heart of both diagrams is "Friedländer's graphical solution" for the previously discussed interaction between bow force and string velocity. The "right hand vertical branch," of this curved graph, represents where string velocity equals bow velocity, so the bow "captures" the string, and the "left hand curve" represents "the dependence of the sliding friction on the relative velocity," which equals bow velocity minus string velocity.

In the mid-seventies, Robert Schumacher published a paper, suggesting a model of the bow, in which "the hair is a somewhat lossy transmission line terminated, particularly at the tip end, (the 'head') by parallel mechanical resonant circuits that represent the normal modes of stick" (Schumacher 1975). The researcher further states that the "lowest, clearly identifiable such mode" is between 500 and 600 Hz, and additional modes "occur irregularly with an average spacing of about 300 Hz up to 2000 – 2500 Hz," having optically measured these modes with a light beam and phototransistor tracking the vertical vibration of a needle excited against the hair of a bow. He additionally defines "the fundamental normal mode for longitudinal hair vibrations" as the velocity of sound traveling through bow hair divided by twice the length of the hair.

In a subsequent paper, from the late-seventies, Schumacher applies the same integral equation that he used to study the organ pipe and clarinet, "to calculate the velocity of a bowed string at the bowing point, and the force between the string and the bow, in the limit of steady state periodic motion" (Schumacher 1979). Like Cremer, he is concerned with "the transverse velocity of the string moving in a plane, bowed at a point," and presents a model of "those periodic oscillations that have a single slip per period" or "those that approximate the classical Helmholtz motion."

In particular, the author is concerned with the "bow pressure effect," in which slipping decreases as pressure increases, and the "flattening effect," where the pitch of the bowed string lowers with added pressure. In addition, Schumacher is interested in the "ripple effect," "surprisingly large fluctuations" in string velocity, "with regular bumps or ripples whose relative positions within the cycle are related to the bowing point," measured at the point of bowing, while the bow is sticking to the string.

The model that Schumacher shows, represents "a unit length of perfectly flexible string of characteristic impedance … terminated at each end by an infinite string of much larger (real) impedance," on which "a pulse traveling on the center section reflects from either end inverted, diminished in magnitude, but unchanged in shape." The results of this model correspond to "the many types of bowed string motion described by Raman," including the Helmholtz motion, as well as "the periodic limit of the difference equations of Friedlander."

Using the same Friedlander "graphical visualization" of "the frictional force between bow hair and string" that Cremer used in his model, Schumacher plots the solution of his equation, "at various times during a cycle of the oscillation," represented as straight lines that intersect the friction curve. The author explains that "the solution is unique and unambiguous as long as there is a single intersection between the straight line and the … curve." Cases, in which the solution intersects the curve in three places, have been solved by McIntyre and Woodhouse, by insisting that "the system remain in its current state, slipping or sticking, for as long as it is able to do so." Or as further explained by Schumacher, "the system sticks until the maximum sticking force is reached or slightly exceeded, at which time the only solution corresponds to the slipping velocity."

This hysteretical behavior explains the pressure and flattening effect. And, through calculations "made over nearly the full range of bowing pressure for a single bowing point" with the model, these effects, as well as "the fluctuations in string center of mass velocity at the bowing point during sticking,," can be shown.

In a companion paper, Michael McIntyre and James Woodhouse propose their model, mentioned by Schumacher, that "predicts the flattening effect and associates it with a hysteresis phenomenon" (McIntyre and Woodhouse 1979). In addition, through the unification of "earlier methods of treatment of the bowed-string problem," producing "a formulation which encompasses a wide range of possible models and which gives insight into the range of behaviour to be expected from these models," the researchers come upon "an efficient method for numerical simulation of general, transient bowed-string motions, with realistic corner-rounding taken into account." Finally, they propose a new measurement of bowed-string instruments, called the "Green's function," which takes the "impulse response at the bowing point," and from which a model of the instrument can be formulated.

The authors begin their paper by presenting Raman's two bowed-string models, one "a kinematic description of a hierarchy of periodic motions, including the basic 'Helmholtz motion'," and the other "a dynamical model in which the string was assumed to be an ideal, flexible string terminated in real, frequency-independent mechanical resistances." For this second model, the equations that represent the motion produced by the string bowed at a single point can be reduced to a nonlinear difference equation, "because propagation and reflection are non-dispersive."

Ignoring the finite width of the bow, McIntyre and Woodhouse present the basic equation using bow speed and force for a bow of zero width. Or, as written by the authors, "a force is applied at one point of the string," and the "frictional force exerted by the bow on the string depends on relative velocity only," as shown by the same Friedlander function curve, as used by Cremer and Schumacher. For that function, if the point plotted for the values of friction force and string velocity lies on the "negatively-sloping part of the friction curve," then "the string is 'sticking' to the bow," otherwise it is "slipping." In addition to this friction curve, the equation includes "the dynamical behaviour of the string and its terminations," or aforementioned Green's function, resulting in a model "formulated in terms of the motion of the string at the bow," albeit for a bow that is essentially "a rigid, rosined stick having a single point of contact with the string."

In order to model the behavior of the rounding of the Helmholtz motion, propagating from either side of the bow, as the waves reflect off of either end of the string, the scientists simulate the "total modification" of the wave, caused by "the reflection properties of the terminations," with two transfer functions or "corner-rounding functions." These transfer functions, which can be derived from measured Green's functions, or, in the case of modeling "a string with harmonic overtones, but with damping smoothly increasing with frequency," can be "simple, symmetrical humps," are then convolved with the original Helmholtz motion and each successive reflection, producing the appropriate rounding.

In an earlier joint paper by all three scientists, McIntyre, Schumacher, and Woodhouse present an elucidating description and illustrations of this rounding of the Helmholtz motion (McIntyre, Schumacher, and Woodhouse 1977). In addition, after an overview of the flattening effect already discussed, the authors explain that "the extent of flattening depends on the amount of hysteresis as well as on the amount of corner-rounding."

The three continue with a description of another effect they have studied, namely, "the gradual buildup of noise accompanying the musical note, which is noticeable when trying to play more and more loudly near the bridge." When studying the "transverse force exerted by the string on the bridge during a noisy note," the cause of the effect, sharp spikes on the slope of the Helmholtz motion, were clearly visible.

In order to determine the cause of these spikes, the scientists first bowed a string with a "smooth, round, rosined stick," which did not produce the noise. Next, the trio cut a groove along the length of the stick, creating two parallel edges, which they smoothed, rosined, and used to bow the string, again producing noisy spikes in the waveform. Like with a width of bow hair, the "short section of string" in contact with the two edges of the stick "must slip momentarily during the nominal 'sticking' part of the Helmholtz cycle," and "as bow force is increased differential slipping need occur less often, but will tend to be more violent since the short section of string will have been forced further out of line beforehand." The researchers were able to simulate similar differential slipping "using a two bow-hair version of the simple Raman model."

In another paper by these three scientists, McIntyre, Schumacher, and Woodhouse follow up their previous study of hysteresis, jitter, and spikes, by further studying these aperiodic behaviors of the bowed string and bowed-string physical model (McIntyre, Schumacher, and Woodhouse 1981). The authors ask "whether all (or indeed any) regimes of musical interest can in fact be described to sufficient accuracy as periodic motions." In order to answer the question, the scientists rely on evidence from three sources: "measurements of the variations in period lengths of successive cycles of bowed-string waveforms," the mathematical model of a "nondissipative … string with rigid terminations, bowed at a single point dividing the string in a rational ratio" developed by Friedlander, and "the marked build-up of audible noise accompanying the musical note when trying to play more and more loudly near the bridge."

Because reports of measurements of jitter were not supported with sufficient information, the researchers decided to repeat the measurements themselves. What they found was that "the jitter is smaller, usually much smaller, than previously reported," so neither "intrinsic to bowed-string dynamics," nor a significant concern.

Similarly, the scientists found that the instability in the Friedlander model, which "takes the form of sub-harmonics of the note being played, which grow exponentially in time," does not occur under similar conditions with real strings. Rather, when bowing real strings, "the sub-harmonic patterns do not exhibit any long-term regularity, seldom persisting beyond a few subharmonic cycles."

The third source of evidence, namely the noise heard when playing loudly by the bridge, as explained in the previous paper, is due to the violent slipping of the string against a "finite width of bow," so is not related to either the jitter or sub-harmonic aperiodicity. In a follow-up to the previous paper, the researchers present illustrations of the spiked waveforms produced by bowing with a regular bow, by bowing the "double-stick" described in the previous paper, and by computer simulation using a "two-bow-hair" version of a bowed-string physical model (McIntyre, Schumacher, and Woodhouse 1982). The figure shows the similarity between the waveforms produced by the three methods, confirming the previous results and assertions of the scientists.

In a seminal paper by the three authors, "On the Oscillations of Musical Instruments," McIntyre, Schumacher, and Woodhouse summarize their work, developing a model that "demonstrates some of the basic nonlinear behavior of the clarinet, violin, and flute families" (McIntyre, Schumacher, and Woodhouse 1983). After describing the basic model in terms of a non-linear function relating air volume flow rate, mouth pressure, and fluctuating pressure for a clarinet embouchure, and a linear function characterizing "the acoustic pressure signal … in the mouthpiece as the sum of two contributions representing incoming and outgoing waves," the researchers explain the specifics of applying the model to the bowed string.

After first adapting the model to the case of the bowed-string, relating the frictional force of the bow on the string to the air volume flow rate of the clarinet, and the reflecting waves of the clarinet to waves propagating from and reflecting to the bow at the middle of the string, the authors again explain the Friedlander function, relating frictional force to string velocity, their findings correlating the flattening effect to the hysteresis of the sticking string jumping to a sliding behavior, and their simulations of subharmonics.

What is particularly interesting in this paper, is the section on adapting the simple model to a more realistic bowed-string model. In Appendix B of the paper, the authors "allow for an asymmetrically terminated string bowed at any point," by introducing independent reflection functions for the left and right sides of the string. In addition, the researchers built into their model the effects of torsional string motion, by adding "torsional-to-transverse 'transfer' reflection functions" to the equation. Other possible additions to the model, mentioned by the trio, include introducing "reflection functions for longitudinal waves on the bow hair," and also for "transverse string motion normal to the bow hair."

In the early nineties, James Woodhouse published a tutorial on modeling bowed strings (Woodhouse 1992). Along with a succinct and effective description of the previously described models, the author explains the importance of investigating torsional damping, studying the "physics of rosin friction," measuring "the correct time-dependent set of control parameters" for transients, and developing refined simulations, to facilitate improvements in the bowed-string physical model.

A year later, Woodhouse presented a pair of papers concerned with the "playability" of violins, which he explains is the performer's reaction to "some desirable quality in the responsiveness to bowing." In the first paper, the author makes clear the derivation of the reflection function from the bridge representing "a mixture of decaying sinusoids representing vibration modes of the violin body," and how torsional waves, which are "straightforward in principle, although not easy to carry through in practice since reliable measurements of torsional response are hard to make," can be represented as waves "superposed on transverse motion" (Woodhouse 1993a).

The majority of this first paper is devoted to the study and implementation of "narrow reflection functions," or those that have "significantly non-zero values only during a time interval which is short compared with the period of the note." Although these don't realistically represent the physics of a violin string, they are useful for "simple analytical calculations," correspond to most published simulations, and are consistent with Cremer's model, which Woodhouse sites as "a valuable benchmark against which the changes produced by more realistic models may be judged." Also, because playability is judged according to energy dissipation and "anharmonicity of string modes," a narrow reflection function, which dissipates energy but is harmonic, can be used to isolate the playability effects.

The second paper discusses "two specific problems related to playability," calculating the minimum bow force required to produce a Helmholtz motion, and testing the playability of transients with computer simulations (Woodhouse 1993b). Through an extension to Schelleng's model, Woodhouse was able to use the input admittance function of a violin, "measured at the lowest string-notch on the bridge," to deduce a "note-by-note variation of minimum bow force." The author was unable to test the results against actual variations in playability, however, because of the lack of a "reliable bowing machine."

In an attempt to apply the analysis described above to the playability of a bowed-string physical model, the researcher used a model with narrow reflection functions, as described in the first of these two papers, to calculate minimum bow force. The findings showed that although the model with narrow reflection functions had very small bow force, it could not "reliably be calculated using Schelleng's argument."

The second playability problem discussed in this second paper concerns the computer simulation of transients in the bowed string. Using the model discussed in the first paper, and in the previous paper on the oscillations of musical instruments, by McIntyre, Schumacher, and Woodhouse, the researcher simulated the "initial and final forces" of a bow stroke, "to map out some part of the player's parameter space, and then represent the results in diagrammatic form so that any interesting structure may be readily discerned." The author describes the process, comparing it to the "computations of the famous Mandelbrot set."

> … for each point in the parameter plane, a nonlinear process is simulated using the coordinates of the point as input data. The simulation is continued long enough to indicate the eventual outcome (in our case, whether a periodic Helmholtz motion is or is not produced), then that point can be coloured in some way to represent this outcome, and the calculation moves on to the next point. When a reasonable area has been covered in this way, a picture will have been built up of the region of the parameter subspace in which Helmholtz motion actually occurs from a starting transient.

The results, illustrated in an effective figure, with steady bow force plotted horizontally and the ratio of initial to steady bow force plotted vertically, and white points representing Helmholtz motion and black points representing other motion, show a band of Helmholtz motion sweeping widely from the bottom middle right up narrowly through the top middle left, with the other types of motion labeled from left to right as “4 slip,” “3 slip,” and “Double slip,” before the Helmholtz motion, and “Multiple fly back,” after. The results further show that the upper bow force limit of the simulation roughly approximates Schelleng’s value, and that the minimum bow force is higher than that deduced in the previous section of the paper, making the disagreement with Schelleng’s argument insignificant. Woodhouse’s final analysis is that this simulation shows that Cremer’s model, with its lower bow-force region containing “unacceptably long starting transients,” and its higher bow-force region “cluttered with islands of multiple-flyback motion,” is not easy to play.

In another seminal paper, authored by a colleague of the aforementioned authors, who is cited in Woodhouse’s writings, Julius Smith presents “a simple computational model for bowed strings and techniques for its calibration” (Smith 1982). This model consists of “a linear digital filter which models the vibrating string,” partially based on the model developed by McIntyre and Woodhouse, and an excitation of this filter, which can be “a series of impulses which convey pitch and amplitude information,” or “a two-way bow-string interaction based on the … basic physics of the bowing process.”

At the base of this model is a wave equation for an ideal string, which represents “the transverse acceleration of a point on the string,” in terms of “the curvature of the string at that point,” string tension, and “mass per unit length of the string.” The general solution of this equation for traveling-waves represents “the sum of two fixed wave-shapes traveling in opposite directions along the string.” And, for the case of a string terminated at both ends, these two traveling waves, which are “eternally reflected back and forth between the ideal terminations,” can be simulated with two delay lines and sign changes.

Smith continues by constructing a transfer function, again for a string terminated at both ends, that includes “frequency-dependent damping and inharmonic overtones.” The transfer function is based on an “acceleration impulse” that initializes the system, moves toward the bridge, “where it is filtered and reflected,” moves past the observation point toward the nut, and again is filtered, reflected, and returns to the observation point. Impulses are output from the system, each time the impulse returns to the observation point.

The same procedure is applied to an impulse initially traveling to the nut, and the transfer function of the string is a linear combination of the transfer functions for the two reflecting impulses, each scaled by a term that represents “the initial position and velocity of the input impulse.” The transfer function for the impulse traveling toward the nut first is scaled by the term, while the one for the impulse moving toward the bridge is scaled by one minus the term. Furthermore, for the plucked string, this term is set to the value of one-half, and for the bowed string, is set to zero for a down-bow and one for an up-bow.

Smith then applies “the first-order model of bowed string motion derived by Helmholtz” to the model, by deriving the acceleration input from the curvature distribution and peak displacement, and combining it with the transfer function previously derived for a down-bow. The transfer function of the up-bow then is derived by similarly determining the transfer function of the plucked string, from a combination of the wave equation and transfer function of the doubly terminated string, and subtracting the transfer function for the down-bow.

To imitate bowing the string, Smith uses an input to the string model that simulates “the effect of a bow with a given pressure, differential velocity, and position.” First the author determines the sum of the reflecting velocities at the contact point of the bow on the string, then solves for “the change in velocity … as a function of the bow pressure, the relative velocity between the bow and string, and the string wave impedance,” by using the Friedlander-Keller function, like that used by the previous authors. The intersection of the “wave-admittance line of the vibrating string,” as produced by the previous transfer functions, with the horizontal axis of the friction function graph, represents the differential velocity between bow velocity and the velocity of the sum of reflecting waves, and the distance between that point and the intersection with the “bow-string friction curve,” determines the change in velocity, which replaces the impulse as the input to the system.

The author includes a diagram of the system, composed of the delay lines and filters mentioned above, and in which bow velocity and pressure are inputs to the model. It is also mentioned that bow position can be used to change the lengths of the delay lines that simulate the reflections from the bridge and nut.

In a subsequent paper, Smith proposed a “simplified implementation of the graphical Friedlander-Keller component of the model,” in which “a table lookup and multiply replace the simultaneous solution of a linear and nonlinear equation" (Smith 1986). The diagram of the bowed-string physical model in this paper shows a system with two delay lines on either side of the bow-string interaction, and although the low-pass bridge filter from the previous model is still included, the nut filter is replaced with a sign change. In addition, at the center of the diagram is the bow-string interaction, which relies on differential velocity, bow velocity minus string velocity, and takes bow force as an input. In this case, however, instead of solving for the change in velocity as described in the previous paper, a table containing the possible pressure wave values is used to look up the value for the input to the system.

Further improvements to the model are proposed in a succeeding paper by the same author (Smith 1993). The paper begins with a tutorial on the "digital waveguide model for vibrating strings," explaining the wave equation for right and left traveling waves, and the simulation of the "ideal, linear, lossy, dispersive, digital waveguide" with delays and filters. But then Smith shows how the simulation can be simplified by "commuting losses out of unobserved and undriven sections of the medium and consolidating them at a minimum number of points," resulting in the combining of filters, and a model of a "rigidly terminated linear string," composed of a delay line and loop filter.

Smith continues to explain that in a model that includes an excitation, string, and resonator, the string and resonator are linear and time invariant, so can be commuted, and the excitation convolved with the resonator, "to provide a single, aggregate, excitation table," which is used to drive the string. In the case of the bowed string, the string is periodically plucked by the resonator impulse response, and since the impulse response is usually "longer than the period of the tone," it is either interrupted or overlapped, during this periodic plucking.

Somewhat later, after publishing a comprehensive overview of the developments in physical modeling of musical instruments (Smith 1996), the same author presented a system in which bow velocity, force, and position can be used as inputs to a "bow-string interaction model" that drives the "commuted-synthesis model" described above (Smith 1997). The system is comprised of a "single-hair" bow model that excites a string model, according to the input of the three bowing parameters. The output from this string model is read by an "impulse prioritizer," which "measures the timing and amplitude of the largest impulses in the string waveform at the bridge and passes on the most important ones subject to complexity constraints." The selected impulses are either passed to the commuted model directly, or convolved with pulsed noise representing bow noise during slipping or string flyback, and then used as the filtered noise impulse for the input to the commuted model, as directed by a "stick/slip bit." The result is a system that provides "the desirable combination of a full range of complex bow-string interaction behavior together with a reduced-complexity body resonator."

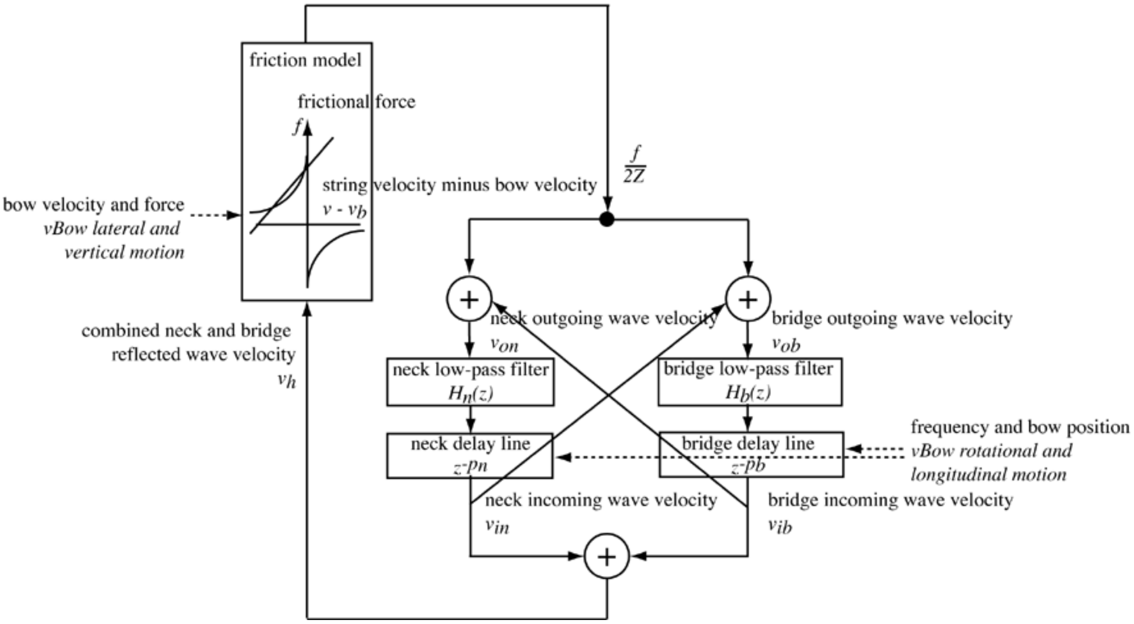
Before collaborating with Smith on refinements of the bowed-string physical model, Stefania Serafin worked with Christophe Vergez and Xavier Rodet, at IRCAM on the implementation of two bow-string interaction models (Serafin, Vergez, and Rodet 1999). The researchers first incorporated a hyperbolic friction model, simulating the interaction between the bow and string, into the bowed-string physical model, comprised of a non-linear function relating frictional force and string velocity, between two delay lines and lumped low-pass filters. The friction model, "a function of the relative velocity … of the bow and the string," was approximated "by fitting an hyperbola to data measured in a real instrument," leading to a second order polynomial equation, that produces essentially the Friedlander friction curve. This model was programmed by Serafin as a Max/MSP patch, and later as the STK bowed-string physical model used by the vBow software.

In addition, the group from IRCAM incorporated a more accurate friction model into the bowed-string model. In this case, the team used Dahl's friction model, as elaborated upon by Armstrong and Hayward, to represent the interaction between the bow and string. The Dahl model, which represents the frictional force between two objects in contact and connected by a spring, and the improvements by Armstrong and Hayward, that expand the stick-slide model to include slipping behavior, are also used by the vBow software to simulate the haptic feedback of friction for the lateral and longitudinal motion, so will be discussed further in the subsequent section.

Before it was used by the vBow software, this bowed-string physical model was used by Serafin and Rodet, along with other researchers from IRCAM, Richard Dudas and Marcelo Wanderley, in the sound synthesis software for a real-time performance system based around a WACOM graphics tablet (Serafin et al. 1999). The project was initiated to study "the model's behaviour, when submitted to different bow strokes, such as detaché, balzato, staccato, flying staccato …," and the graphics tablet was chosen for the ability of its stylus to control multiple synthesis parameters, with "a direct correspondence between the physical parameters of the stylus and those of the bow." The x, y, and z positions of the stylus were mapped to the bow velocity, position, and pressure parameters of the model, while the x-axis angle was used to change strings, and the y-axis angle determined the amount of bow hair used. The tablet was also "fitted with additional pressure and position sensors," to control "pitch changes, vibrati, and glissandi," with the other hand. The result was that the researchers were able to "reproduce most of the bow strokes … without resorting to any special non-linear mapping of stylus output parameters to model input parameters."

Synthesis

Like the graphics tablet system developed by the team at IRCAM, the vBow system was designed to linearly map component bowing gesture sensor output to bowed-string physical model synthesis parameter input. Simply said, it was constructed to map lateral, vertical, and longitudinal motion of the vBow to bow velocity, force, and position parameters of the bowed-string physical model, and rotational motion to string frequency.



adapted from (Serafin, Vergez, and Rodet 1999)

Figure 26. Bowed-string physical model block diagram

Velocity

Anders Askenfelt, in his paper, "Measurement of Bow Motion and Bow Force in Violin Playing," describes the primary importance of bow velocity to the production of a good violin tone (Askenfelt 1986).

> Physically, the momentary velocity of the bow is one of the player's chief controls of the sound level, the excursion of the string being directly proportional to the bow velocity.

Supporting this assertion, Percival Hodgson, in his text, *Motion Study and Violin Bowing* (Hodgson 1958), explains the influence of the lateral bow stroke on the amplitude of string vibration, or loudness.

> The volume of the sound is decided by the amplitude, or width, of the vibrations. An increase in power is therefore achieved by adding to the pull or push exerted sideways on the strings.

Similarly, Walter Kolneder, in his book, *The Amadeus Book of the Violin* (Kolneder 1998), affirms that the loudness of the violin is affected by bow velocity, in concert with bow force.

> Tone volume depends chiefly on the speed of bowing and bow pressure, which affect the amplitude of the vibration.

Both the first version of the vBow, which only allowed for lateral motion, and the current version, have shown that the bowed-string physical model used in the vBow software, responds expressively to the player's control of bow velocity. For both versions of the vBow, the sampled encoder reading, from the shaft rotation of the servomotor for the lateral degree of freedom, is used directly as data for the velocity parameter of the bowed-string physical model. The sampled encoder count, divided by the maximum encoder count for the length of the cable, and added to a velocity offset, is passed to a method of the bowed-string object, which changes the bow velocity value of the Friedlander friction function. If the stick of the vBow, and consequently the attached cable spinning the capstan secured to the servomotor shaft, is moved in a lateral motion at an optimal speed, which is analogous to the normal draw of a bow across a violin string, the physical model responds with a clear bowed-string sound.

The *Dictionary of Bowing Terms for Stringed Instruments* (Seagrave and Berman 1976) explains that flautando, "a light airy style of bow-stroke" also called flautato, is produced by varying the bow velocity.

> A high ratio of bow speed to pressure is employed to produce the 'flute-like' tone quality.

In addition to responding to an optimal bow velocity, by producing a clear tone, the bowed-string physical model also responds to fast and slow bow strokes of the vBow, by producing changes in the brightness of the timbre. If the lateral motion of the vBow is faster than optimal, spinning the servomotor shaft encoder quickly and sending high bow velocity values to the synthesis software, the bowed-string physical model produces a flautando timbre, bringing out the higher partials. If the lateral motion is slower, producing low bow velocity values, the physical model produces a scratching sound, similar to the hair of the bow scraping along a violin string, too slowly to excite a steady-state vibration.

Frequency

The frequency of the note played is the result of a bowing parameter inasmuch as the player rotates the bow across the strings of the violin to choose which string to bow. Because the vBow is not currently used in conjunction with a vString, or linear position sensor virtual string, rotation of the vBow is so far the only means possible to change the velocity parameter of the bowed-string physical model, in the vBow software.

Currently, the bowed-string physical model responds to the rotational motion of the vBow by playing the frequencies of the open strings of a violin. As the stick and housing piece of the vBow rotate, spinning the capstan attached to the servomotor for the rotational degree of freedom with the corresponding cable, the quantized reading of the encoder is mapped to the frequency of the pitch played by the physical model. In the vBow software, the maximum encoder count, for the length of cable secured to the bottom of the rotation piece, is divided by four, so that when the encoder senses that the vBow has rotated into each quarter length, the bowed-string physical model receives one of four frequencies, corresponding to the four open strings. These frequencies are used by the bowed-string object to calculate the base delay line length, from which the bridge and neck delay line lengths are calculated, for the reflected waves of the Helmholtz motion.

Force

Like his observations about bow velocity, Askenfelt explains the effect of bow force in terms of its influence on the behavior of the string.

> According to the basic Helmholtz model of string motion, the bow force does not influence the vibrations of the string, provided the frictional force between bow and string is high enough to maintain the stick-slip process of

> the string under the bow. However, as familiar to all string players, the bow force does affect the string vibrations, an increased bow force giving a perceptually more "brilliant" tone quality.

The scientist continues by describing the role that bow force plays, interacting with the reflected Helmholtz motion, in order to produce this brilliant tone.

> This change in tone quality with bow force is due to the fact that the circulating corner is rounded off at the periodical reflections at the string terminations, mainly at the bridge. During the passage under the bow the corner is resharpened, an effect which becomes more prominent with increasing bow force. This resharpening effect enables the player to boost the higher partials in the radiated spectrum by increasing the bow force. Such a change in spectral content will affect the tone quality as mentioned, but at the same time the perceived loudness will increase, although the amplitude of the string vibrations remains essentially unaltered.

Lothar Cremer, in his paper, "The Influence of 'Bow Pressure' on the Movement of a Bowed String: Part I," also describes the importance of bow force in terms of how it is used to change tone quality (Cremer 1972).

> … change in bow pressure is of importance to the player as his third means for changing the sound of his instrument, especially in that it changes the timbre.

As stated in the section about bow velocity, Kolneder reinforces the importance of bow force, in combination with bow speed, to the volume of the tone produced by the bowed string. Hodgson also writes about this cooperative influence of bow force and velocity on tone production.

> Downward pressure in itself tends to prevent free vibration, and thus strangles the tone. It is only used comparatively slightly in order to pull the string, and will obviously need to be proportionate to the sideways force employed at the time.

Askenfelt additionally describes the interaction between bow force and position, again characteristically in terms of string behavior, as well as performance practice.

> The minimum bow force required to maintain the string oscillations increases as the bow is moved closer to the bridge. The player observes this law by normally increasing the bow force while decreasing the bow-bridge distance.

Similarly, John Schelleng describes the interaction between bow force, velocity, and position, as it relates to the violinist's control of dynamics (Schelleng 1973).

> Bow force is important primarily as the catalytic agent that makes possible a correct reaction between bow speed and bow position. Usually one increases volume by increasing both velocity and force or by bowing closer to the bridge and increasing force.

The bowed-string physical model has proven to be responsive to bow force values approaching and exceeding the optimal value, as generated by the vertical motion of the vBow, and preliminary results have shown that the interaction between bow force and the other two bowing parameters produces the expected dynamic and timbral variations in tone.

The reading from the encoder on the servomotor for the vertical degree of freedom is mapped to the bow force parameter in the physical model. Like the encoder count for lateral motion, the sampled encoder reading for vertical motion is divided by the maximum encoder count for the length of cable used, and that value is used directly for the bow force parameter in the bowed-string physical model.

In the vBow software, the encoder reading for the cable length is divided into two regions of above and below the point of optimal bow force. As the vBow is moved downwards toward the violin-shaped body, the bow force value increases. As it is lowered toward the point of optimal bow force, the bow force value approaches one, and as it is pushed beyond the optimal point, the bow force exceeds one.

In the first case, the encoder reading is divided by the maximum encoder count for the upper region, and subtracted from one. In the second case, the absolute value of the encoder reading is divided by the maximum count for the lower region, and added to one. In both cases, the resultant value is used by the bowed-string object to change the force value of the Friedlander function in the bowed-string physical model.

As the stick, housing, rotation, and arm pieces of the vBow are lowered, bow force increases toward the point of optimal force, and the loudness and fullness of timbre increases in the bowed-string physical model. As the vBow assembly is pushed further toward the body piece, bow force increases beyond the point of optimal force, and the timbre darkens, until the force is great enough to stop the oscillation of the physical model, simulating a bow pushing against the string with enough force to keep the string from vibrating.

Position

According to the *Dictionary of Bowing Terms for Stringed Instruments*, the contact point between the hair of the bow and the string, or "the distance of the bow from the bridge" is very important for the timbre produced by the violin, describing it as "a crucial factor in the control of tone production." In the same entry, it is also explained that the tone produced at this contact point changes in relation to other bowing parameters: "The point at which the desired sound is produced will vary according to the speed and pressure of the bow."

As with the other bowing parameters, Askenfelt explains the use of bow position for controlling the tone of the violin, from two perspectives. First the author describes the physical effect of bow force on the string.

> String physics tells that the string spectrum will include a continuous succession of partials up to an order number proportional to the ratio between string length and bow-bridge distance.

Next the scientist explains the player's technical considerations of bow force.

> … bowing close to the bridge will reinforce the higher harmonics considerably compared to the lower harmonics. In addition, loudness will also increase, …

Kolneder also attests to the importance of bow position to the quality of the tone produced by the bowed string, naming it as the primary component determining the quality of tone produced, and describing changes in elasticity and timbre, as the bow moves toward the bridge and fingerboard.

> Timbre is determined by many factors, but chiefly by the bow's point of contact with the string. A normal violin tone results from bowing at a distance of ca. 20 mm from the bridge; … . Closer to the bridge, the string is harder, offering more resistance to the bow, … . Near the bridge the tone grows louder but also harsher because certain higher overtones are more prominent. … Composers of program music especially occasionally want this effect, indicating it in the music by the words "sul ponticello" (at the bridge). Placing the bow closer to the fingerboard, closer to the largest amplitude of the string, the bow meets with less resistance; the tone is more gentle but also weaker. Composers who desire this effect indicate it with the words "sulla tastiera" (over the fingerboard). Choosing the bow's point of contact with the string is essential for regulating dynamics and timbre.

These expressive markings, sul tasto and sul ponticello, are also discussed in relation to the contact point of the bow, by composer and educator, Samuel Adler, in his treatise, *The Study of Orchestration* (Adler 1982). He explains, in technical and musical terms, that sul ponticello or “playing very near or, in fact, right on the bridge instead of in the regular space allotted for the bow stroke” changes the timbre of the violin by accentuating the “upper partials of the tone not usually heard,” producing an “eerie, metallic, and somewhat glassy timbre.” Similarly, he describes sul tasto or the technique of playing “with the bow over the end of the fingerboard” as producing a “rather flutey, soft, and hazy tone.”

In the introductory chapter on stringed instruments in Walter Piston’s seminal text, *Orchestration* (Piston 1955), the composer and teacher also describes how bow position changes the timbral quality of the tone produced.

> The bow is drawn at right angles to the string, ordinarily at a place about halfway between the bridge and the end of the fingerboard. For a louder and more brilliant tone, and for the normal production of high notes, the bow is played nearer the bridge. For softer tones it is moved nearer to the fingerboard.

Later in the same chapter, in a section entitled “Effects of Color,” Piston details the technique behind sul tasto.

> To obtain a tone of very soft floating quality the strings may be directed to play on the fingerboard. The bow is placed so far from the bridge that it is actually over the upper part of the fingerboard, where there is greater amplitude in the vibration of the string.

The composer continues to direct the student in the mechanics of sul ponticello, once again describing the timbral variety produced.

> Playing with the bow very close to the bridge, or even upon it, produces a special kind of sound, due to the bringing out of upper partials not usually heard. The sound has been called glassy and metallic.

Like an acoustic violin, the physical model responds to longitudinal motion, by changing the timbre of the bowed-string sound. As the vBow assembly moves longitudinally toward the player, the timbre changes from a normal violin sound, to a richer and noisier sul ponticello timbre, and as it moves away from the player, the timbre changes to a lighter and softer sul tasto sound.

The reading from the encoder on the servomotor for the longitudinal degree of freedom is mapped to the bow position parameter of the physical model, in the vBow software. Like the encoder readings used for bow force, the encoder count for the length of cable used for bow position is divided into two regions.

After the initial position of the servomotor shaft and attached encoder is set, the encoder readings are read above the initial position as positive, and below this point as negative, as the entire vBow assembly is moved longitudinally toward and away from the player. Although the readings from the upper and lower encoder count regions are later normalized to between zero and one, dividing the length of cable used for longitudinal motion by an initial position ensures that the ranges of motion and encoder readings for sul ponticello and sul tasto effects will be of the desired length.

The encoder count for longitudinal motion is used by the physical model object to calculate the lengths of the delay lines representing the segments of string between the bow contact point and the bridge, and the bow contact point and the string termination at the nut or left-hand finger contact point.

The longitudinal position of the vBow, or virtual bow contact point, is scaled and multiplied by the base delay line length, which is determined by the frequency parameter of the physical model, to calculate the lengths of the bridge and neck delay lines. The bridge delay line length equals the scaled longitudinal position multiplied by the base delay line length, while the neck delay line length equals the scaled longitudinal position subtracted from one and multiplied by the base delay line length, or the remainder of the length of the virtual string.

Haptics

In addition to directing the mappings from the output of the encoders to the input parameters of the bowed-string physical model, the vBow software also controls the voltage output from the servomotor control card to the servomotors, simulating various kinds of haptic feedback.

The control software, which produces the haptic feedback of friction and vibration for the lateral motion, detents for the rotational motion, elasticity for the vertical motion, and friction for the longitudinal motion, was also written in C++, using the libraries that came bundled with the ServoToGo servomotor control and data acquisition card (http://www.servotogo.com/).

Vibration

To simulate the vibration of the string as felt on the bow, the vBow software maps the output of the bowed-string physical model sound synthesis directly to the servomotor attached to the housing piece, that provides the haptic feedback corresponding to lateral motion. The result is a force feedback simulation of vibration, that directly relates to the sound synthesis of the system.

Like the function used to map lateral motion to the bow velocity parameter of the bowed-string physical model, for sound synthesis, the vBow software uses the sampled sensor reading from the encoder tracking lateral motion, divided by the maximum encoder count for the length of cable used to spin the capstan attached to the servomotor shaft secured to the housing piece, as the parameter value for the method that changes the velocity value for the bowed-string physical model. The output tick of the physical model is then scaled and passed to the function, that outputs a voltage through the servomotor control card, to the servomotor that simulates haptic feedback for lateral motion.

As the stick of the vBow, and the corresponding cable, is drawn laterally, the periodic vibration produced by the servomotor, from the scaled bowed-string physical model output converted to a voltage, is felt at the frog.

Friction

Based on a photo of the microscopic barbs on a bow hair, and the speculation that the barbs of multiple hairs strung on a bow are naturally misaligned, the first version of the vBow used a simple randomly triggered alternating voltage to simulate the feel of a bow catching and releasing a violin string.

This simple function compared the absolute value of the sampled encoder reading to a random number modulo a constant limit plus a constant offset. If the absolute value of the encoder reading was greater than the calculated value, alternating scaled voltages were passed to the function that controlled the output of voltages from the servomotor control card to the servomotor. The output voltages, alternating between positive and negative voltages for down bows, and between negative and positive voltages for up bows, were delayed by a sleep function, passed a duration value calculated again by a random number modulo a constant limit plus a constant offset.

The resulting haptic friction simulation felt like a semi-periodic vibration that added some resistance to the lateral bowing motion.

The friction model, used to control the servomotors for both the lateral and longitudinal degrees of freedom of the current version of the vBow, was developed by Vincent Hayward and Brian Armstrong, from a model previously conceived by Dahl (Hayward and Armstrong 2000), and was programmed by Sile O'Modhrain, for her research into the affect of adding haptic feedback to virtual musical instrument systems (O'Modhrain 2000).

Dahl's stick-slide friction model defines frictional force as proportional to the strain between an adhesion point and a moving mass connected by a spring. When the strain reaches a maximum value, the adhesion point breaks from its position and slides in parallel with the mass.

Hayward and Armstrong's stick-slip-slide friction model adds to this maximum value an additional "stick" parameter, that when less than or equal to the maximum value, allows for the stick-slide behavior of the adhesion point, as previously described for the Dahl model, but when greater than the maximum value, provides for the adhesion point to slip and stick again, "yielding relaxation oscillations akin to a stick-slip behavior."

The output of the encoders used to track lateral and longitudinal motion of the vBow hardware is used as data for one of the parameters of this stick-slip-slide friction model in the vBow software. Consequently, the output of the friction model is sent as varying voltages to the servomotor for both degrees of freedom, producing the haptic simulation of friction, corresponding to lateral and longitudinal motion.

As the player draws the vBow laterally or moves the vBow longitudinally, the sampled encoder reading value is used by the friction model as the position of the moving object. In the function that calculates frictional force according to the Hayward and Armstrong friction model, an "adhesion map" value is set to zero, if the absolute value of the strain between the adhesion point and the position of the moving object, or sampled encoder reading, is less than or equal to the "stick" constant, that determines at what amount of strain the adhesion point starts to slip. If the absolute strain is greater than this stick value, the adhesion map value is set to one divided by the maximum strain constant.

When this adhesion map value, which “controls the rate of change” of the strain between the adhesion point and the moving mass, times the absolute value of the strain, is greater than one, and the strain is greater than zero, the adhesion point is moved to the previous point plus the maximum strain constant. If the strain is less than or equal to zero, then the adhesion point is moved to the previous point minus the maximum strain constant. But, when the adhesion map value, times the absolute strain, is less than or equal to one, then the adhesion point equals the old point plus the absolute value of the current moving mass position, or encoder reading, minus the previous position, times the adhesion map value, times the strain value.

Finally, frictional force is calculated from the current moving mass position, or encoder reading, minus the current adhesion point, times a spring stiffness constant. This frictional force value is then multiplied by a scaled voltage, and passed as a parameter to the function that sends a voltage, from one of the digital-to-analog converters of the servomotor control card, to the servomotor used to simulate haptic feedback for lateral or longitudinal motion. The result is the feeling of nonperiodic roughness, as the vBow is moved back and forth, or forward and backward, and the capstan attached to the corresponding servomotor engages or releases the cable, attached to the vBow piece for that motion.

The resolution of the simulated friction, or the amount of strain required to move the adhesion point, can be adjusted by the value of the maximum strain and stick constants, making the spring feel larger or smaller, just as the rigidity of the spring can be varied by the stiffness constant, causing the spring to feel stronger or weaker. Furthermore, because the haptic feedback of friction is simulated independently of vibration, the parameters of each function can be individually adjusted, in the vBow software, to separately vary the effect of each type of force feedback.

Detents

Inspired by a lecture given by Vincent Hayward, on his research with a haptic device called the Pantograph (Ramstein and Hayward 1994), and his subsequent work simulating virtual surfaces (Robles-De-La-Torre and Hayward 2000), the force feedback of detents, simulating the feel of a bow crossing violin strings, is produced by varying the amount and direction of force applied to the servomotor for the rotational degree of freedom of the vBow. The general definition of the term detent is used in this case, to describe a mechanism that holds a part in place until it is released by an opposing force.

The haptic feedback of detents is produced by applying an increasing, then decreasing opposing force, followed by an increasing, then decreasing parallel force to the rotational degree of freedom. The result is a simulation of the feel of a bow rolling over the round surface of four violin string, as the vBow swivels from one side to the other, through the length of cable attached to the bottom of the rotation piece.

In the vBow software, the maximum encoder reading, for the length of cable that spins the capstan attached to the servomotor for rotational motion, is divided into four regions, each corresponding to one string. Each of the four regions, of cable length and encoder readings, is further divided into three segments, corresponding to a string, with space on either side. Each segment is additionally divided into six slices, representing the six force values used to simulate the slope of the surface of the string.

As the vBow hardware rotates through the length of cable and range of encoder values, the vBow software registers when the controller is in a region, for each string, a segment, representing a string or a space on either side, or a slice, in which the software produces opposing and parallel full and half forces. As the vBow swivels, starting at one end, the encoder values move through one segment, representing space on the side of the string, through the first slice, of the second segment, representing the virtual string surface, with a half opposing force, at the bottom of the ascending slope of the virtual string surface, through the second slice, with a full opposing force, at the middle of the slope of the surface, through the third slice, again with a half opposing force, at the top of the slope, through the fourth slice, with a half parallel force, at the top of the descending slope, through the fifth slice, with a full parallel force, in the middle, through the sixth slice, again with a half parallel force, at the bottom of the descending slope, and at the end of the virtual string surface, into the third segment, representing the space on the other side of the string. As the vBow continues to rotate, it moves through three more groups of encoder reading segments, and surface contour simulating force slices.

These opposing and parallel full and half forces are scaled and passed to the function that produces a voltage on the servomotor control card, engaging the servomotor and corresponding cable.

Elasticity

As Hodgson is describing the relationship of bow position to bow velocity and force, the author not only describes the timbral changes that the performer responds to, but also the kinesthetic cues, implying that haptic feedback is as valuable as auditory feedback, when sensing correct bow placement.

> … no study of tone production is adequate which does not focus a considerable amount of attention on feeling the tension of the string consciously with the bow, while seeking a relatively constant resistance. This search for the ideal place of contact becomes instinctive to the fine player, who listens at the same time to the resulting variations in tone quality, and thus develops his sense of touch to a high degree.

The simulation of this combined elastic resistance of the violin string and bow hair, as the bow pushes into the string, is produced in the vBow software, by a linear mapping of the encoder position, in relation to a maximum encoder reading, to the voltage applied to the servomotor, for the vertical degree of freedom of the vBow, producing a continually increasing or decreasing force. As the assembly is lowered vertically toward the violin-shaped body, the player encounters an elastic resistance, that increases as the vBow is pushed down, and decreases as it is lifted. Furthermore, if the assembly is dropped from an elevated position, the haptic simulation will cause the vBow to bounce, or if it is pushed downward, into the elastic resistance, and released, the force feedback will cause the controller to spring upward.

To simulate this elastic resistance, the vBow software simply scales the voltage value, which is passed to the function that controls the servomotor that corresponds to vertical motion, by the sampled encoder position, divided by the maximum encoder count for the length of cable that spins the capstan and shaft of the same servomotor. In order to model the freedom of movement above the violin, before the bow contacts the resilience of the string, the elastic resistance is simulated below a encoder count threshold, that is set at the initialization of the control software.

In addition to simulating elastic resistance for the vertical degree of freedom of the vBow, this direct mapping of the normalized sampled encoder count to scaled voltage is used to produce the haptic feedback of barriers for longitudinal motion. Although the same mapping is used, the normalized encoder count range corresponds to a much shorter length of cable, so the elastic resistance increases much more quickly, resulting in haptic feedback that feels more like a barrier than a spring.

As the player moves the vBow longitudinally, if the encoder count, from the cable spinning the capstan and shaft of the servomotor for longitudinal motion, is within the range of a maximum and minimum threshold, the haptic feedback of friction, described in the context of the force feedback for lateral motion, is simulated for longitudinal motion. If, however, the encoder reading is outside either the maximum or minimum threshold, then the encoder count of the minimum threshold is added to or subtracted from the sampled encoder count, and divided by the length of the region outside the threshold, ending at either end of the cable. Within these encoder count ranges, at the ends of the cable, the force feedback quickly increases, producing the haptic effect of a rigid barrier.

CHAPTER 6
APPLICATION

Overview

The vBow has been designed as a musical controller, for transducing performance gesture into sound synthesis parameter data, and as a haptic human-computer interface, for simulating force feedback cues, with the superseding goal of developing an expressive instrument, that provides the composer with a wide range of dynamic and timbral contrasts, and the performer with a subtle responsiveness and versatile sensitivity. Further development of the vBow hardware and software will endeavor to integrate the mapping of bowing gesture to sound synthesis and haptic feedback, into an expressive interactive computer music composition and performance system.

These future developments will include mapping performance gesture to other types of sound synthesis and simulating additional kinds of force feedback, in the dynamic context of a performed composition.

Synthesis

In addition to playing the bowed-string physical model, described in the previous chapter about the vBow software, the instrument will be used to test the playability of other physical models. For instance, the vBow is an ideal instrument for evaluating the bowed-string physical model that accounts for torsional waves, and includes a friction model that simulates the "'plastic' deformations at the bow-string contact" due to melting rosin, that researchers at CCRMA and the University of Cambridge tested, using a computer simulation that resulted in a Schelleng diagram of timbre (Serafin, Smith, and Woodhouse 1999). Similarly, the vBow is well suited to test the effect of different attacks, produced by various initial bow velocities and forces, on the output of bowed-string physical models, as the same researchers at CCRMA studied, again through the use of computer simulations and Schelleng diagrams (Serafin and Smith 2000).

Other physical models that would be interesting to incorporate into the vBow sound synthesis software, include the "exciter-resonator" models of a glass harmonica and bowed saw, in which the excitation is simulated by either a friction or spectral model, and the resonator is comprised of digital waveguides (Serafin et al. 2002), and a Tibetan singing bowl, modeled with circular waveguide networks (Serafin, Wilkerson, and Smith 2002), developed by research groups, headed by Stefania Serafin, at CCRMA.

Along with the inclusion of other physical models in the vBow software, future developments include the implementation of polyphony, so that more than one string can be bowed at a time. Because of the latency of the currently used computer hardware and operating system, a faster CPU and possibly RTLinux will be necessary, to simultaneously track four encoder positions, while generating the sound synthesis, as well as the haptic feedback, for multiple strings, in real-time.

While mapping component bowing gestures to bowed-string physical model synthesis parameters is an obvious fit, the vBow is also a suitable controller for the real-time performance of other programmed sound synthesis instruments. When mapping the degrees of freedom of the vBow, to bowed-string physical model parameters, there is a direct correlation between the composite bowing gesture and sound synthesis parameters, due to the development of both the vBow and the bowed-string physical model, according to the mechanics of the interaction between a bow and a violin string. In order to imitate this one-to-one relationship, mappings of constituent bowing gestures, to parameters of other kinds of sound synthesis, such as signal models, will be chosen according to how closely the pairings emulate the acoustic response expected from bowing a violin. As suggested in David Jaffe's influential paper on evaluating synthesis techniques, signal models will be chosen for the vBow software, that provide parameters that "map in an intuitive manner to musical attributes," as well as produce an "obvious audible effect" when changed (Jaffe 1995).

Strategies for mapping between musical controllers and sound synthesis programming are the subject of several papers in computer music literature (Bowler et al. 1990; Winkler 1995; Rovan et al. 1997; Wanderley, Schnell, and Rovan 1998; Garnett and Goudeseune 1999; Hunt, Wanderley, and Kirk 2000; Wanderley 2001; Hunt, Wanderley, and Paradis 2002). In one such paper, Todd Winkler advises that when mapping performance gestures, that are "free from the associations of acoustic instruments," to synthesis parameters, it should be understood that the system includes "similar limitations that can lend character to sound through idiomatic movements" (Winkler 1995). Although this recommendation was made in the context of using "the body and space as musical instruments," this strategy, of ensuring that "the sound reflects … the effort or energy used to create it," is just as important, to producing "musically satisfying results," when mapping controller output to synthesis input. This concern for the musical propriety of mapping strategies, as expressed by Jaffe and Winkler, will guide the choices made for the one-to-one pairings of vBow motions to synthesis parameters.

But, one-to-one mappings are by no means the only possibility. In a subsequent paper, a team from IRCAM, including Butch Rovan, Marcelo Wanderley, Shlomo Dubnov, and Philippe Depalle, employed different strategies for mapping the output of a Yamaha WX7 MIDI wind controller to the input of a FTS real-time digital signal processing system (Rovan et al. 1997). For these authors, the mapping strategy is as important to the expressivity of an interactive performance system, as the gestural controller and synthesis software. This is especially the case when a signal model, such as additive synthesis, with its many time-varying parameters, is used for the synthesis software. When mapping controller output to the many inputs of an additive synthesis signal model, the right strategy can allow for "higher level couplings between control gestures."

The authors categorized these strategies as "one-to-one mapping," in which "each independent gestural output is assigned to one musical parameter," "divergent mapping," where "one gestural output is used to control more than one simultaneous musical parameter," and "convergent mapping," in which case "many gestures are coupled to produce one musical parameter." In addition to considering the musical propriety of what kinds of motion are directly mapped to what types of synthesis parameters, the vBow will allow for an exploration of other mapping strategies. As discussed in the chapter about the motivations behind this project, each degree of freedom of the vBow will be used to control the behavior of one parameter for multiple partials of resynthesis, like a global envelope shaping the behavior of multiple local envelopes.

In addition to controlling the time-varying behavior of this hybrid approach to additive synthesis, resynthesizing each partial with a sine wave, formant-filtered pulse-train, frequency-modulating pair of oscillators, or plucked-string physical model, the vBow also will be used to experiment with the sound synthesis of ring modulation, waveshaping, scanned synthesis, and granular synthesis, as well as real-time interactive spatialization of sound.

Ring-modulation, like frequency-modulation, allows for a one-to-one mapping, that emulates the acoustic response produced by bowing a violin. In most cases lateral motion will map to overall dynamic, or in these cases carrier amplitude, and rotational motion will map to pitch, or for these signal models carrier frequency. Because bow-bridge distance is naturally associated with changes in timbre or brightness, longitudinal motion maps well to modulator amplitude or index, leaving bow force to map to modulator frequency, which correlates well to changing the carrier frequency with rotational motion: while amplitude parameters are mapped to motion along the horizontal plane, frequency parameters are mapped to motion within the vertical plane.

Like ring- and frequency-modulation, waveshaping synthesis efficiently produces spectrally complex timbres, with parameters that map intuitively to the degrees of freedom of the vBow. Again, as with the previous example, lateral motion could be used to scale the overall amplitude, and rotational motion could be used to sweep through the frequency range, of the sine wave used to read through the lookup table, of the transfer function that shapes the wave. And, again, because bow position is used to control the brightness of the timbre of an acoustic violin, longitudinal motion could be used to control the amplitude of the sine wave, increasing the higher frequencies as the vBow is moved toward the player. Similarly, in the case where the amplitude of the sine wave being shaped is controlled by another wave, the longitudinal motion could be mapped to modulation amplitude or depth, again controlling the brightness of the timbre with bow position, while vertical motion could be mapped to modulation frequency or rate, regulating the speed of timbral sweep or pulse below audio range, and producing side-bands at audio rate, with bow force. Alternatively, rotational motion could be used to choose between various lookup-table transfer functions, and bow force could be used to pick different waveforms to shape.

Another synthesis technique involving wavetable lookup, called scanned synthesis, was developed at Interval Research, and first described by Bill Verplank, Max Mathews, and Robert Shaw, in which the shape of a virtual vibrating string is directly manipulated with a controller, producing variations in its timbral output (Verplank, Mathews, and Shaw 2000). This virtual string is modeled with masses interconnected by springs, and grounded by parallel springs and dashpots, and the shape of this physical system is periodically scanned, at a frequency that determines the pitch of the virtual vibrating string. A controller is used to excite the masses, and the displacement of each mass is stored as an amplitude value in a dynamic wavetable.

Extensions to this synthesis technique have been developed by Richard Boulanger, Paris Smaragdis, and John ffitch, in which masses can be connected by multiple springs with independent stiffnesses, producing physical systems of various shapes and with different vibration behaviors, that can be read by diverse scanning trajectories (Boulanger, Smaragdis, and ffitch 2000).

The vBow could be used to bow one of these scanned virtual strings or surfaces, controlling the excitation with lateral and vertical motion, producing various percussive attacks. Furthermore, rotational motion could be used to change the scanning frequency, again using vBow rotation to change pitch, and longitudinal motion could be used to vary the spring stiffnesses. Once again, the expressive potential of this synthesis technique could be explored by experimenting with different mapping strategies between the vBow sensor output and synthesis parameter input.

One of the synthesis techniques I have enjoyed experimenting with, in the context of realizing a composition for MIDI violin, computer, and sampler, has been granular synthesis, using Fernando Lopez-Lezcano's "grani" instrument, programmed in Bill Schottstaedt's Common Lisp Music sound synthesis and signal processing package. Among many other parameters, Lopez-Lezcano's granular synthesis instrument allows for control over the duration of the grain of samples taken from a sound file, where in the sound file the grain is taken from, and the density of grains within the resynthesized sound file. In addition, the programmed instrument provides parameters that determine a range of random variation to be applied to these values.

The vBow will be an excellent controller for interfacing with this granular synthesis instrument. As with the other mapping strategies, lateral motion will naturally control overall amplitude, but because of the multiple parameters to vary, in Lopez-Lezcano's grani instrument, a divergent strategy will be necessary. Vertical motion could control grain width, longitudinal motion could map to grain density, and rotational motion would vary sound file location, while simultaneously influencing the random variation between values, with a function relating each range of motion with an array of random values. Alternatively, lateral motion could be mapped, in parallel with amplitude, to independently expanding and contracting ranges of random values, for each parameter.

Finally, it will be interesting to experiment with controlling the spatialization of sound, with the degrees of freedom of the vBow. While lateral and vertical motion could be mapped to synthesis parameters, rotational motion could be used to sweep the output of the system across the stereo field, with longitudinal motion moving the sound to the front and back. From the perspective of the violinist, it would be a natural mapping to use bow velocity and force to generate the sound, an arching movement to pan from left to right, and motion toward and away from the player to send the sound backward and forward.

Haptics

Along with mapping the vibrations associated with the output of additive and subtractive synthesis, amplitude- and frequency-modulation, waveshaping, scanned synthesis, and granular synthesis, to the servomotor corresponding to lateral motion, simulating the elastic resistance that corresponds to the spring stiffnesses of the scanned synthesis physical model, with the servomotor for vertical motion, and using the haptic feedback of friction, elasticity, and viscosity to assist with navigating through the range of values for each of the other synthesis parameters, the vBow will be used to experiment with the simulation of haptic cues associated with advanced bowing techniques, as well as force feedback that has no analogue in the physical world.

In a chapter about the mechanical properties of the bow, in a book detailing his motion studies of violin bowing, Percival Hodgson describes the key to off-the-string bowing technique, not in terms of how it sounds, but according to how it feels to the player (Hodgson 1958).

> … the first step in cultivating martellato, solid or flying staccato, spiccato, sautillé, or ricochet, is to find the part of the bow which provides the precise degree of elasticity required;

Likewise, in *The Study of Orchestration*, Samuel Adler describes spiccato as “a conscious effort to make the bow ‘spring’” (Adler 1982), and Walter Piston, in his treatise, *Orchestration*, explains that this type of bowing “makes use of a springing or bouncing of the bow-stick” (Piston 1955).

As described in the previous chapter about the vBow software, preliminary results show that the vBow is capable of producing the same spring as a bow bouncing on the violin string. Although a simple spiccato bowing may be currently possible, the response of the haptic simulation of combined bow and string elasticity may need refinement, to provide for more sophisticated off-the-string bowing, such as jeté, a slurred spiccato. Furthermore, simulation of string elasticity will need to be varied, according to longitudinal position, just as string resistance varies as the violinist moves the bow from at the bridge, where resistance is high, to over the fingerboard, where resistance is low. The same is true for the simulation of bow elasticity, which should vary according to lateral motion, with less resistance at the middle, and more at the tip and frog.

In addition to replicating the force feedback associated with synthesis models or bowing techniques, the vBow will be used to experiment with generating new potentially useful haptic cues. For instance, the system could be used to simulate multiple layers of strings that when bowed with an optimal force, produce the expected friction and vibration, but when pushed harder, give way to another set of strings below. Furthermore, the vBow software could simulate the haptic effects of different materials and various windings for each layer of strings. For instance, one set of strings could be nylon, another steel round-wound, and the other silver flat-wound.

Although simulating multiple levels of strings made with different textures from various materials is currently only an idea, research into modeling different surface textures and material properties, that may assist with this application for the vBow, is being performed by other researchers. Christian Müller-Tomfelde and Tobias Münch, at the Integrated Publication and Information Systems Institute in Darmstadt, have modeled the sound of a pen drawing on different surfaces (Müller-Tomfelde and Münch 2001), and Federico Avanzini and Davide Rocchesso, at the Universities of Padova and Verona, have simulated the collision sounds of a hammer hitting rubber, wood, glass, and steel. While both research groups are focused on producing the sounds corresponding to interacting with the texture or material of a surface, the resulting output from their systems may be useful for simulating the haptic cue of vibration. Further study of previous research into the haptic simulation of surface texture and material properties is clearly the next step.

Composition and Performance

In the aforementioned paper, Winkler advocates that interactive music systems be used to extend “the performer’s power of expression beyond a simple one-to-one relationship of triggered sound, to include the control of compositional processes, musical structure, signal processing, and sound synthesis.” Because the system software can map the four encoder readings to any sound synthesis or musical algorithm parameter, the vBow is ideally suited for this kind of high level control of compositional process and musical structure. Furthermore, because the output voltage of any haptic simulation can be mapped to each of the four servomotors of the vBow hardware, the force-feedback of the instrument can change along with the sound synthesis or musical algorithm. Because the feel of the instrument can change between or even within pieces, force-feedback can now be used as a compositional element, limited only by the range of motion of the performer, and the imagination of the composer.

APPENDIX

PHOTOS

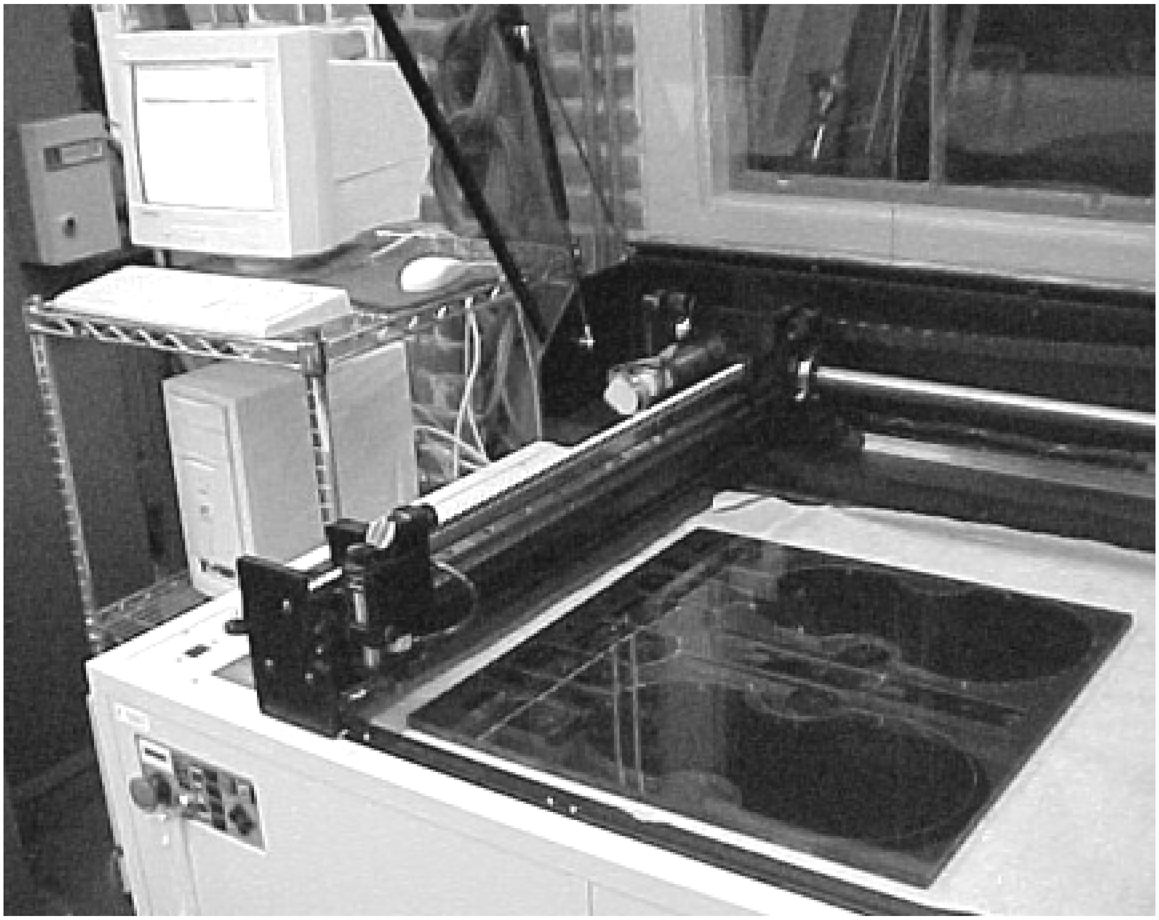


Figure 27. Laser-cutting acrylic pieces

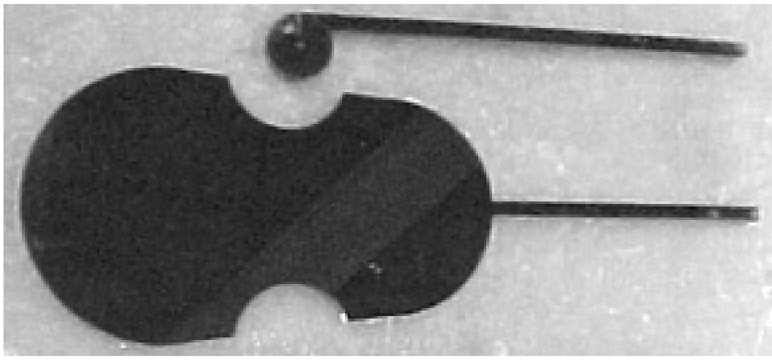


Figure 28. Acrylic arm and body pieces

Figure 29. Machining acrylic pieces on a mill

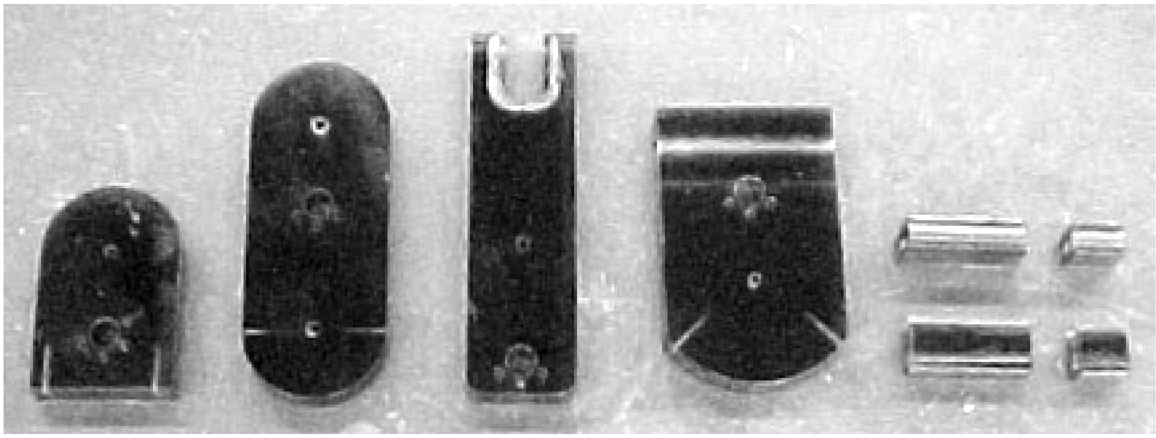


Figure 30. Acrylic base, longitude, rotation, housing, frog, and tip pieces

Figure 31. Turning aluminum capstans on a lathe

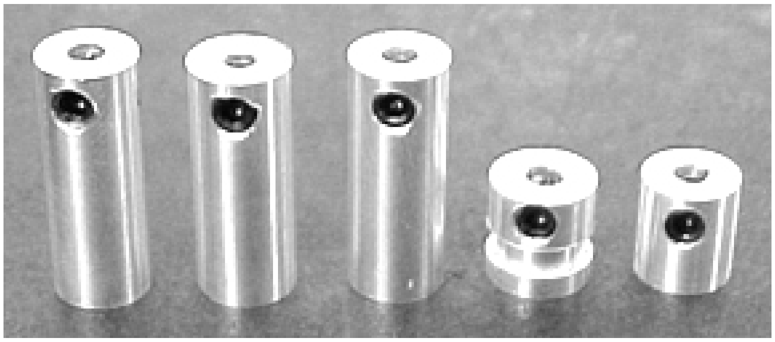


Figure 32. Aluminum capstans

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