# New Frontiers of Expression Through Real-Time Dynamics Measurement of Violin Bows

by

**Diana S. Young**

B.S. Electrical Engineering, Johns Hopkins University, 1999
B.A. Music, Johns Hopkins University, 1999
Performer's Certificate in Violin, The Peabody Conservatory of Johns Hopkins University, 1999

Submitted to the Program of Media Arts and Sciences, School of Architecture and Planning
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at the Massachusetts Institute of Technology
September, 2001



Signature ________________________________________

Diana S. Young
Program in Media Arts and Sciences
August 31, 2001

Certified by ________________________________________

Tod Machover
Professor of Media Arts and Sciences
Program in Media Arts and Sciences
Thesis Supervisor

Accepted by ________________________________________

Andrew Lippman, Chairman
Departmental Committee on Graduate Students
Program in Media Arts and Sciences

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## Abstract

The violin has long been admired as one of the most beautiful, complex, and challenging musical instruments. With its capacity for nuance, richness of tone, and flexibility of range, its expressive qualities have been surpassed by none, despite the fact that its construction has not been changed for hundreds of years. It is the form and function of the traditional violin that inspired the work detailed in this thesis. Here, the design and construction of a new violin interface, the *Hyperbow*, is discussed.

The motivation driving the research of this instrument was the desire to create a violin bow capable of measuring the most intricate aspects of violin technique, the subtle elements of physical gesture that immediately and directly impact the sound of the instrument while playing. In order to provide this insight into the subtleties of bow articulation, a sensing system was implemented to measure changes in position, acceleration, and the downward and lateral strains on the bow stick. These sensors were fashioned using an electromagnetic field sensing technique, commercial MEMS accelerometers, and foil strain gauges.

Because the forces and stresses applied to the bow are immediately connected to a violinist's experience while playing, the implementation of a new music controller that utilizes these intimate aspects of physical interaction between a player and an instrument may inspire altogether new methods of expression. The measurement techniques used in this work were found to be quite sensitive and yielded sensors that were easily controllable by a player using traditional right hand bowing technique. In addition, the *Hyperbow* proved to be helpful in recognizing and analyzing the physical parameters of common bowstrokes.

Thesis Supervisor: Tod Machover
Professor of Media Arts and Sciences

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by

**Diana S. Young**

Approved by

Reader ________________________________________

Joseph Paradiso
Principal Research Scientist
MIT Media Laboratory

Reader ________________________________________

Martin Schmidt
Professor of Electrical Engineering and Computer Science
Director of Microsystems Technology Laboratory
MIT Department of Electrical Engineering and Computer Science

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# Chapter 1

# Introduction

The goal of this work is to develop a sensing system for a violin bow that captures as much information as possible concerning the forces applied to it by a violinist during play. The hypothesis is that the data signals collected from our bow will yield unique results for different bow strokes and associated articulations. Additionally, this information can be useful for controlling real-time modifications of amplified sound, providing new ways of exploring violin bowing technique, and developing altogether new styles of bowing.

The problem considered here is the same as that of earlier projects at the MIT Media Lab. That is, how to enhance a traditional string instrument with the incorporation of various technologies so that an experienced player can explore completely new methods of musical expression. One of the first attempts to create such an interface, and indeed the most well-known at MIT, was the *Hypercello* project, initiated by Tod Machover in 1990 [Mac92]. Machover collaborated with fellow researchers Neil Gershenfeld and Joseph Paradiso to enhance an electric cello. The instrument chosen for this project was a RAAD cello, designed and built by instrument maker Richard Armin of Toronto, Canada. The RAAD is an electric cello, principally made of wood, that also possesses the feature of a floating top plate (see §3.3). That is, the wooden plate is free to vibrate unhindered by adhesive. The un-amplified sound of this instrument resembles that of a muted acoustic violin of professional quality.

The cello was fitted with custom sensors designed to track such physical gestures as the right hand wrist movement and the changing speed and position of the bow with respect to the bridge [PG97]. These gestures were used to communicate to various synthesizers and computers, granting soloist Yo-Yo Ma control over his own accompaniment and amplified musical effects. For instance, in certain sections of the piece composed for him by Tod Machover, *Begin Again, Again*, he could cue different instruments, control their volume levels, and determine the manner in which the sound from his instrument blended with the sounds of the electronic orchestra. This performance was premiered at the Tanglewood Festival in August 1991. At this time, the idea to provide a virtuoso with a new kind of instrument that she could play with traditional technique to achieve wholly untraditional musical results, was new [Mac92]. (In addition to the *Hypercello* project, a *Hyperviola* and *Hyperviolin* were created, each sporting similar sensing systems to that described above.)

These early *Hyperinstruments* projects were extremely successful not only in performance, but also in initiating dialogues concerning physical measurement of expressive gesture, playability of new interfaces, and possibilities for acoustic and digital instruments to converge. Because these instruments were also developed in conjunction with the composition of pieces intended for specific players, the foundations of these projects were strong.

Still yet to be explored at this time were questions concerning the possibilities of creating instruments especially suited for improvisation, and those of musical intent and underlying musical expression manifested in gesture, and that of allowing an audience to more readily understand the physical gestures and technique of a fine musician. Also, there remained the ever present question of how to improve the physical measurements without impinging on the performer's ability to play. Consideration of all of these issues lead to the pursuit of more intimate descriptions and measurements of musical gesture and technique.

This thesis project signifies the beginning of a new level of inspection of the physical gestures demanded of bowed string instrument players. This work aims to capture the details of violin bowing technique that are hidden from audience members, or indeed from non-players. In other words, the motivation is to illuminate those aspects of bowing most intimately connected with the experience of the player and that most immediately affect the sound of the violin strings.

The relationship between an instrument and its player is extremely complex, as the player relies on instant physical and aural feedback from the instrument during performance to adjust the sound produced. There is great interest in the field of acoustics to understand as much as possible about the nature of violin sound and the interaction between the hair of the bow and the strings of the violin. Similarly, there is a large body of work that seeks to create analysis systems capable of recognizing and characterizing different violin sounds and new synthesis engines robust enough to reconstruct violin sounds based on physical gesture data.

However, though this research holds a great amount of interest, if it were to become so advanced as to be able to detect most of the physical actions of a violinist through the sound created, the product would still be lacking in its description of the performance itself. The importance of the physical instrument to a performer is almost indescribable, and it is true that people still desire to witness performances in which the emphasis and focus truly is placed on a real performer. Therefore, the importance of developing new kinds of instruments rather than just new types of audio analysis and synthesis is real.

Even among those who agree that there is a definite need for new instruments, there is some contention as to what types of instruments should be built. That is, whether they are simple or complex, easy or difficult to master. Often, technology is seen as appropriate for use in the development of simple interfaces for novices, or music toys for children. In these cases, technology allows for simpler physical control and less musical experience. So that everyone can enjoy learning and making music, these instruments are important, especially when one takes into account the extreme difficulty of learning a traditional classical instrument. There is often not the same support for enhancing, altering, and evolving traditional instruments. Even among those who believe that it is possible to develop instruments of great sophistication, the approval for working with violins is sometimes absent. As there is great esteem and appreciation for this instrument, unique in its capacity for expressivity and nuance, it is understandable why many would choose to resist altering the instrument in any way.

The assertion put forth in this thesis is not that the violin, or any member of its family, should be replaced by a newer model touched with technology. Rather, the belief embraced here is that traditional instruments should continue to inspire and inform research into new musical instruments, as there are few instruments that possess physical interfaces as rich and compelling as those of acoustic instruments, and as much should be learned about the experience they offer a player as possible. An important priority maintained throughout the progress of this project is that all experimentation was performed on modern, commercial carbon fiber bows and the limited adjustments made to the single electric violin used for the position sensor testing were temporary. Therefore, the work outlined here in no way harmed or detracted from the work of other instrument makers.

The task of learning to play a bowed string instrument is one of the hardest to do, even from the perspective of simple physicality. Not only is special care required of the left hand to correct pitch and provide appropriate vibrato, but one must also master the art of bowing to control the amplitude, tone color, rhythm, and attack of the pitch provided by the opposite hand. Moreover, in order to begin to evaluate one's progress on the instrument in the technique of either hand, considerable ability in both is required. It is well understood that problems in the technique of one hand often arise due to failures of the other.

It can be easily argued that the problem of learning to play the violin is even greater than learning to play another instrument of the same family–viola, cello, or double bass. As the violin requires its player to grasp it between the chin and left shoulder while operating the fingerboard with the left hand fingers and the bow with the right hand, and as it is the smallest instrument in its family, the physical interface of the violin is inarguably awkward.

The difficulty in teaching a novice how to play such an instrument is clear. Part of this is due to the inability of many teachers to describe quantitatively a student's problems. There are very few tools available to help describe and enable communication about physical technique. It is possible that research in the area of physical interaction and investigation of bowing technique could help to create such tools.

The research in this thesis differs from previous research in this area at the Media Lab in that it broadens the data field to include a focus on the forces applied to the instrument by its player, rather than simply the position of the player's hands and that of the bow. Ultimately, the work continued beyond the scope of this document aims to incorporate entirely within the form of the violin's standard physical interface the sensors used to enhance it.

To accomplish these goals, we developed the *Hyperbow*–an enhanced violin bow capable of measuring all of the forces applied to it by the violinist during play.

The *Hyperbow* project also aimed to enhance the capabilities of an acoustic violin while preserving the nature of its original acoustic function and the essence of natural string sound, as well as the range of movement required and the sophistication of expression made possible by the physical interface and traditional violin techniques. The *Hyperbow* may be played with an electric violin that produces amplified sound when the strings are excited and then alters that sound with the use of the enhanced bow; or the same may occur using an acoustic violin with an electronic pickup.

The task of building a new violin interface was first posed for the purpose of creating a new instrument for virtuoso Joshua Bell, who is a participant and contributor to the *Toy Symphony* project, conceived of and designed by Tod Machover.

In the work described by this thesis, several violin bows were augmented with strain gauges, accelerometers, and position sensors. Position of the bow relative to the bridge of the violin, the accelerations of the bow along all three axes in space, and downward and lateral strain in the bow stick were measured. Therefore, all of the information considered relevant by acoustic scientists to the interactions between the bow and the strings of a violin can be inferred from this data–with the notable exception of the distance to the bridge [Ask86, Ask89, Sch73]. In addition, measurements of torsional forces were explored.

The interface described here is one that reflects the physical relationship between a player and the instrument and illustrates the tactile component of playing, as the forces applied to the instrument, rather than simply the large physical position changes corresponding to pitch and bow movement that were seen in the *Hypercello* project [Mac92, PG97], are explored.

In the author's opinion, a great violinist is not one who knows or remembers exactly where her fingers should be to play different pitches, or how to move the bow in order to produce the same sound as she has played before. Rather, a great violinist is a player who is able to constantly adjust her playing technique in small ways in reaction to the sound produced immediately before. A precise coordination between the ear and muscles is extremely important, and muscle memory plays a key role as a player learns by physical feedback from the instrument. The ability to execute quick and subtle real-time adjustments in physical gestures and in the forces applied to a violin and bow is crucial to fine playing. As stated by virtuoso and pedagogue Ivan Galamian,

> I would like to point to the one-sided overemphasis on the purely physical and mechanical aspects of violin technique, the ignoring of the fact that what is paramount in importance is not the physical movements as such but the mental control over them. The key to facility and accuracy and, ultimately, to complete mastery of violin technique is to be found in the relationship of mind to muscles, that is, in the ability to make the sequence of mental command and physical response as quick and as precise as possible.[1]

The intricacies of these physical responses are the focus of this project, as they are fundamental to a player's musical expression.

The sensing system for the *Hyperviolin* described in this document was designed to give a violinist fine control over a vast new realm of sounds as well as provide the ability to affect the acoustic signal from the instrument itself in ways yet unheard. Further, it was a priority to grant these opportunities in a manner still idiomatic to the violin and violin playing technique.

In the following pages of this text, relevant background and related work in the fields of acoustics, audio synthesis, and physical measurement of violins and bows will be reviewed.

[1] [Gal62]

Also, in the Background section of this document, violin controllers and similar music interfaces will be discussed. The Implementation chapter contains all relevant details of the design and construction of the *Hyperbow* sensing systems, including descriptions of the sensors themselves and the electronics, the instruments altered through this development, and the results of the experiment. Next follows the Evaluation chapter, in which data will be shown that illuminates the value of the interface created, as well as user feedback. The Applications chapter discusses various possibilities for the use of the data capture and a description of a simple introductory music demonstration. In the section entitled Future Works, a series of tasks are outlined to continue the progress of the work begun for this thesis project. Specifically, further suggestions for analysis of the data produced by the *Hyperbow*, as well as possibilities for music controllers related to this one are introduced. Finally, the Conclusion chapter of this thesis summarizes the progress made thus far in terms of new instrument design and the collection of rich physical gesture data.

# Chapter 2

# Background and Related Work

So as to better understand the work documented by this thesis, it is helpful to consider the project within several different contexts. The *Hyperbow*, developed out of an interest in the classic violin and bow and the scientific study of each, was influenced by the research of many other new music controllers. Here, some effort is made to equip the reader with some limited background concerning these influences.

In reading this document, it is necessary to have the benefit of some knowledge concerning the traditional acoustic violin and bow and the complex and difficult problems they pose for musicians. Therefore, contained within this chapter is a brief review of the construction of the violin and bow, a description of how they function together to produce sound, and a description of both the left and right hand playing techniques.

Also within this section, the reader will find discussions of research related to this project. Work in violin acoustics, physical measurement of violins and bows, synthesis of violin sound, and violin controllers and similar music interfaces is reviewed.

## 2.1 Fundamentals of the Violin

The violin family of instruments finds its origin among early European musical instruments that produce sound by means of a bowed or plucked string, but the earliest appearance of a violin occurred in the sixteenth century. Remarkably, the art of making violins has changed little in the past four hundred years and that of making bows has remained almost the same for about two hundred years [Sto92]. Here, the fundamental design and construction of the violin and the bow are summarized and the principles underlying the manner in which they generate sound are briefly discussed.

### 2.1.1 Violin

The violin has four strings–G, D, A, and E–all tuned a perfect fifth apart from each other. Roughly, when the string of a violin is plucked or struck by a violin bow, the string is set into a periodic oscillation. These vibrations are transmitted by the bridge of the violin (which experiences its own sympathetic oscillations) to the top plate of the violin. The vibrations are then coupled to the back plate by means of the sound post, located under the foot of the bridge nearest the E string. (The sound post stands in the cavity of the violin in contact with both plates.) The oscillations of the string are amplified inside the body of the violin (see Fig. 2.1).

### 2.1.2 Bow

As with the violin, the construction of the violin bow is fairly standardized. The stick is carved of pernambuco wood, chosen for its robust strength and flexibility. The circumference of the bow decreases from frog to tip. The tension in the bow is altered by adjusting the screw at the end of the bow stick, which has the effect of sliding the frog along the stick, pulling the bow hair (see Fig. 2.4). The frog is generally made of ebony. Horse hair is still the only material suitable for the bow hair. Its color is almost always white, though black horse hair is sometimes used. The approximate weight of a bow is 60g, while the length is around 74cm [Sto92].

In recent years, there has been some experimentation to find new materials with which to construct bows. Carbon fiber, or graphite, bows are the most successful of these innovations. They are not only widely available, but are common and highly regarded by some

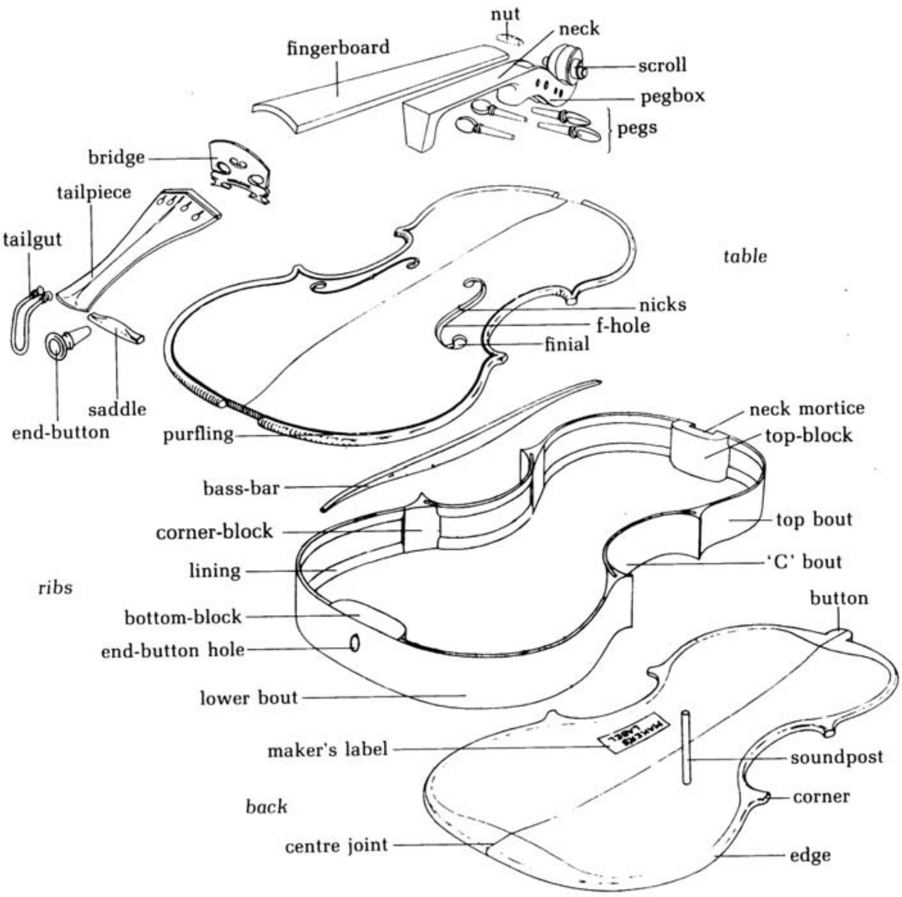


Figure 2.1: An overview of the parts of the violin and the terminology used to refer to them (from [Sto92]).

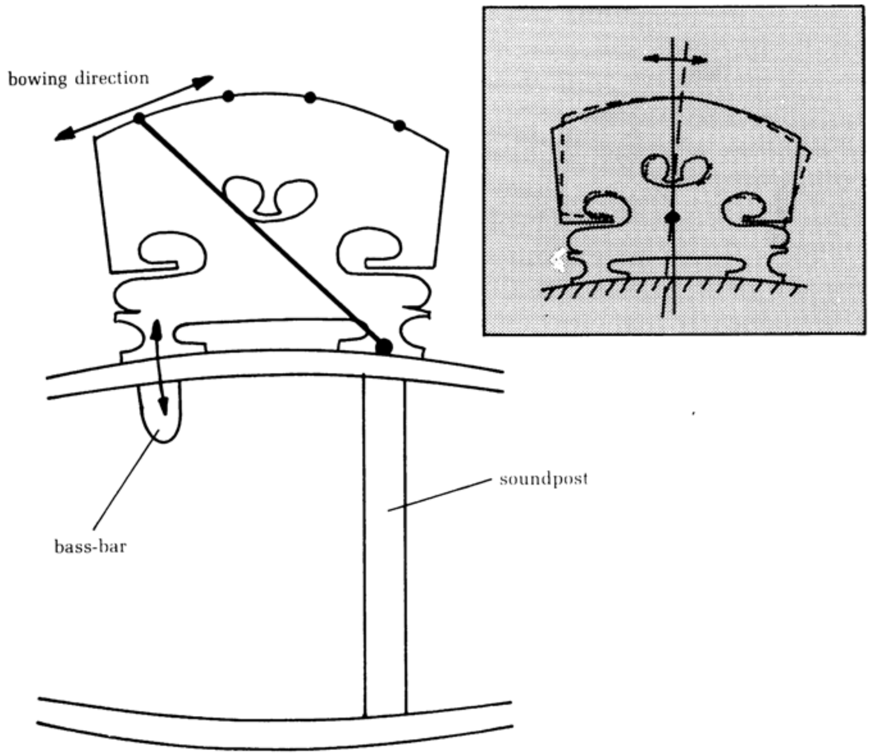


Figure 2.2: The bridge aids the sound production of the violin differently depending on the vibration frequency of the string. In the lower frequency range, the bridge acts as a rigid body and creates a node in the area of the treble bridge foot. The sound post then acts as a fulcrum and the bridge itself moves as a lever causing the bass bridge foot to move up and down on the top plate of the violin. This action effectively converts the lateral motion of the vibrating string into motion normal to the to the plates of the violin, thus increasing the strength of the body vibrations. In the middle frequency range, the top and bottom plates resonate with the string vibrations more readily and the sound post moves up and down. When the strings vibrate at high frequencies, as seen in the figure on the right, the bridge has strong resonant behaviors independent of the sound post that serve to increase the amplitude of the sound (from [Sto92]).

professional players.

The strings of a violin are excited by their interactions with the bow, or, more specifically, the bow hair. A violinist holds the bow at the frog with the right hand and passes the bow back and forth across the strings, causing the strings to vibrate. As will be discussed later, the characteristics of a given bowstroke that affect the oscillations of a violin string are the velocity of the bow motion, the friction between the bow hair and the string of the violin (as evidenced by the pressure inflicted on the bow), and the point along its length where the string is struck by the bow hair (the location between the bridge of the violin and the nut).

The features of the bow hair alone do not provide sufficient friction to create the resonance desired of the violin. The application of rosin–pine tree resin–to the bow hair increases the friction between the bow and strings, thereby facilitating their interaction widely known as “stick-slip” motion.

When a violin bow is drawn across a string, the string appears to swing back and forth. However, a closer inspection reveals that this envelope of motion is actually described by a “kink” that divides the string into two straight halves and moves in a cyclic path traveling from the bridge to the nut and returning. When this “kink” is in the part of its journey between the bow and the nut, the string moves with the bow and is said to be “sticking” to the bow. When the “kink” is between the bow and the bridge, the string slips rapidly in the direction opposite that of the bow movement and is said to be “slipping”. The period of the string motion is the time it takes for the “stick-slip” cycle occur once. The frequency of the perceived pitch of the string is the inverse of this value.

## 2.2 Violin Technique

The violin is an especially expressive instrument, affording its player the ability to alter the dynamic level or timbre of the notes gradually or abruptly, to play as many as four pitches at any one time, to adjust the attack and decay characteristics of each sound, vary the space

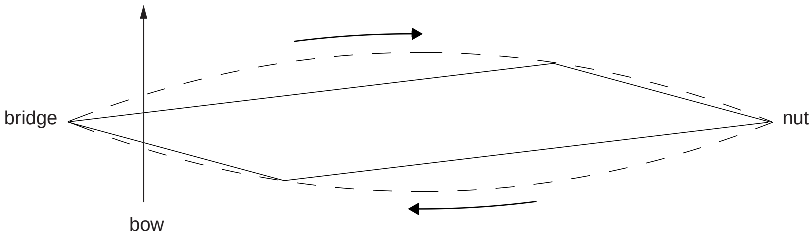


Figure 2.3: The friction between the bow hair and the string is essential to the tone produced by the violin. The string experiences two types of movement while vibrating. The first occurs as the string sticks to the bow hair and is displaced at the same rate as the bow moves. After a period of traveling slowly with the bow the string slips rapidly in the direction opposite the bow movement and then reverses direction again as it swings back into contact with the hair. The time that it takes the string to complete one stick-slip cycle determines the period of the string vibration and therefore the pitch sounded. At any given time the string is subdivided into two straight sections, and the point that divides these two parts moves in a cyclic pattern between the bridge and the nut. The sticking and slipping states of the string correspond to the position of this point with respect to the bow. When the dividing point is between the bow and the nut, the string sticks to the bow hair; when the point is between the bow and bridge, the string slips away from the hair.

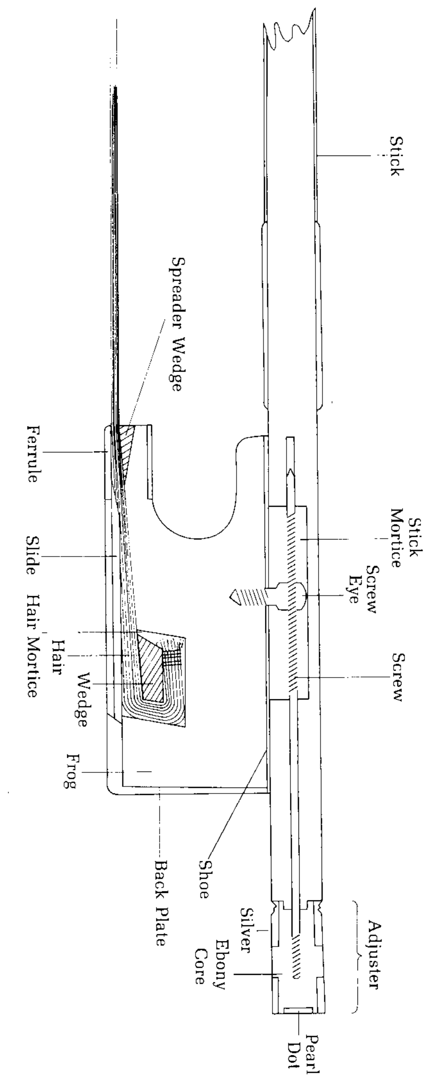


Figure 2.4: The modern bow is constructed from pernambuco wood for the stick, ebony for the frog, and metal for the mechanical components that act together to adjust the tension of the bow hair (white horse hair). The other end of the bow, not pictured here, is referred to as the tip (from [Sto92]).

and nature of the connections between every set of notes, and a large frequency range over which to voice these notes. A violinist is granted control over every aspect of the sound produced by her instrument and throughout any playing period may recreate the character and tone continually. It is due to the possibility, the flexibility, and the versatility of the violin that the instrument is such an enigmatic and compelling vehicle of expression. It is because of this capacity for expression that it remains perhaps the most challenging of all instruments.

It can be easily argued that the violin has one of the most difficult physical interfaces of any musical instrument. The violin is a small instrument and for its operation requires movements that are quite unnatural and awkward. These performance gestures range in size from extremely small to large, but it is also the number of simultaneous movements coupled with the fine precision demanded in executing them that make the violin so complicated to master.

A violinist creates and controls the sound of the instrument through great physical skill acquired by both the right and left hands. Violin technique is difficult to learn and maintain not only because the movements required of the player are so demanding, but because the tasks assigned to each hand are so different from each other. The problem presented by the vastly different physical skill sets for the right and left hands of a violinist is one not faced by many other musicians. For instance, piano technique requires the right and left hands to be capable of performing identical movements and to gain equal strength and coordination. In contrast, musicians who study the violin must achieve completely different kinds of strength and coordination in each hand. This is not to say that an instrument such as the piano does not have its own great obstacles in the path of success, but it is true that the physical interface of the violin presents a much more difficult starting point.

What is attempted here is only the most general and brief of descriptions of left and right hand violin techniques. Methods of teaching and playing are highly personal and must always be customized for the individual in order to accommodate each player's physical differences (e.g., size and length of fingers, hands, and arms, etc.). It is always the goal of any player to make the movements required when playing as natural and comfortable as possible, for tension and tightness of any sort are detriments to the sound and easily cause physical injury. Through this discussion of technique, our goal is to illuminate the many intricacies and interdependencies over which a violinist must have strong command. Only with this information can we begin an investigation focused on creating new violinistic music controllers.

The following discussions of left and right hand technique follow those of Galamian in [Gal62].

### 2.2.1 Left Hand

For the purpose of easily indicating the positions of the left hand fingers, the fingers are numbered one, two, three, and four. These numbers represent the index, middle, ring, and small fingers, respectively. The body of the violin rests between the left shoulder and chin, and the neck of the violin is gently held between the thumb and side of the first finger. It is important not to clutch the instrument with the hand, as the purpose in this contact between the neck of the violin and the hand is not as much to support the instrument but rather to help guide the hand as it fingers the strings. The hand is generally oriented such that the outside edge of the fourth finger faces the body of the violinist. Even this starting posture is awkward to maintain for the inexperienced player.

With respect to even this simple starting position, there is a great deal of consideration to be made concerning possible adjustments to accommodate a player's individual physical characteristics. For instance, different types of shoulder pads to help support the violin and create a comfortable position for the neck are often employed. Similarly, adjustments of the elbow position–how far it is away from the player (how high the violin is held) and how far to the right the elbow is stationed–must be made to suit each player.

The posture of the left hand fingers with respect to the fingerboard is also a source of debate. How straight and how high above the strings the fingers should be, and how close the hand is to the scroll of the violin are questions that must be addressed. Every slight alteration in the position of the fingers, thumb, and hand has a direct impact on the ease and ability to finger the strings of the violin, for a violinist must be able to finger multiple strings, shift positions of the hand along the length of the fingerboard, and execute rapid position and pressure changes. It is also worth noting that a violinist must take into account the width of her fingertips when finding the correct default hand position.

When playing the violin, it is the left hand that governs intonation (though faulty bowing may also contribute to its deterioration). In order to produce proper intonation at all times, a violinist must mindfully alter the position of her fingers on the fingerboard of the violin so as to determine the fundamental pitches of the notes played. While doing so, she must also adapt the character of the vibrato–the rapid and subtle variation of pitch–to produce the appropriate tone color.

**Pitch Selection**

The act of stopping a string against the surface of the fingerboard effectively shortens the length of that string. This reduction in length increases the frequency, or pitch, of the string. A six percent decrease in the length of a given string increases its fundamental pitch by a semi-tone. The mass and the tension of the string also affect its pitch–as mass increases pitch decreases, and as tension increases pitch increases. (Violin strings increase in mass, or thickness, from the E string to the G string in order to maintain consistency in the tension of the strings.)

There are several fundamental movements used for pitch selection that must be within the control of any violinist in order to be successful. These movements consist of: 1) the vertical motion required to stop and release the strings; 2) the sliding movement of the fingers while the hand remains stationary; 3) the complex motion required to cross strings, which is a combination of vertical and horizontal motion; and 4) the sliding movement of the fingers and hand from one hand position to another (with fingers either depressed or not).

When playing a string instrument like the guitar, the problem of intonation is rather simple provided that the instrument has been properly tuned, for the fingerboard of the guitar possesses frets. Frets serve to stop the string at a consistent point as long as the left hand finger is depressed anywhere within the space delineated by the corresponding fret and the next one below it. In order to remain in control of the intonation of a violin, the player must find the appropriate pitch by carefully correlating physical feedback from the left hand with the audio information received by the ear. This means that a violinist rely strongly on the sense of touch while using the judgment of her ear. It is often said that a good violinist should be able to play an out of tune violin in tune. That is, the coordination between the hand, fingers, and ear should be so refined that the violinist is able to dynamically adapt her technique to accommodate an inferior instrument. Galamian articulates this necessity as follows:

> Lastly, in this discussion of intonation, it is necessary to consider what type of intonation ought to be used: the “tempered” or the “natural.” This is not the place to go into the technicalities of the two systems. No violinist can play according to a mathematical formula; he can only follow the judgment of her own ear. Be this as it may, no one system of intonation will suffice alone. A performer has to constantly adjust her intonation to match her accompanying medium.
>
> The artist must be extremely sensitive and should have the ability to make instantaneous adjustments in her intonation. (The best and easiest way to make such adjustments is by means of vibrato.) An intonation adjustable to the means of the moment is the only safe answer to the big question of playing in tune.
>
> The most important part in all of this is assigned, obviously, to the ear, which has to catch immediately the slightest discrepancy between the pitch desired and the pitch produced and then demand an instant reaction from the fingers.[1]

[1] [Gal62]

The importance of the instantaneous reactions of the left hand fingers to the observations of the ear cannot be overemphasized.

### Vibrato

Vibrato is the effect achieved by altering the position of the finger or fingers on the fingerboard such that the pitch or pitches are varied. This serves to alter the tone color and is an invaluable tool of expression for any violinist. Because listeners are more sensitive to higher pitches, all instances of vibrato should begin with the sound in tune, on the pitch that would be indicated by a music score, and alternate between this position and a position on the flatted side of the pitch. The ear is much more forgiving of this kind of alteration in frequency than it would be of an occurrence of vibrato that tended toward the sharp side of the pitch as the resultant sound would be perceived as sharp. It is also usually important to begin the vibrato motion at the start of the pitched sound and to vibrate the pitch continuously.

There are also three main methods of executing vibrato. The first is known as arm vibrato and is accomplished by moving the forearm back and forth while the left hand follows the impulse generated at the elbow. The vibrato finger bends and straightens in response to the arm movement and consequently flattens the pitch once every vibrato cycle as the pressure of the fingertip shifts backward. The second type of vibrato is hand vibrato, but the impulse driving the motion of the finger is supplied by the hand as it rocks back and forth from the wrist joint. The finger experiences the same change in its posture, from a curved shape to a straightened shape when the pitch is lowered. The last kind of vibrato is finger vibrato and is performed by the vibrating finger itself, moving from the base knuckle, and it much harder to achieve than the first two vibrato techniques described. The width of vibrato possible with this method is also smaller.

The parameters that describe the character of a player's vibrato are the speed (i.e., how quickly the transitions between the notated pitch and the flatted pitch occur), the width (i.e., how flat is the second pitch, or the great is the distance between the two finger positions), and the intensity (i.e., a combination of how great is the pressure of the vibrating finger on the string and the angle of the fingers with respect to the string). A fine violinist can vary all three of these elements independently and in conjunction with each other as the occasion demands. The careful cultivation of vibrato technique greatly personalizes a player's individual violin sound.

It should be noted that although vibrato may be used to quickly and easily correct pitch (or at least the perception of it), or enhance the tone of that pitch, the option of employing vibrato does not eliminate the need to nurture the other left hand skills that determine the quality of intonation. The substitution of vibrato in place of proper pitch adjustment is often the focus of criticism by many violin teachers, as expressed by Leopold Auer:

> No, the vibrato is an effect, an embellishment; it can lend a touch of divine pathos to the climax of a phrase or the course of a passage, but only if the player has cultivated a delicate sense of proportion in the use of it.[2]

The careful administration of vibrato and use of all other left hand movements required for pitch selection must be appropriately coordinated with the bowstrokes to actually sound the notes. Most problems stem from this difficulty in coordination between the two hands, or from the bowing technique itself [Gal62].

### 2.2.2 Right Hand

Though the left hand must control intonation and vibrato, all other issues relating to the sound quality of the violin are addressed by the right hand. Certain comparisons may be made between fingering notes on an instrument of the violin family and the physical actions necessary to play other instruments, such as selecting pitches on the trumpet, clarinet, or flute. In contrast, bowing a string instrument is unlike any other musical activity. It is also well understood within the violin community that these physical actions required of the right hand fingers, hand, and arm are more challenging than those demanded of the left

[2] [Aue80]

hand [Gal62]. A player must learn to work with the bow as an extension of the right arm, hand, and fingers.

The bowing of string instruments is not only incredibly complicated, but it is very little understood by non-players. Because there are so many degrees of freedom and the response time required to correct any deficiencies in the sound of the violin is so small, violin bowing technique is one of the most difficult physical pursuits of all.

Through various articulations of the bow, the right hand must control the amplitude of the sound, the rhythm (also controlled in coordination with the left hand), the attack and decay of notes, and the fullness of tone. Poor bowing does not just result in tone that is unsatisfactory, but may also add a great deal of noise to the sound of the violin–sometimes even producing scratching sounds.

As in the terminology relating to the left hand, the fingers of the right hand are referred to as numbers one, two, three and four, corresponding to the index, middle, ring, and small fingers. When the right hand grasps the bow in the manner required to play, the tip of the thumb should be placed in the gap between the stick and the bow hair so that it touches the end of the frog. The second finger should meet the thumb on the side of the bow furthest from the player. The third finger arches over the top of the stick and is placed against the outside of the frog, while the tip of the fourth finger is positioned roughly on the top of the stick (it is actually a little closer to the body of the player, slightly on the inside of the stick). The index finger rests on the stick at the middle joint, whose knuckle points toward the tip of the bow.

In order to draw the bow across the strings and produce a fine resonant sound, one must develop the ability to perform many different physical actions with the fingers, the hand, and the arm. Without the hand and the arm held stationary, the fingers of the right hand should be capable of lifting the bow off the strings and replacing it, and moving the bow in a horizontal direction, performing small strokes. The fingers must also be able to rotate the bow in such as way as to be able to alter the angle of the bow so that it is tilted slightly away from the player. Using a similar technique, one can also change the amount of bow hair that contacts the strings.

The last type of motion necessary to train the finger is the vertical rotation produced when force is applied to the bow stick by either the fourth finger or the index finger. In the first case, the tip of the bow swings upward, and in the second it is the frog that is raised. It is helpful in understanding this motion to view the system of the fingers and the bow as a lever, in which coupling between the thumb and second finger acts as a fulcrum. The ability to balance the bow and shift its weight from tip to frog is crucial to master passages that instruct a violinist to cross the bow from one string to another, as it is in every bowstroke to manage the changing pressure applied to the bow throughout its motions. In general, the fingers of the right hand are responsible for the most subtle changes in a given bowstroke. Correspondingly, the hand and the arm achieve larger, broader effects.

The critical motions of the right hand, independent from those of the fingers and arm, are the vertical and horizontal movements from the wrist joint. Used together, a violinist can move the right hand in any direction as demanded by different bowstrokes. The upper arm should easily have the same horizontal and vertical freedom from the shoulder joint and also readily combine movements of this type. In almost every type of standard bowing, the forearm hinges at the elbow, bending and straightening as the player performs up-bow and down-bow strokes. In addition, the forearm must also twist independently from the upper arm.

The interdependence of the postures of the fingers, hand, forearm, and upper arm can be seen in the simplest of bowstrokes: the long, straight stroke. Beginning with the bow set on the string at the frog, the object is to draw the bow downward until the tip is reached so that the bow hair maintains a more or less constant distance from the bridge. (It is true that in this "straight" stroke, the bow usually does travel back and forth with the tip end slightly further from the bridge, causing the bow to be slightly slanted with respect to the bridge.) In order to accomplish the task, the player must straighten the forearm while pushing the upper arm forward. This motion is a difficult one, as the natural tendency is to pull the upper arm backward toward the player. The hand must also gradually move its weight to the left in order to compensate for the increasing lightness of the bow (from the perspective of the string) as the tip is approached. It is helpful to view the straight motion achieved in this bowstroke as a combination of movements in the arm, hand, and fingers that are essentially circular in nature–that is, their movements describe arcs [Gal62].

The bow is largely responsible for the quality and character of the tone produced by the violin. There are many types of bowstrokes, defined by how much of the bow length they require and the motions required to produce them. The sounds created by them–their amplitudes, attack and decay profiles, their durations, their timbres–are determined by three basic factors particular to the bowstrokes. As mentioned before, these are bow velocity, pressure, and how far from the bridge the bow is when it makes contact with the string. In order to achieve a given sound on the violin, a player must be capable of assessing the contribution of each to the sound produced in real-time. A change in one of these parameters necessitates a change in at least one of the others. It is a source of great interest that a given effect may be achieved to satisfaction with more than one method.

When the speed of the bow motion increases, the volume of the sound produced increases as well, as more energy is transmitted to the vibrating string. Obviously, a decrease in bow velocity has the opposite effect. Therefore, a violinist must budget the length of the bow not only in consideration of the duration of the notes she is to play, but also with a keen understanding of their relative dynamics.

The amount of pressure the bow applies to the string of a violin is directly proportional to the amplitude of the sound produced. Applying pressure to the bow in fashion appropriate to the desired sound is complicated, as a player must work with the pressure produced by the weight of the arm and hand on the bow, the change in the weight distribution of the bow itself along its length, and the force applied through the action of the fingers, hand, and arm. As discussed previously, it is actually quite difficult to produce a constant volume of sound (with constant speed), for this result requires a non-constant amount of pressure so as to compensate for the changes in the weight of the bow.

As a consequence of the speed and pressure applied to the string, the proper point at which the bow should make contact with the string–the distance from the bridge–is determined. This point is also dependent upon the length, thickness, and tension of the violin string bowed, and so must also be altered with each change from one string to another and in each change of hand position. In general, the location of this point moves closer to the bridge as the bow moves from the lowest string (G) to the highest (E) and as the hand moves from first position (hand closest to the scroll) to the positions higher on the fingerboard.

It is also well understood that these physical actions required of the right hand fingers, hand, and arm are more challenging than those demanded of the left hand. (Part of the challenge is in learning to exploit the elasticity of the bow, whose form is a wonderful example of both strength and flexibility.) But these actions are so difficult due to the extreme range of expression made possible by the bow. With well-cultivated left and right hand techniques and fine coordination between the two, a violinist is capable of creating and shaping every aspect of sound that emanates from the instrument.

It is because of the difficulty of bowing, the underlying expressivity of each movement required, and the creative power sourced from these physical actions that bowing technique is so compelling a research topic.

## 2.3 Related Research

The primary concern addressed by this thesis was to enhance and illuminate the relationship between the violin and its player. Previous to this work, many researchers in the fields of physics and acoustics have considered the violin from a physical perspective through analysis, synthesis, and measurement of the physical attributes and characteristics of the violin, whereas others of the computer music and engineering communities have explored the violin as a musical interface and have developed novel instruments and controllers related to its physical interface.

### 2.3.1 Analysis/Synthesis/Measurement

The field of computer music is said to have begun in 1957, when Max Mathews, an engineer at AT&T Bell Telephone Laboratories, wrote the first sound synthesis program, known as *Music I* [Roa98]. Mathews was the first to demonstrate that a computer could be used to generate sound and might be viewed as a musical instrument.

Mathews focused much of his early work specifically on the violin, and in 1972 designed with J. Kohut a kind of electric violin lacking a wooden resonance chamber, replacing this functionality with a setup of electrical oscillators whose output amplitudes were controlled by magnetic pickups near the strings [MK73]. Even at such an early date, researchers were not only interested in the analysis and synthesis of violin sounds but the use of this understanding to create new instruments.

Advances in the research field of acoustics have coincided with progress in computer music. In particular, a great deal of research has been done in the fields of physics and acoustics to understand the science of violin sound production. Indeed, there is a huge amount of interest in discovering the mysteries of the great violins of Stradivarius and Guarneri [Lip94, Wei93]. Just as the violin's structure and physical properties are studied, mathematicians and computer scientists specializing in acoustic modeling seek to successfully analyze and model violin sound.

As might be expected there have been two basic approaches to understanding the dynamics between string and bow. Researchers have worked on developing ever more complex string models deduced from an understanding of physical laws and from numerical and computer simulation. This approach appears to be the more theoretical, in contrast to the more experimental approach in which the focus is on understanding string behaviour through ever more precise measurements and physical experiments.

Researcher James Woodhouse has long been interested in understanding the physics of how contact forces between a violin's strings and the bow hair produce the excitations in the strings that are ultimately responsible for the produced sound. Woodhouse's apparatus deduced the bow-string contact force by measuring the force on a string at the ends, and applied these forces to detailed physical simulations of mathematical bowed string models [WSG00, Woo92]. Gabriel Weinreich has also written numerous papers on computer simulations of string motion under various types of excitation [WC91, Wei93].

Julius Smith and Chris Chafe, collaborators of Woodhouse, have also designed complex software models of bowed string dynamics, have done extensive work to simulate performance on bowed stringed instruments, and have done work to develop mathematical models as well [Cha88, SSIW99, OSCSI00]. By finding software models that support good playability, this research works to increase understanding of how violin strings behave.

Anders Askenfelt has done a great deal of research in the measurement of the bowing parameters of bow velocity, bow force, and bow-bridge distance. He is interested in bowing gesture, and recorded a wide set of strain gauge sensor readings from different players bowing in different styles [Ask86, Ask89]. His research is an example of a use of foil strain gauges to measure bowing parameters. However, he was not interested in the overall usability of the final instrument and focused only on measurement accuracy.

### 2.3.2 Novel Instruments and Controllers

With the emergence of such modern means of making music, the possibility of including both traditional acoustic instruments and novel electronic instruments in performance has held a great deal of interest for musicians and composers. Artists such as Pierre Boulez of IRCAM began to investigate how live acoustic instruments may be used in conjunction with sounds generated by computers, as exemplified by his piece, *Répons* (1981). Interest in combining both acoustic and electronic elements in the creation of new instruments has also grown.

Teresa Marrin, a former researcher at the MIT Media Lab, designed the *Digital Baton*, a conductor's baton augmented with 11 different sensors for detecting position, orientation and pressure. Used in the Brain Opera, this device is an example of a complex musical controller based on pressure and motion through space. Marrin also designed the *Conductor's Jacket*, an article of clothing created with sensors to act as a physiological monitoring device, worn by a conductor, capable of sensing her heart rate, respiration, skin conductance, etc., such that a conductor could arrange for her internal emotional and physical states to augment her conducting performance [Nak00]. The bearing of Marrin's research on this project is that it shares the philosophy of taking traditional musical devices out of their standard contexts in an attempt to create new instruments founded upon traditional technique.

Special efforts have been made to design new music controllers with violin interfaces. At the MIT Media Lab, this research followed two projects of related aims: the *Hypercello* project [MC89, PG97, Par97] and the *Digital Stradivarius* project [Sch00].

The *Digital Stradivarius* project was a descendent of the *Hypercello* project. With a sensing system very similar to that of the *Hypercello* built onto a traditional violin, the *Digital Stradivarius* project aims to model the sound of a Stradivarius violin using physical gesture data as criteria. Once this feat is successfully performed, a violin controller may eventually be built (from which no acoustic sound would emit) that will use sensor data to play the Stradivarius model.

The *BoSSA* project [TC99] produced several innovations that captured aspects of musical gesture so as to control electronic sounds. This system incorporated commercial accelerometers onto the stick of the bow and a force-sensitive resistor placed under the hair at the tip of the bow. Also integral to the *BoSSA* was the introduction of new amplification techniques by means of specialized array of speakers that approximated the natural sound quality of a violin by imitating the manner in which violin sound radiates and diffuses in an acoustic space. Interestingly, the *BoSSA* possesses the basic components of a violin's physical interface, while lacking both a resonant cavity and strings.

Charles Nichols has designed a haptic force-feedback bow–a device superficially similar to a violin bow, permanently mounted to a base through a set of servos. As the user moves the bow about, back and forth, the user's bowing parameters are delivered to a computer. In addition, the computer's simulation of the expected force feedback is delivered back to the user [Nic00]. This is an example of a novel instrument which feels somewhat like a violin and detects some bowing parameters.

Sile O'Modhrain designed experiments to examine the extent to which haptic feedback improves the playability of virtual musical instruments. She designed a controller, known as the *Moose*, which is gripped in a user's hand and moved back and forth in a bowing motion. This controller was connected to force-feedback system which simulated the feeling of friction between a bow and violin string [O'M00].

The field of electronic/computer music research has produced many tools and interfaces for the composition and performance of new music. New techniques for audio processing grant musicians a much larger domain of sounds to manipulate than given by traditional acoustic instruments, and current audio systems provide the ability to control such musical events. Despite such progress in the realm of new sound generation, comparatively little work has been done to understand, exploit, and enhance the interaction between a fine musical instrument and the musician who plays it. As this interaction is of key importance to any musical performance, research into ways to evolve standard musical instruments and to create new music controllers is crucial.

# Chapter 3

# Implementation

The goal of this project was to provide a new violin bow interface. This interface measured aspects of the physical performance that describe the interaction of the player with the instrument. To achieve this goal we focused on three separate sensory inputs. Together, these measurements provided adequate data to extract more information provided by the player through the instrument than had been collected previously [Mac92, PG97, Sch00]. Although some information describing physical performance can be interpreted from audio analysis alone, the data provided in this thesis offered a richer picture of the performance as a whole.

The three sensory inputs explored in this work were position of the bow with respect to the bridge of the violin, acceleration of the bow, and strain in the bow stick. The accelerometers served to generate data corresponding to the movement of the bow in the bowing direction, in the direction parallel to the neck of the violin, and in the direction normal to the strings. The strain measurements helped to illuminate the influence of the bow hair on the strings by reporting the amplitude of the strain exerted on the bow stick. Together these measurements provide a characterization of the forces applied to the bow in all directions within 3-dimensional space. (In addition to the force information collected, the position sensor was built in order to provide velocity information in the future, as any velocity values extrapolated from the acceleration data would only be unique only up to an additive constant of integration.)

## 3.1 System Overview

Though we were interested in creating a violin bow with capabilities unlike any other and expect the form of the bow to differ from the traditional as a result, we wanted to maintain certain traits of the physical interface so as to enable a player to use the same posture of the right hand wrist and fingers on the bow. Therefore, the hardware implementation of the *Hyperbow* measurement subsystems was designed so as to provide the performer with an instrument as similar to a traditional bow in size, weight, and weight distribution as possible.

In addition to the requirements of the physical interface of the bow itself, there were several basic requirements for the architecture of the sensing system (see Fig. 3.1). Though the printed circuit board on the bow performed the functions necessary to attain and send strain and acceleration data, it acted as only part of the position sensor. The second part of the position sensor was the tailpiece-mounted antenna described below. Because the progress of the position sensing subsystem was separate from that of the rest of the project and the subsystem was designed for use in musical applications different from those of the strain and acceleration sensing subsystems, the hardware to receive position data was isolated from the other subsystems. Ultimately, the data from the bow sensors was meant to be viewable by both a workstation running a Microsoft Windows variant for the purposes of analysis, and a Macintosh workstation for the development of music applications. A serial protocol was used to carry the combined strain/acceleration data stream and the position data stream to an external computer.

A crucial design objective was that the bow remain wireless, without power or data cables. The small electronics board that was mounted to the bow was powered by a lithium battery and sent the sensor data from its transmitter to a receiver on a separate electronics board (see Fig. 3.2). This data transfer was performed via a Linx HP-SeriesII RF module,

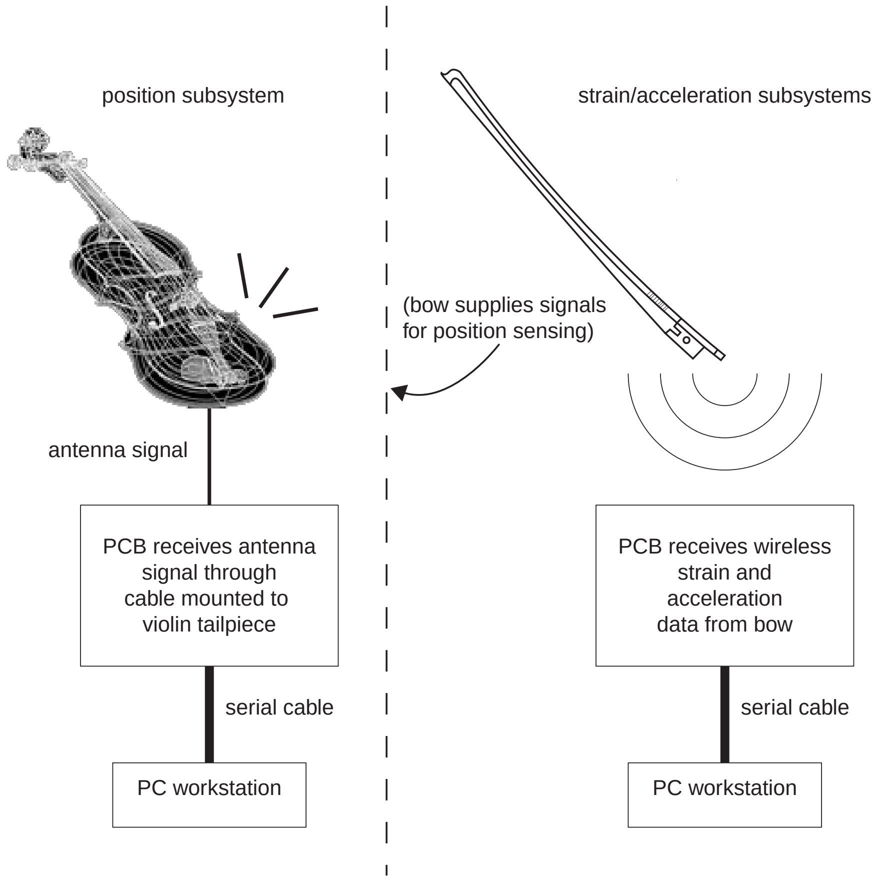


Figure 3.1: The measurement system of the *Hyperbow* was composed of three individual subsystems for position, acceleration, and strain sensing. However, the data for these three measurements was collected in two separate data streams. The position sensor signal was sent through a cable attached to the antenna mounted on the violin. This signal was received by a custom printed circuit board that sent the position data encoded in a serial format to a PC workstation where it was interpreted. The acceleration and strain sensor information was transmitted wirelessly to a receive board that sent the related data to a PC via a serial cable as well. The acceleration and strain of the bow could be measured on any violin, or indeed without a violin. However, the position measurement relied on the inclusion of the *Hyperbow* to provide one half of its sensor.

Figure 3.2: The printed circuit board designed to receive the accelerometer and strain data from the *Hyperbow* was very simple, containing only the Linx $1/4$ wave whip antenna (ANT-916-CW-QW), the Linx RXM-900-HP-II receiver, a MAX233 RS-232 level converter, and a serial port. (Note: The three green wires depicted here were included to correct an error in the implementation of the MAX233 chip.)

manufactured by Linx Technologies, Inc. of Grants Pass, OR. This module operates in the 902-928MHz band, is capable of transmitting data for distances up to 1000ft, and has eight selectable channels (making it possible to adapt this sensing system for use in several instruments simultaneously). The antenna for the transmitter was a simple $\frac{1}{4}$ wave whip antenna made from a piece of solid conductor wire cut to the appropriate length. The wavelength for the desired frequency band is given by

$$\lambda = \frac{c}{f} \tag{3.1}$$

where $\lambda$ is the wavelength in meters, $c$ is the speed of light in meters per second, and $f$ is the frequency in Hertz. For frequency 903MHz, and converting to feet, the (3.1) evaluates to

$$\lambda = \frac{984 \times 10^6 \text{ft/s}}{903\text{MHz}} \approx 1.09\text{ft} = 13.08\text{in}. \tag{3.2}$$

For the $\frac{1}{4}$-wavelength antenna, $L_{1/4} = \lambda/4 = 3.27$in.

### 3.1.1 Position Sensing Subsystem

Though the first two prototypes of the *Hyperbow* were not capable of capturing position data, the measurement system for the third experimental bow included an additional position sensor. The method of sensing the position of the bow relative to the bridge of the violin used in this thesis was an adaptation of the system used in the development of the *Hypercello* [PG97] and later in the *Digital Stradivarius* project [Sch00].

In this method, two square wave signals of different frequencies were employed, one originating from the tip of the bow and one from the frog-end of the bow. The signals were connected to opposite ends of a resistive strip that ran along the length of the bow. A simple electrode antenna was placed behind the bridge of the violin. This antenna was connected to a circuit that amplified the combined signal and sent it to a remotely mounted board, whose task it was to separate the two signals from each other and measure their varying strengths via a cable. Bow position could then be determined from this data in software on a computer connected to the output of the board.

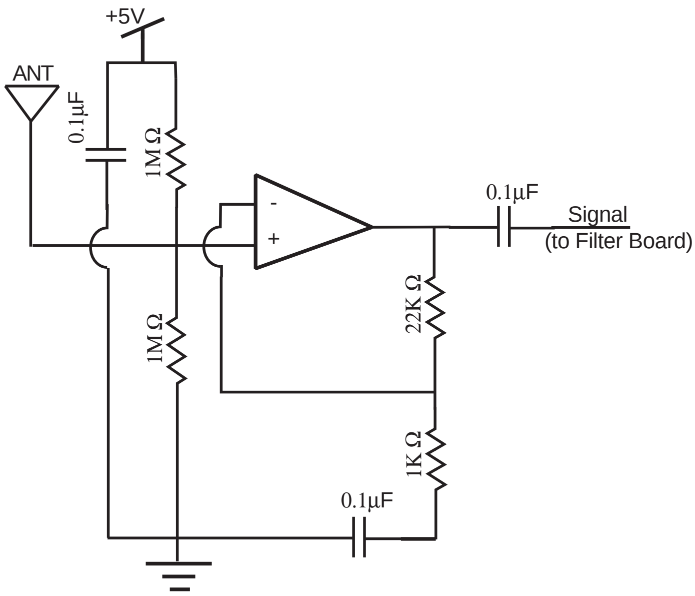


Figure 3.3: The electrode antenna received a signal that was a combination of the two signals sent from the bow. The individual strengths of these signals varied with the position of the bow, as the signals themselves originated from opposite ends of the bow. Because this signal was naturally weak, an amplifier was crucial to the design. The amplifier circuit included on the position sensing antenna consisted of one operational amplifier with the necessary passive components. The gain of this amplifier is approximately 23 in our frequency range (50-100KHz).

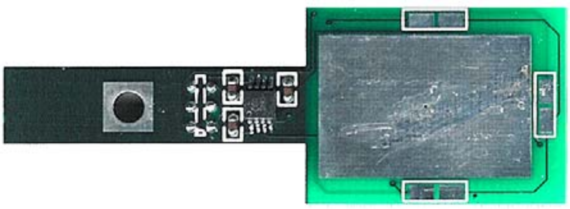

Figure 3.4: The printed circuit board antenna was designed to be secured to a threaded rod mounted to the tailpiece of a violin so that it was suspended just behind the bridge, with its large electrode facing toward the scroll of the instrument. The electronics on this board consisted only of the small circuit used to amplify the signal from the electrode (which is 0.859in long and 0.575in wide), and three LEDs so as to provide the option of indicating power and the varying strengths of the two signals transmitted from the *Hyperbow*.

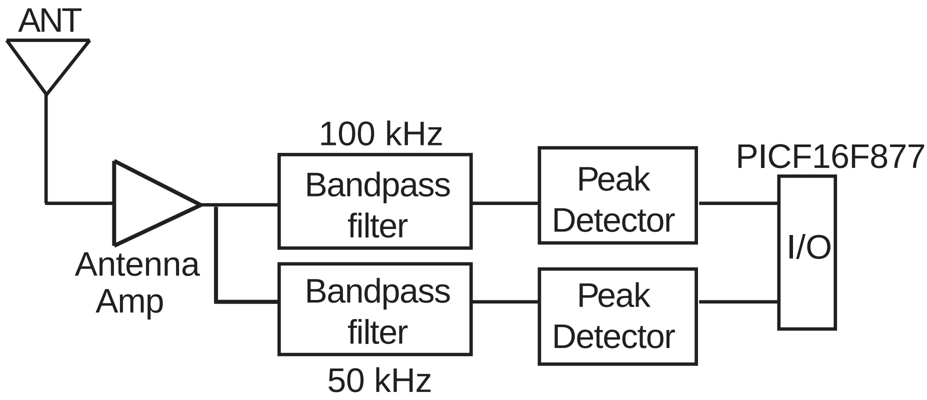


Figure 3.5: The amplified signal from the antenna board on the violin was a combination of the two signals sent from the bow. In order to determine the position of the bow, the combined signal first had to be separated into two signals once again. This function was performed by directing the combined signal into two bandpass filters, one designed to pass 50KHz signals and one for 100KHz signals. The outputs of these filters were then converted into DC voltages by two peak detectors and sent to the PIC16F877 microprocessor. The PIC encoded these values in a serial format, and the data was sent to the PC workstation via a serial cable.

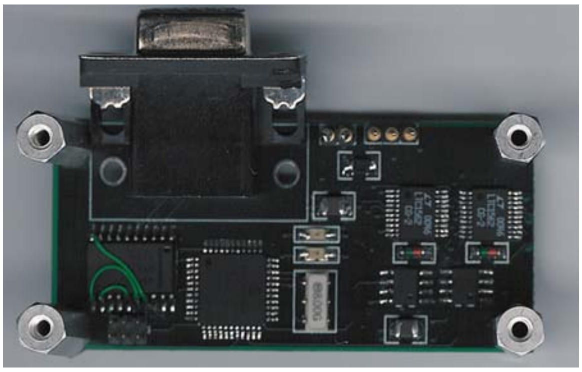

Figure 3.6: The printed circuit board used to receive the signal from the position sensing antenna housed one PIC16F877 microprocessor, two LTC1562-2 filter chips, two OPA2350 operational amplifier chips (used to make the peak detectors), and a MAX233 RS-232 level converter in addition to the passive components. The PCB itself contained 4 layers corresponding to the front, back, power, and ground planes and was 2.75in long and 1.22in wide. (Note: the green wires depicted here were added in order to correct an error made in the implementation of the MAX233 chip.)

In this project, the implementation of the position sensor was completed with as little alteration to the rest of the existing sensing system as possible. So as to add a minimal number of hardware components to the small board mounted on the bow, the two square wave signals were generated by the PIC16LF877 manufactured by Microchip Technology, Inc. of Chandler, AZ. A 100KHz signal was produced using the PIC's `Timer2` module in PWM mode, and a 50KHz signal was produced using the built-in `Timer1` oscillator. (These frequencies were the same as those used in the first implementation of this electromagnetic field sensing method for the *Hypercello* and were chosen so as to maintain compatibility with existing hardware.)

The design of the electrode antenna remained almost identical to the original, except for the replacement of the original source-follower circuit with an operational amplifier circuit (see Fig. 3.3). The gain of this amplifier was determined as follows:

$$A_v = \frac{V_{\text{out}}}{V_{\text{in}}} \tag{3.3}$$

$$V_{\text{in}} = I_{\text{in}}\left(1\text{K}\Omega + \frac{1}{j\omega C}\right) \tag{3.4}$$

$$V_{\text{out}} = I_{\text{out}}\left(22\text{K}\Omega + \left(1\text{K}\Omega + \frac{1}{j\omega C}\right)\right) \tag{3.5}$$

$$I_{\text{in}} = I_{\text{out}} \tag{3.6}$$

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{\left(23\text{K}\Omega + \frac{1}{j\omega C}\right)}{\left(1\text{K}\Omega + \frac{1}{j\omega C}\right)} \tag{3.7}$$

Since $C = 0.1\mu\text{F}$ and $\omega = 2\pi \cdot 100\text{KHz}$, the $\frac{1}{j\omega C}$ term was neglected and

$$A_v \approx 23 \tag{3.8}$$

Some slight cosmetic changes were also made in the design to provide the option of including LEDs to indicate power and the varying strengths of each of the two signals, but the appearance of the electrode antenna remained mostly unchanged from earlier implementations (see Fig. 3.4).[1]

[1]The schematics for the bridge antenna and position receive board appear in Appendix A.

The board that received the signal from the antenna consisted of two bandpass filters, composed using two LTC1562-2 chips (manufactured by Linear Technologies of Milpitas, CA) that were designed to separate the two different signals of different frequency from each other, peak detectors that converted the signals to analog DC voltages equal to the signal amplitudes, and a PIC16F877 (powered with 5 Volts rather than the 3 Volts supply used to power the PIC16LF877 on the bow board) microprocessor with a built-in 10-bit A/D converter that received these voltages and sent them to a PC workstation in the form of a serial data message (see Fig. 3.5 and Fig. 3.6).[2]

### 3.1.2 Acceleration Sensing Subsystem

In order to sense the changes in acceleration of the bow, ADXL202 accelerometers from Analog Devices, Inc. of Norwood, MA, were employed. This accelerometer is capable of measuring accelerations with a full-scale range of $\pm 2$g. Because the ADXL202 is a 2-axis accelerometer, two of these devices, one mounted orthogonal to the plane of the electronics board containing the other, were used in the design in order to attain acceleration data along all three axes. This accelerometer has a digital output for each of its two axes of sensitivity that has a maximum resolution of around 14 bits. The acceleration measured by the accelerometers is encoded in the digital output signal by modulating the duty cycle–the ratio of pulsewidth to the period–linearly with the acceleration. The acceleration was thus retrieved by simply counting the duty cycle in a software loop.

One difficulty in developing the firmware for the microprocessor was seen in counting the width of the pulsewidths efficiently enough to attain adequate measurement resolution. The low-voltage PIC16LF877 used in this board uses an external clock of 4MHz, thus each instruction takes $1\mu$sec ($4 \cdot 1/4$MHz). Most of the firmware code for this project was written in the C programming language, but an exception was made for the code that counted the duty cycle of the outputs of the accelerometers due to the execution timing requirements. Inspection of the machine code generated by the C compiler used by MPLAB indicated an

[2] See Fig. A.3 of Appendix A.

inability to achieve the count of a duty cycle in a number of instructions small enough to yield at least 8 bits of resolution. The period of the digital signal output of each channel of the accelerometers had a period of 1msec (set by one external resistor of $125\text{K}\Omega$). In order to attain a resolution of 8 bits, the duty cycle had to be sampled 256 times per period. Therefore, each sampling of the duty cycle value had to be executed in no more than four instructions from the PIC ($1\text{msec}/(4 \cdot 1\mu\text{sec}) = 250$), yielding a resolution of $7.97 \approx 8$ bits. The requirement was met by developing this module in low-level Assembly code rather than high-level C code.

Initially, the ADXL202JQ ceramic package of the device was used, but the revised bow board included two ADXL202E accelerometers. The two types differ only in size, as the length and width dimensions of the ADXL202E are 5.0mm and 4.5mm, each less than half of the corresponding value for the ADXL202JQ. Additionally, the ADXL202E is much lighter.

### 3.1.3 Strain Sensing Subsystem

Because of its direct effect on the violin string and its close relationship to the experience of a violinist while playing, the measurement of the downward force on the bow stick was pursued.

After this initial consideration, the possibilities of measuring other forces applied to the bow stick, such as shear, or torsion, force and lateral force (along the axis of the violin strings), were pursued. In researching the methods of measuring these forces on the bow that correlate so strongly to the forces of the bow hair on the strings of a violin, several options for sensors were considered. The first type considered was the force sensitive resistor, which was used in the original *Hypercello* and the *Digital Stradivarius* project to indicate the pressure of the right hand index finger on the bow stick. Fiber optic bend sensors were also considered. Finally, strain gauges were isolated as a promising sensor to measure the different strains in the bow stick.

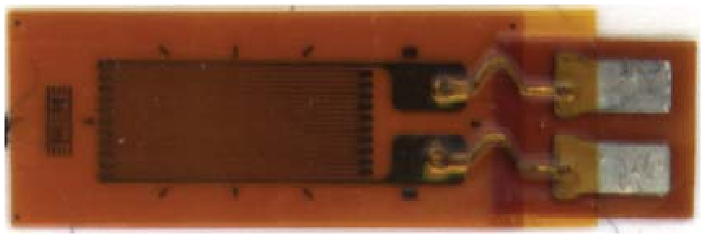

Figure 3.7: This uniaxial strain gauge (EK-06-250BF-10C) has a nominal resistance of $1000\Omega$ and is designed to measure strain in the direction of its grid lines. Its grid is composed of modified Karma, or K-alloy (nickel-chromium), an alloy characterized by good stability and fatigue life and a relatively flat thermal output curve. (The gauge grid is 6.35mm long and 3.18mm wide, and the dimensions of the entire object are 13.2mm long and 5.6mm wide.)

**Strain Gauge Operation**

The sensors used in this project were commercial foil strain gauges from Vishay Measurements Group, Inc. of Raleigh, NC. The gauges are two-terminal devices that behave as variable resistors. They are each composed of a special metal alloy wound into a given geometrical pattern and encapsulated in kapton film. The metal alloy has a fixed sheet resistivity (i.e., resistance per square) so when the lines of the resistor are stretched along one axis, the length of the resistor increases and thus the overall resistance increases. Conversely, when the gauge is compressed, its resistance decreases. Therefore, the proper operation of the gauges demands that they be securely and permanently affixed to the material that is under strain such that the stretching of the gauge is identical to the stretching of the material. The strain gauges used in this project were of two different geometries. The first was a uniaxial pattern (see Fig. 3.7) designed to measure strain along one axis (in the direction of the grid lines) as in a bending beam, and the second was a shear pattern (see Fig. 3.8), which actually contains two strain gauges in one package.This device is designed to measure torsional, or twisting, strains. In adhering the strain gauges to the surface, special care had to be taken because of the requirement to conform to a cylindrical surface rather than a flat surface (see Fig. 3.9). The high-precision foil strain gauges presented many implementation issues and constraints. Because the strain gauge measurement could easily degrade when operating at high temperatures (due to expansion in the alloy),

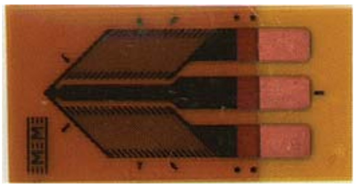


Figure 3.8: This is a two-element pattern (CEA-13-062UV-350) in which there are two gauges oriented such that they may measure shear, or torque strains. The devices are composed of A-alloy, or constantan, a nickel-copper alloy, the oldest and most common of strain gauge alloys. (The dimensions of the gauge grids are 1.57mm long and 1.60 wide each, and the dimensions of the entire object are 10.7mm long and 5.8mm wide.)

Figure 3.9: The process of installing strain gauges on a test object whose surface area was small and curved, i.e. the carbon fiber violin bow, was quite difficult. Various steps had to be taken in preparation of the test surface and in the positioning of the devices. Because four gauges were used in each strain sensor and were installed within very close proximity to each other, there were further complications in applying the adhesive for a given gauge so as not to tamper with other gauges. These two uniaxial strain gauges (EK-06-250BF-10C) each had nominal resistances of approximately $1000\Omega$ and were 6.35mm long and 3.18mm wide each. The winding of the metal alloy wire that composes the gauge can be seen running back and forth in the direction parallel to the bow. The terminals of this wire are connected to solder tabs.

special care had to be taken when choosing appropriate operating current levels to avoid generating large amounts of power dissipation in the form of heat. Also, a foil strain gauge relies on the material on which it is mounted to assist in heat conduction away from the gauge body itself. The gauges are temperature-matched to either steel or aluminum due to their high heat conductivity. Because this work was done on a carbon fiber bow, whose heat dissipating capabilities were not nearly as good as those of metals, the supply voltage for the sensor circuits was set much lower than that suggested for typical applications. The electronics that comprised these sensors used a 3 Volt power supply, in the form of a lithium battery, which was capable of operating both the PIC16LF877 microprocessor and the Linx TXM-900-HP-II transmitter, the crucial components of the bow board.

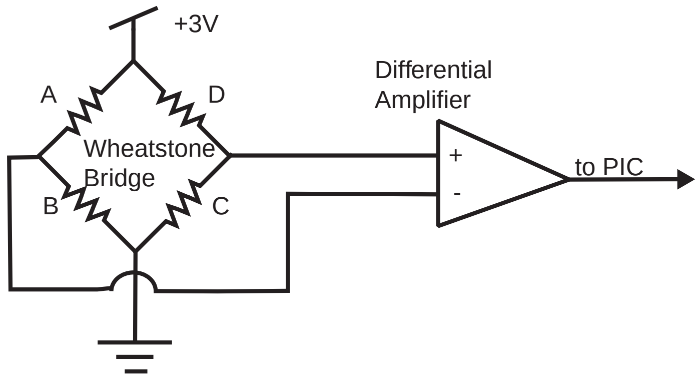


Figure 3.10: The value of the strain sensor was determined by taking a differential measurement. All four resistors in the Wheatsone Bridge configuration had nominal resistances that were approximately equal. Therefore, the voltage difference between the midpoints of each leg of the bridge–at the point between resistors A and B and the point between resistors C and D–was approximately zero at rest. When the values of the individual resistors changed, the voltage difference was altered in accordance.

**Wheatstone Bridge Configuration**

The strain gauges were arranged in a Wheatstone Bridge configuration with the midpoints of each "leg" of the bridge connected to a differential operational amplifier (see Fig. 3.10). So as to allow for the best measurement possible, a full bridge configuration, i.e., two strain gauges in each of the two legs of the bridge, was implemented. The sensor measured the strain at the point located approximately halfway between the two sets of gauges (see Fig. 3.11). At rest, the resistances of all of the gauges were approximately equal, and so the corresponding voltage values between the midpoints of the bridge and ground were also approximately equal, resulting in a voltage difference of zero at the output of the differential amplifier. So, as the bow was laterally strained in one direction, the gauges on one side of the stick were compressed and decreased in resistance, while the gauges on the opposite side of the stick expanded and increased in resistance. Thus, the left "leg" of the Wheatstone bridge experienced an increase in the upper resistance value and a decrease in the lower, while the right "leg" experienced the opposite. The voltages at the midpoints of the bridge were shifted in opposite directions. The voltage difference between these two points was then taken as the sensor value.

A principle advantage of the full Wheatstone Bridge configuration was that it rendered

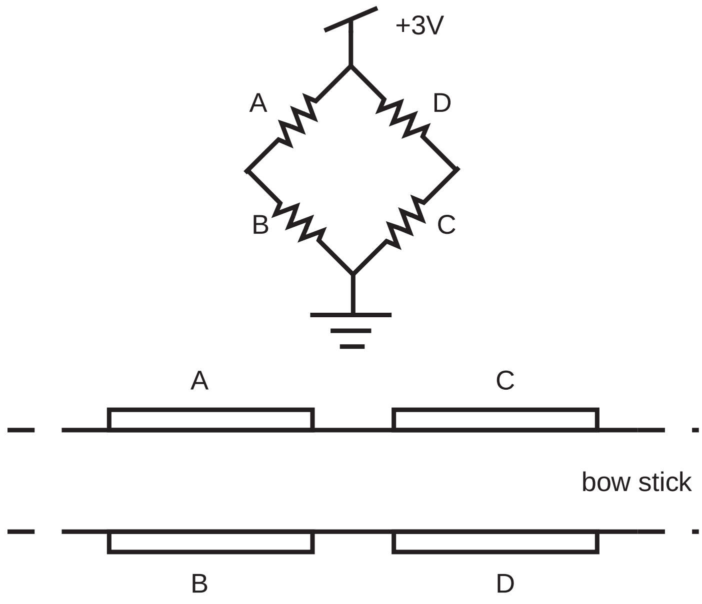


Figure 3.11: The arrangement of the strain gauges that comprised the Wheatstone Bridge circuit on the bow stick was designed so that the sensor measured the strain roughly halfway between the two legs of the bridge (A/B and C/D). In the case that a lateral (parallel to the strings) force was applied to the bow, gauges A and C were compressed and therefore decreased in resistance, while gauges B and D expanded and therefore increased in resistance. Therefore the voltage drop over B increased while the drop over C decreased, resulting in a nonzero differential voltage between the two midpoints of the legs of the bridge. If a force was applied to the bow in the opposite direction, the opposite changes occurred in the resistances of the gauges causing a differential voltage measurement of opposite sign.

the strain sensors unaffected by temperature changes in the bow. If a half-bridge configuration had been used, for example, such that resistors A and C were strain gauges, while B and D were fixed precision resistors (see Fig. 3.11), the gauges would have experienced temperature changes affecting their values while the fixed resistors would have been unaffected. In this case, the Wheatstone Bridge might have been quite unbalanced. Therefore, the gauges were arranged on the bow such that two of the gauges are placed directly above the other gauges in opposite legs of the Wheatstone Bridge circuit. Therefore all four gauges in each bridge experienced approximately the same changes in temperature and expansion of the bow, as heat was dissipated through the carbon fiber bow.

After adhering the gauges on the bow stick in the full-bridge configuration and powering the circuit with a 3 Volt supply, the temperature effects on the strain gauges were assessed. In the case of the $1000\Omega$ uniaxial gauges (EK-06-250BF-10C), the temperature of the bow was measured using a thermistor probe and found to be approximately $26.5°$C, while the temperature of the gauges was found to be approximately $27.1°$C. (Each of these measurements was made over the time period of about 30 minutes.) This small difference of $0.5°$C indicated that the performance of the strain gauges was unimpaired by thermal effects.

The gauge factor temperature coefficient for each strain gauge was equal to $(-1.0 \pm 0.2)\%/100°$C. Therefore, given the observed temperature change of $0.5°$C, the effective gauge factor variation with temperature was

$$0.5°\text{C}\frac{-1.0 \pm 0.2\%}{100°\text{C}} = -0.005 \pm 0.001\%. \tag{3.9}$$

The device strain limits are $\pm 1.5\%$ at room temperature. Thus, the maximum resolution for each gauge is

$$\text{resolution} \approx \frac{1.5\%}{0.005\%} = 300 \tag{3.10}$$

i.e., the sensor can distinguish or resolve 300 distinct values at most, or ≈8 bits. This figure is a measure of the accuracy of the sensor, but not of the precision *per se*. With respect to the strain data, the desired goal was not to attain an accurate measurement, but rather a precise, relative measurement. In other words, the strain values were never used to quantify absolute strain, but rather were employed to register subtle, relative, variations. Therefore, the limit imposed by the calculation above was not of great concern, nor did it negate the benefit of the 10-bit A/D converter used to sample the strain values.

**Amplification**

The voltage difference between the two midpoints of the Wheatstone Bridge was amplified using a differential amplifier to yield a voltage value within the range of 0-3 Volts, as this was the range of the A/D convertor in the PIC16LF877. The goal was to ensure that when the bow was idle the voltage value would be stable at approximately the midpoint of this range, and when the bow was in use the voltage value would exhibit significant deviation without risk of saturation. This amplification was achieved by adjusting the external resistors of the differential amplifer appropriately. The differential amplifer was constructed using an INA2321 instrumentation amplifier manufactured by Burr-Brown Corp. of Tucson, AZ, which has a maximum gain of 1000. In most cases, the strain sensor voltages were amplified by 500 or 750.)

### Power Consumption

One of the greatest concerns of the strain sensing hardware was that of power consumption. In each "leg" of each Wheatstone Bridge, the current drawn was equal to $I = V/(2 \cdot R_{\text{rest}})$, where $V$ was the power supply voltage. In the first complete prototype of the bow system, the nominal resistance of each strain gauge used was $350\Omega$, and there were 6 strain sensors. So, the current through each Wheatstone Bridge was $I = 2(3V/(700\Omega)) \approx 8$mA for a 3 Volt supply. Therefore, the total amount of current drawn through both legs of the Wheatstone bridge was 8mA, and the total amount of current drawn by the strain sensors was 48mA. Because of this, a battery capable of sourcing a large amount of current (more than 68mA) was used (Panasonic CR-2PA/1B). This battery had a capacity of 750mAH, a standard current drain of 20mA, and weighed approximately 11g. This considerable contribution to the weight of the bow was unavoidable, as it was the lightest battery found capable of sourcing enough current to power the bow board.

In order to reduce the power consumption of the system so as to extend the lifetime of the battery, strain gauges with a nominal resistance of $1000\Omega$ were used in the second and third incarnations of the bow. This reduced the current through each leg of each Wheatstone bridge to

$$I = 2(3V/(2 \cdot 1000\Omega)) = 3\text{mA}. \tag{3.11}$$

So, the current drawn by each Wheatstone bridge was 3mA, a 5mA improvement. To further improve this figure, a power cycling scheme was implemented by powering each bridge and its accompanying instrumentation amplifier with a pin from the PIC (see Fig. 3.12). The scheme utilized the shutdown mode of the INA2321 instrumentation amplifier. The power cycling was accomplished as follows: the electronics for a given strain sensor were

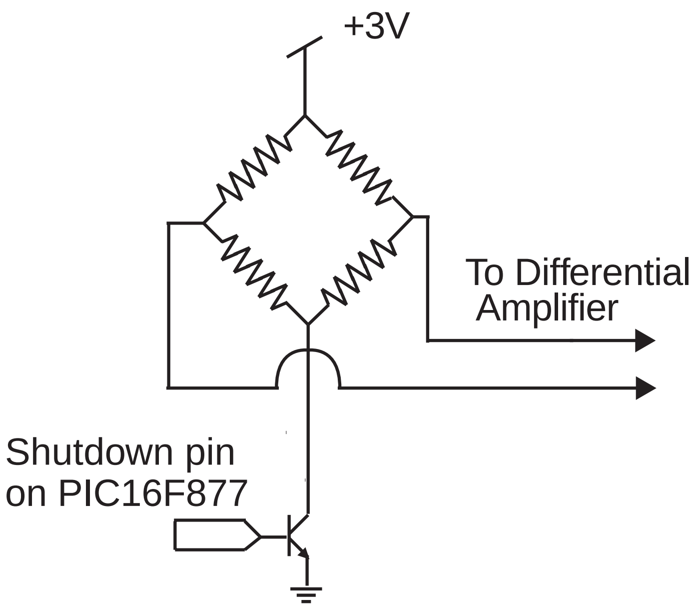


Figure 3.12: In order to save power, the strain sensor Wheatstone Bridges were power-cycled so that only one was on at any given time. This was accomplished by powering each one by an assigned pin from the PIC16F877 that was connected to the base of a transistor. When the pin was held high, the transistor turned on and current flowed through the bridge. When the pin was low, the transistor was off, current stopped flowing and no power was consumed by the circuit. This shutdown pin was also connected to the shutdown pin of the INA2321 instrumentation amplifier that served as the differential amplifier, so this device also consumed power only when the pin was high.

powered, the associated strain data channel was read, the sensor was powered down, and then the electronics for the next sensor were powered. This power cycling scheme allowed only one strain sensor to be powered at any given time, reducing the current drawn by the strain sensors, essentially dividing it by the number of strain sensors present in the design.

The power consumption of the bow board electronics was improved in the second and third prototypes of the *Hyperbow* by reductions in the number of strain sensors and increases in the nominal resistances of the gauges. Ultimately, the amount of current drawn by the bow board was so small that the power cycling sheme was no longer necessary.

**Application and Alignment**

There were some major difficulties that arose in the process of adhering strain gauges to the surface of the bow. The first was in simply achieving a solid bond between the strain gauge (by carefully preparing the surface of the bow, abrading it, applying fast-curing adhesive and catalyst between the gauge and bow surface, and then applying pressure until set) and the bow surface and the second was found in the task of properly aligning the devices (see Fig. 3.11).

The accuracy of a strain gauge measurement is highly sensitive to the relative alignment of the group of strain gauges along the bow surface. Any difference of the angle made between individual strain gauges and the axis of the test object alters the effective lengths of the strain gauges along the strain axis and therefore affects their relative rest and strained resistances. Discrepancies between the orientations of the individual gauges and how they conform to the surface of the bow contribute to the difference between their nominal resistance values, and this in turn creates problems in the performance of the bridge. Since the measurement taken is really the voltage difference between the two voltages at the midpoints of each leg of the bridge, when the gauges are not closely matched this value at rest is nonzero and the dynamic range of the measurement is impaired.

Therefore, though considerable pains were taken to ensure that the devices were well matched from the onset, there were seemingly unavoidable deficiencies in the balancing of the bridge in its rest position due to differences in the nominal resistances of the strain gauges after installation as in the third *Hyperbow* prototype (see Table 3.1). It should be noted, however, that the accuracy of strain gauge resistance measurements was difficult to assess, as the mere act of probing the gauges caused their values to change.

## 3.2 *Hyperbow* Prototypes

In the development of the bow sensing system, four commercially available carbon fiber bows of professional quality were used for experimentation. The first, a Durro bow, was used as the original test object for the application of strain gauges. The integral parts of the strain gauge circuitry were tested on a breadboard with this bow.

After the initial tests and the manufacture of the bow boards, three bows, which will

|  | Original Value (Ω) | Value after Installation (Ω) |
| --- | --- | --- |
| A (downward) | 999.9 | 999.8 |
| B (downward) | 999.9 | 999.8 |
| C (downward) | 999.8 | 1000.2 |
| D (downward) | 1000.0 | 1000.9 |
| A (lateral) | 1001.1 | 1001.3 |
| B (lateral) | 1001.1 | 1001.3 |
| C (lateral) | 1000.9 | 1001.0 |
| D (lateral) | 1001.1 | 1001.4 |

Table 3.1: In the process of applying the strain gauges to the third stick of the third *Hyperbow* prototype, the nominal resistance values of each gauge were altered. This result was caused mostly by the changes in the shapes of the devices from flat to curved, as they were forced to fit the contour of the stick. Differences such as these may greatly affect the performance of a sensor, as the bridge may become unbalanced. Also, due to differences in shape and alignment of the gauges with respect to each other, they are not likely to not experience the same effects of different strains on the bow stick.

be referred to as the first, second, and third prototypes of the *Hyperbow*, were outfitted with the bow board and evaluated. The first version was a *Colours* bow from CodaBow International, Ltd. of Winona MN, and the second and third versions were CodaBow *Conservatory* bows. The most distinguishing characteristic of the *Colours* bow is its finish (see Fig. 3.13). Reminiscent of the traditional pernambuco style, this bow appears at first glance to be reddish-brown in color. However, due to the presence of a special paint applied to the surface of the graphite, the bow appears to change color as the angle of incident light that strikes its surface is varied. The *Conservatory* bow is identical in structure to the *Colours* bow (in size, weight, balance, flexibility, material) but simply lacks the addition of any paint to its surface.

The first bow was instrumented with the original design of the bow board containing two ADXL202JQ accelerometers and inputs for six strain sensors.[3] All inputs were utilized for two downward force, two lateral force, and two torsion force sensors. The lateral force sensors were placed on either side of the midpoint of the bow, the torsion sensors were placed at the extreme ends, and the downward force sensors were placed roughly between the other two types. All of the strain gauges used for this bow were nominally valued at

Figure 3.13: The CodaBow *Colours* bow stick is finished with a special paint that is highly reflective and causes it to appear to change color in the presence of different light sources. This cosmetic feature renders it unsuitable for strain gauge installation.

Figure 3.14: The second prototype of the *Hyperbow* included 6 strain sensors and 2 accelerometers. The printed circuit board used to collect and transmit the data from these sensors was mounted near the tip of the bow. Though the board was 1.94in long and 0.875in wide. It was designed to fit closer to the frog, its location was altered so as to avoid contact with the strings during play (while in use the bow stick is forced extremely close to the strings near the frog). The position of the board and the large number of strain sensors necessitated installation of many wires along the length of the stick. There were 21 in total: 3 for each of 6 gauge bridges, 1 to run power to all of the bridges, and 1 cable to run power and ground signals from the battery near the frog to the board.

$350\Omega$. The bow board was placed at the tip of the bow and secured with two brass brackets.

The second experimental bow followed the same design as the first in the placement and mounting of the board (see Fig. 3.14, Fig. 3.15, and Fig. 3.16), but it utilized only four of the six strain sensor inputs.[4] This reduction in the number of strain sensors was made after it was determined that a user could not purposefully alter more than one downward and one lateral strain sensor with any degree of fine precision. One downward strain sensor and one lateral strain sensor were placed around the middle of the bow stick, the former at the tip-end and the latter at the frog-end. The torsion sensors were again placed at the extreme ends of the bow stick. The uniaxial strain gauges used in the downward and lateral force sensors in this model were nominally valued at $1000\Omega$ and were slightly longer than the first type used in this project. The torsion devices were identical to the original ones used, valued at $350\Omega$.

The third and final bow (see Fig. 3.17) was equipped with the revised version of the

[3]See Fig. A.1 in Appendix A for a full schematic.
[4]See Fig. A.1 in Appendix A for a full schematic.

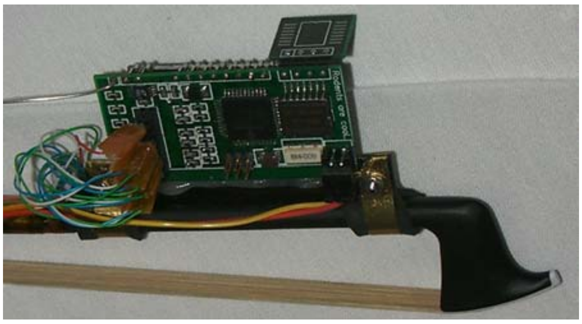

Figure 3.15: The printed circuit board for the second prototype was secured using brass brackets. The inputs from the strain sensors are pictured on the left, and the two accelerometers may be seen on the right. The first ADXL202JQ (large package) was placed next to the PIC16F877, while the second was included on the underside of the “daughter” board that was mounted at a right angle to the main board.

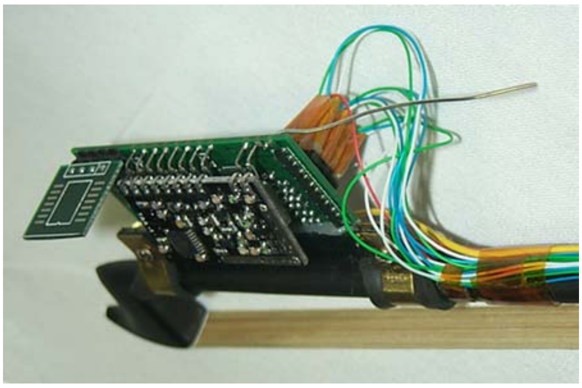

Figure 3.16: The back of the bow board shows the Linx TXM-900-HP-II transmitter that carried the accelerometer and strain data to a remote receive board.

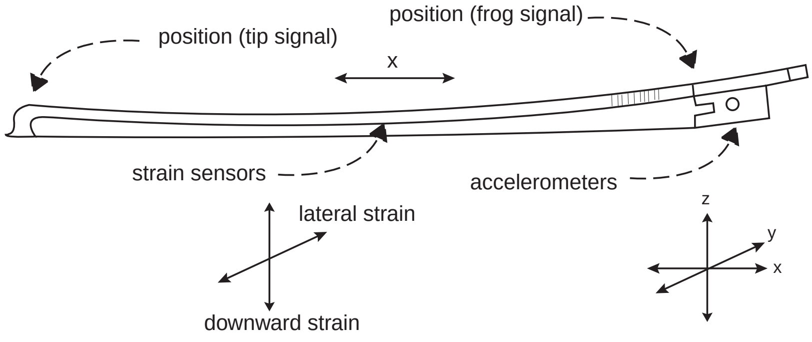


Figure 3.17: The third and final prototype of the *Hyperbow* included accelerometers, mounted at the frog of the bow, to give acceleration data for all three axes of bow movement, two strain sensors, mounted around the middle of the stick, for downward (normal to the strings) and lateral (parallel to the strings) strains, and the outputs for the two signals necessary for position sensing (parallel to the bridge), located on the stick at the extreme ends of the bow hair.

Figure 3.18: The third prototype of the *Hyperbow* contained 2 strain sensors, 2 accelerometers, and the part of the position sensor that generated the two square wave signals of 50KHz and 100KHz. The printed circuit board on this bow was designed to fit around the frog. Because of these changes, the number of small wires along the bow stick was reduced to 7: 3 for the bottom and midpoints of each gauge bridge and 1 bus that was used to supply power to the bridges. As the battery was still housed behind the frog, as in the first prototype, it was connected easily to the board in its new location. The position sensor added 1 coaxial cable and one resistive strip of plastic along the length of the bow stick as well. These two components may be removed if the position sensing subsystem is inactive.

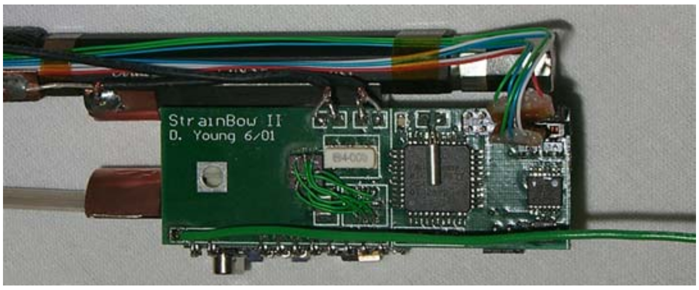


Figure 3.19: The printed circuit board for the third *Hyperbow* prototype was reduced in size and weight from its predecessor due mainly to the reduction in the number of strain sensors. The inputs for the 2 remaining strain sensors can be seen on the right. The coaxial cable outputs for the 2 signals used for the position sensor are visible on the upper left. The added crystal oscillator necessary for the generation of the 50KHz signal was positioned over the PIC16LF877. The large green wire is the antenna that was used for the wireless transmission of the accelerometer and strain data. The board is 2.35in long and 0.80in wide. (Note: The 8 green wires depicted on the board were added in order to correct an error in the implementation of one of the ADXL202E accelerometers.)

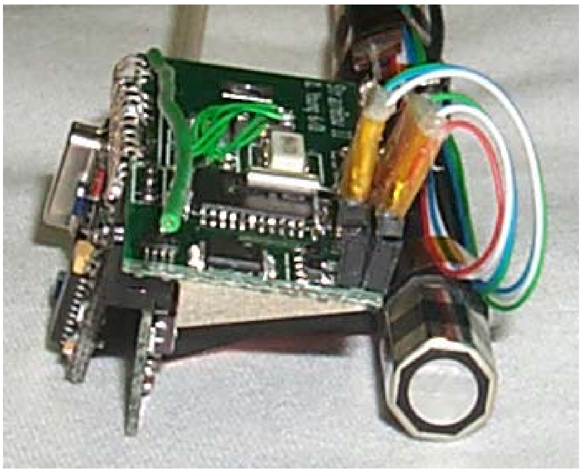

Figure 3.20: The rear view of the board for the third prototype shows the Linx TXM-900-HP-II transmitter on the left, positioned at a right angle to the main board such that it lies flat against the underside of the bow frog. The “daughter” board on which the second ADXL2020E accelerometer was mounted was positioned on the same plane as the transmitter. So that a player could easily handle the bow without interfering with the electronics, there was nothing added to the other side of the frog except copper tape used for grounding purposes in the position sensing subsystem. The battery, not shown here, occupied the space defined by the main board, the “daughter” board, and the end screw.

bow board, which included outputs for the two signals required for the position sensor, two ADXL202E (smaller package) accelerometers and only two strain sensor inputs (see Fig. 3.18). The torsion strain sensors were abandoned, as they proved difficult to control. The single downward strain sensor and the single lateral strain sensor were each placed around the middle of the bow in the same manner as for the second bow. The type of uni-axial strain gauges used (EK-06-250BF-10C) remained unchanged. In this implementation of the system, the bow board was moved from the stick of the bow to the frog (see Fig. 3.19 and Fig. 3.20, and Fig. A.2 of Appendix A for a full schematic).

## 3.3 The RAAD Violin

Because the strain and acceleration sensing subsystems required no alterations to the violin played, an acoustic or electric violin could be used in these measurements. Because of dependence of the position sensing subsystem on the tailpiece-mounted electrode antenna, an electric violin was better suited for applications involving position sensing, as the addition of a mechanical structure on the tailpiece of an acoustic instrument would have provided unfavorable stress. Therefore, though acoustic violins were used to test the general feel, weight, and balance of the *Hyperbow*, an electric violin was used to test the sensing system itself.

The RAAD violin (see Fig. 3.21) was the played with the *Hyperbow* by all of the test subjects for this project. This violin, designed and built by instrument maker Richard Armin of Toronto, Ontario, belongs to the same family of instruments as the original *Hypercello*. Though it has no resonant cavity, it is composed of wood and has a “floating” top plate, i.e. the plate is not affixed to the rest of the instrument with glue, but is simply held in place by the pressure of the assembly. This plate vibrates as the strings oscillate, so that even though the sounds of the RAAD strings are detected by pickups mounted under the bridge and then amplified electrically, the overall sound of the instrument retains some of the characteristics of an acoustic violin.

Figure 3.21: The RAAD violin, designed by instrument maker Richard Armin, is made of wood and contains pickups underneath the bridge of the instrument. It receives power from a 9V battery and has a quarter inch output connector for the amplified audio sound. (Note: In this picture, the fingerboard is covered with a thin film of steel (0.005in) that was previously installed as part of the left hand finger position sensing for the *Digital Stradivarius* project.)

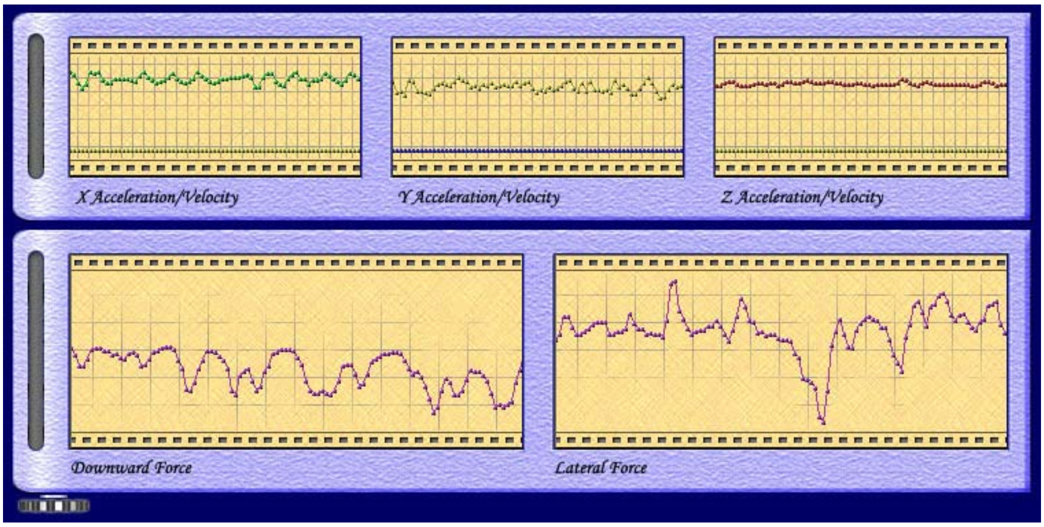


Figure 3.22: The relative accelerations of the bow along the $x$, $y$, and $z$ axes, as well as the downward and lateral force strain measurements were displayed by `Turnkey`.

(For the development of the musical applications involving only the acceleration and strain subsystems the RAAD violin was the principle instrument used, because of the convenience of its audio output. However, an acoustic violin may also be used with a commercial pickup affixed to its bridge.)

## 3.4 Data Visualization

The sensor data for the bow was displayed using a generic program called `Turnkey`, written by Egon Pasztor, a research assistant in the *Hyperinstruments* Group at the MIT Media Lab. The primary function of this program was to receive serial data and display each channel of data on an individual strip chart, or overlay streams of data as appropriate. `Turnkey` also had the ability to record a stream of data and save it to a file.

Two copies of this program were employed–one to display the position data and one to show the accelerometer values for each of the three axes as well as the downward and lateral strains on the bow. (Two separate applications were necessary, as the serial data stream for the bow position was separate from that of the accelerometer and strain sensors.) In order to render the program suitable for these applications, the structure of the serial protocol used was specified within `Turnkey`, the data channels were assigned to appropriate strip charts, and the appearance of the graphical user interface was customized (see Fig. 3.22).

The `Turnkey` display of the position data used three strip charts for the strength of the signal from the tip of the bow, the strength of the signal from the frog of the bow, and the normalized signal denoting the position of the bow.

Before the data could be shown in a helpful way, minor changes had to be made to the raw data received by the Dell Inspiron 3800 laptop (Intel Pentium III 750MHz with 256MB RAM) used for this project. Because the accelerometer values sent by the microprocessor on the bow board were proportional to acceleration (rather than calibrated acceleration values) these numbers were converted via the relation

$$\text{Acceleration} = (\text{Duty Cycle} - \text{Duty Cycle at Zero g})/\text{Duty Cycle per g}. \tag{3.12}$$

As specified in the ADXL202E data sheet, the nominal duty cycle output is $50\%$ at $0$g and $12.5\%$ duty cycle change per g. So acceleration may be calculated as

$$\text{Acceleration (in g)} = ((T_1/T_2) - 50\%)/12.5\% \tag{3.13}$$

where $T_2$ is the period set by an external resistor ($125\text{K}\Omega$) to be 1ms.

In addition to this manipulation of the acceleration data, the data from the strain sensors was offset for visual purposes and scaled to obtain similar dynamic ranges. These kinds of calibrations are necessary despite all efforts to construct strain sensors with identical behaviors because of the irregularities in the individual strain gauge values previously discussed.

Also, the assembly of the third *Hyperbow* left the Wheatstone Bridge circuit designated for the downward force measurement distinctly misaligned with the center axis of the bow. As a result, the downward force sensor was sensitive to the effects of the lateral force on the bow as well. The downward and lateral force sensors were intended to measure two orthogonal forces applied to the bow. However, because of the deficiency in the installation of the gauges as described above, some crosstalk between the two signal paths was inevitable. And in fact, this bow was shown to contain minor coupling between the two force measurements as it was not possible for a player to apply a force on the bow normal to the strings of the bow without simultaneously affecting the value of the lateral strain force.

As a means of decoupling the sensor data, the zero force output for each sensor was measured in order to determine the bias of each sensor. Then the interference in each sensor resulting from an applied force intended for the other was measured. The "true" sensor data could then be computed via a linear transformation constructed from the biased data points through a simple matrix inversion. For given data elements containing the measured values for the downward force $d_s$ and the lateral force $l_s$ the sensor output vector

$$s = [d_s, l_s]T, \tag{3.14}$$

the offset vector c containing the zero-force readings

$$c = [c_d, c_l], \tag{3.15}$$

the unbiased sensor data may be constructed as a linear combination of the biased outputs as

$$t = M(s - c) \tag{3.16}$$

for a given output data vector. The "true" data values may be found by solving the following linear equations:

$$d_t = m_{00}(d_s - c_d) + m_{01}(l_s - c_l)l_t = m_{10}(d_s - c_d) + m_{11}(l_s - c_l) \tag{3.17}$$

To compute the coefficient matrix $M$, we require two data points $(d_{s0}, l_{s0})$ and $(d_{s1}, l_{s1})$ to correspond to $(d_{t0}, l_{t0})$ and $(d_{t1}, l_{t1})$, respectively. So $(d_{t0}, l_{t0}) = (1, 0)$ and $(d_{t1}, l_{t1}) = (0, 1)$. So, we have

$$S = \begin{bmatrix} d_{t0} & d_{t1} \\ l_{t0} & l_{t1} \end{bmatrix} \tag{3.18}$$

$$T = \begin{bmatrix} (d_{s0} - c_d) & (d_{s1} - c_d) \\ (l_{s0} - c_l) & (l_{s1} - c_l) \end{bmatrix} \tag{3.19}$$

$$\begin{bmatrix} d_{t0} & d_{t1} \\ l_{t0} & l_{t1} \end{bmatrix} = \mathbf{M} \begin{bmatrix} (d_{s0} - c_d) & (d_{s1} - c_d) \\ (l_{s0} - c_l) & (l_{s1} - c_l) \end{bmatrix} \tag{3.20}$$

Therefore $M$ is found as

$$M = S \backslash T \tag{3.21}$$

where the \ operator denotes the left matrix division via Gaussian elimination.

## 3.5 Results

The first bow (CodaBow *Colours*) showed a great decrease in the sensitivity of the strain gauges, which was noticeable even within a period of three days. Ultimately, the resistance values of several of the strain gauges failed to change with the flexion of the bow stick. Because of this, it was determined that the foil gauges were no longer properly adhered to the surface of the bow stick. Though considerable care was taken to abrade the surface of the bow before proceeding with the installation of the strain gauges, and the same application techniques were used for this bow as for the preliminary test bow, the weakness of the bonds between the devices and the bow were most probably caused by the properties of the paint applied by the manufacturer. It was decided that any special finish applied to the carbon fiber bow stick renders the bow unsuitable for strain gauge installation. Therefore, all plans to work with the CodaBow *Colours* bow, or indeed any bow lacking a raw graphite surface, were abandoned at this point in this research project.

Like the original test bow used to confirm the operation of the strain gauges, the last two bows altered to carry the *Hyperbow* electronics were made of composite graphite without any chemical applications. None of the strain gauges installed on either of the CodaBow *Conservatory* bows utilized exhibited any problems similar to those on the *Colours* bow. That is, there was no signal degradation over the period of this thesis project. Though data from only the last iteration of the *Hyperbow* is shown in this document, both of these bows were capable of producing reliable and responsive data.

### 3.5.1 Computation of Sampling Frequencies

The position data was sent to a PC workstation at a baud rate of 19200 bps. In the serial protocol used to package the data, each sensor value was sent in a 5 byte packet. Including start and stop bits, there were 50 bits per sensor packet, therefore $2 \times 50 = 100$ bits were necessary to transmit each of the two sensor values corresponding to the strengths of the signals from the tip and the frog once.

The time required to transmit the two position sensor values once was

$$\frac{100\text{bits}}{19200\text{bits/sec}} = 0.005208\text{sec} \approx 5\text{msec}.$$

There was a 1 msec delay written into the firmware code for the PIC16F877 on the position receive board between the time at which the A/D converter was set and the time at which it was read. Therefore, 2 msec must be added onto the total computed time, resulting in a figure of approximately 7 msec for the time it took to send each of the two position sensor values once. So, the sampling rate of the position sensing subsystem was $1/7$msec/sample $\approx 142.86$samples/sec.

The baud rate for the acceleration and strain data was also 19200 bps. As in the case of the position data, the serial protocol used to package this data sent each sensor value within a 5 byte packet. Therefore, including start and stop bits, there were 50 bits per sensor packet. So, $5 \times 50 = 250$ bits were necessary to transmit each of the five sensor values once.

The time required to transmit all five sensor values once was

$$\frac{250\text{bits}}{19200\text{bits/sec}} = 0.01302\text{sec} \approx 13\text{msec}.$$

In the firmware code, there was a 1 msec delay between the time at which the A/D converter was set and the time at which it was read, so, for two strain gauges, 2 msec must be added onto the total computed time. In addition, each of the three digital accelerometer signals had a period of 1 msec, resulting in an increase of 3 msec.

Finally, there was a 6 msec delay after sending each one of the sensor values once. Therefore, the total time spent to sample each sensor once is approximately $13+2+3+6 =$

| Component | Current Drawn |
|---|---|
| Linx 900MHz transmitter | 15mA |
| strain gauge bridges | 6mA (3mA each) |
| PIC | 0.6mA |
| accelerometers | 1.2mA (0.6mA each) |
| remaining components | 3.2mA |
| **TOTAL** | 26mA |

Table 3.2: The itemized power budget for acceleration and strain subsystems. The power for this prototype containing 2 strain sensors composed of $1000\Omega$ gauges has been greatly reduced from that of the first prototype that contained 6 strain sensors using $350\Omega$ gauges.

$24$msec. Thus, the sampling frequency for the acceleration and strain subsystems was $1/24$msec/sample $\approx 41.67$samples/sec. This value, as well as that corresponding to the position sensing subsystem, could easily be improved by increasing the baud rate.

### 3.5.2 Power Budget

The total power drawn by the bow board on the third *Hyperbow* prototype was measured to be 26mA. Below in Table 3.2 appears an itemized list of the power consumption, including the Linx transmitter, the PIC microprocessor, the strain gauge bridges and accelerometers, and the remaining components that comprise the electronics system, i.e., the differential amplifiers (2), NPN transistors (2), and discrete components.

Because the power consumption of the third and final *Hyperbow* prototype was much lower than that of the first, the Panasonic CR-2PA/1B battery used was much larger than necessary in this case, yielding a battery life of approximately 28.85 hours. A smaller, lighter battery may be used in future, as the 26mA demanded by the final version of the *Hyperbow* is well within the capabilities of many batteries.

### 3.5.3 Dynamic Range and System Noise

The firmware read the accelerometer sensor values as 8-bit numbers. During normal play, the accelerometer sensor values were observed to be constrained within a range possible to describe with 7 bits of data. That is, though the output was a number within the range of

0-255, its value never varied by more than 128. Similarly, the strain sensor values, though reported as 10-bit numbers within a range of 0-1023, also were ultimately represented by 7 bits without losing information.

The noise in the acceleration signals was observed to be negligible compared to the signal strength. However, the measurements of the lateral strain gauge signal yielded a noise variance of $0.89\%$, while the downward strain exhibited $1.4\%$. These measurements were taken from the bow while it was vertically suspended and free of all applied forces.

### 3.5.4 Weight and Balance Point

The overall weight of the *Hyperbow* was improved by more than 8.235g in the third version (see Table 3.3). The difference between the balance points of the second and third *Hyperbow* prototypes was of great importance. In the former, the balance point shifted from approximately 25.5cm from the frog end of the bow stick to 30.3cm, and in the latter the addition of the sensing electronics moved the balance point to 21.7cm. (Both of these measurements were taken without the position sensing components.) The shifts in the balance points of the third prototype in both configurations are both much more favorable than that of the second prototype, as a shift toward the tip of the bow results in a great burden on the right hand. Thus, the playability of the third prototype was improved *Hyperbow* considerably. As mentioned above, the position of the balance point may be improved in future by the adoption of a lighter battery.

| Component(s) | Weight (grams) |
|---|---|
| 3V Lithium Battery (750mAH) | 11.212 |
| Unmodified *Conservatory* CodaBow | 60.930 |
| First Bow Board (+ABS mounting strip) | 12.342 |
| 2nd *Hyperbow* (without position sensor) | 97.986 |
| Revised Bow Board | 8.986 |
| 3rd *Hyperbow* (without position sensor) | 85.114 |
| 3rd *Hyperbow* (with position sensor) | 89.751 |

Table 3.3: The largest single contribution to the weight of the *Hyperbow* was the lithium battery. Because the The reduction in the size of the bow board used for the third prototype was a considerable improvement, as the third prototype's weight, even with the position sensing hardware, was more than 8g less than the that of the second.

# Chapter 4

# Evaluation of Sensor System

## 4.1 Users

In addition to the author of this thesis, five other violinists, including Joshua Bell, tested the *Hyperbow* at various stages of its development. The data exhibited in the following section of the document is that given by two experienced players, both with strong backgrounds and committed training in classical music technique.

## 4.2 Examination of Bowstrokes

The initial evaluation of the sensing system for the *Hyperbow* in its final incarnation before the completion of this thesis, the third prototype, began by recording gesture data, from two experienced violinists as they played a series of repeated bowstrokes. The `Turnkey` program recorded the gesture data for the three acceleration and the two strain measurements corresponding to the assigned bowings.

The set of bowstrokes included legato, detache, martele, spiccato, ricochet, and staccato strokes (see Table 4.1). Recordings of each of these were made at four different dynamic levels, as the players were instructed to play at *p*, *mf*, *f*, and *ff* dynamic levels.[1] Of course, the executions of these dynamics indications were subjective, based on the indi-

| Bowstroke | Description |
|---|---|
| Legato | Multiple notes slurred on one bowstroke; smooth transitions between notes, evenness of tone, “on-the-string.” |
| Detache | Steady notes played with separate bowstrokes, smooth changes in bow direction, even strokes with constant pressure applied to the bow, “on-the-string.” |
| Martele | Percussive notes played “on-the string” with separate bowstrokes; accent at the beginning of each note, rest between notes; requires definite preliminary pressure before each note, release of pressure after each note. |
| Spiccato | Notes played “off-the string”, bow leaves the string after completion of each note and drops onto the string for the next, motion of the bow describes an arc so that the bow hair contacts the string at or near the lowest point in the arc. |
| Ricochet | Succession of notes played on one bowstroke, but only one gesture of force is made as the first note is sounded; the following notes are sounded by the independent bouncing of the bow on the string. |
| Staccato | Succession of short, accented notes played on one bowstroke while the hair of the bow remains in constant contact with the string; quick release of pressure on the bow after the completion of each note. |

Table 4.1: For the purposes of evaluating the sensing system of the *Hyperbow*, sensor data was recorded as 6 of the most common bowstrokes were executed by 4 accomplished violinists. Four recordings were made of each bowstroke at constant dynamic levels described as *p*, *mf*, *f*, and *ff*. The bowstrokes were all performed on the same two repeated notes with no vibrato.

vidual player’s interpretation. All of the bowstrokes were performed with the repetition of notes G and A (440Hz) on the D string (fingered by the first and second fingers in third position).

After inspecting the data using MATLAB, it was clear that the sensor data was repeatable, in that violinists were able to reproduce the same data for identical bowing. Data corresponding to a given bowstroke was markedly different from that of another, as expected.

For example, below, data is shown for two players playing a detache stroke (see Fig. 4.1)

[1]In standard music notation, the dynamic references *piano* (*p*), *mezzo forte* (*mf*), *forte* (*f*), and *fortissimo* (*ff*) indicate “quiet”, “moderately loud”, “loud”, and “very loud”, respectively.

followed by a legato stroke (see Fig. 4.2). The lateral force plots for both players of the datache stroke show the same visual characteristics: a rapid oscillation in force that grows slightly throughout the stroke's duration. In contrast, the force plots for the legato strokes have a markedly different appearance, consisting of wide slow peaks and valleys corresponding to greater and lesser force applied throughout the stroke.

Further, note that the ranges of the sensors were adequate, for no bowing was executed that was not visible in the data (i.e. the sensors did not saturate). Most interestingly, data taken from different violinists playing the same bowstroke was remarkably similar for all five sensors, as had been hoped.

In addition to the data collected of individual bowstrokes, recordings were taken of short fragments of solo music, for the simple purpose of observing the natural range of data for each sensor as played by individual violinists.

In each of the sensor recordings an easily recognizable spike was present in the downward force values, as well as in several of the other data streams. This spike was creating by the act of quickly tapping the bow hair on the string just before the commencement of the repeated bowstrokes. This was done in order to provide a means of synchronizing the sensor data with audio data later. For, in addition to the `Turnkey` recordings of the gesture data, recordings of the audio were also attained using MATLAB.

Of course, there was an obvious complication introduced by recording the data by two separate programs. Because the two recordings were initiated individually, one after the other, the data streams were not synchronized with each other. To solve this problem, the players were instructed to bounce the bow onto the string once before beginning the execution of the bowstrokes. Although analysis of the audio data and the sensor data together has not yet been performed, by inspecting the two separate sets of data and compensating for the differences in their sampling rates, it will later possible to align the data plots with respect to each other using the spikes in the audio and the strain and acceleration values corresponding to the bounced bow event as indicators. Such a study of the sensor data and the audio data will provide an interesting account of the degree to which each sensor

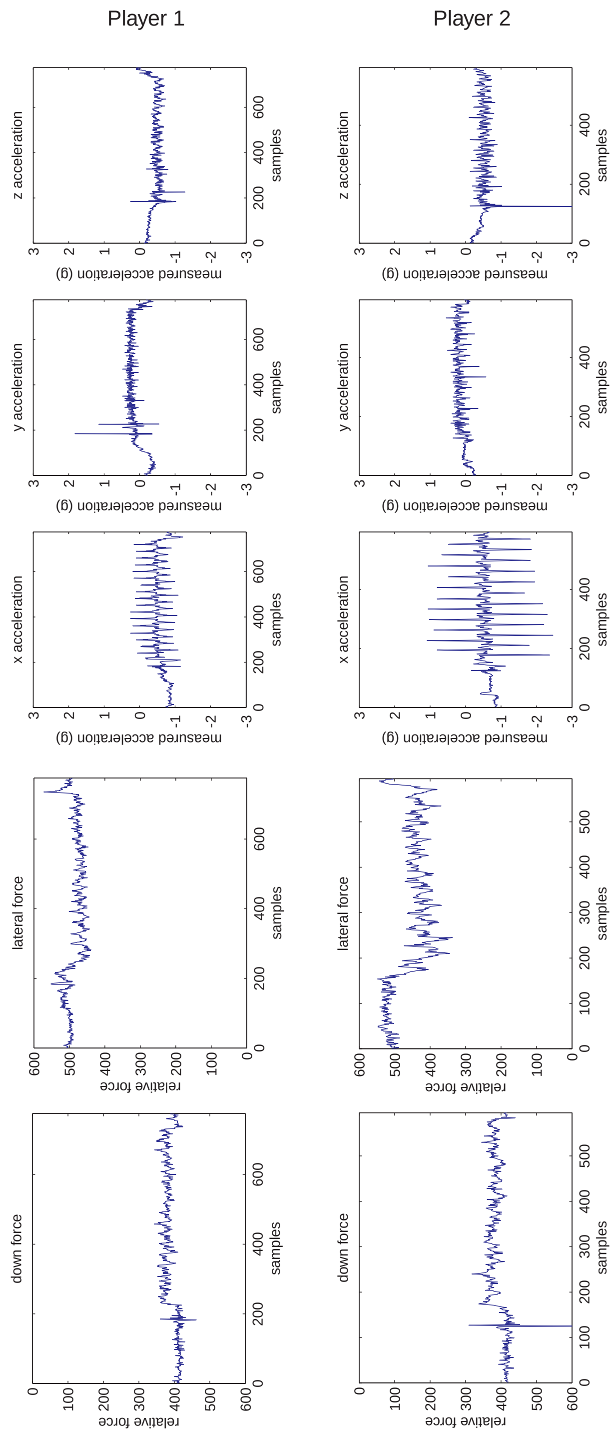


Figure 4.1: The detache bowstroke is performed by drawing a separate stroke for each note. Here, the bowstroke is repeated in alternating pattern with notes G and A on the D string (third position) with two notes per beat at a rate of 72 beats per minute. The start of the detache repetition is preceded by the sharp spike seen most easily in the downward force measurement before sample 200. The behaviors of all five sensors are similar for both players. The change in bow direction is most easily observed from the x acceleration graphs.

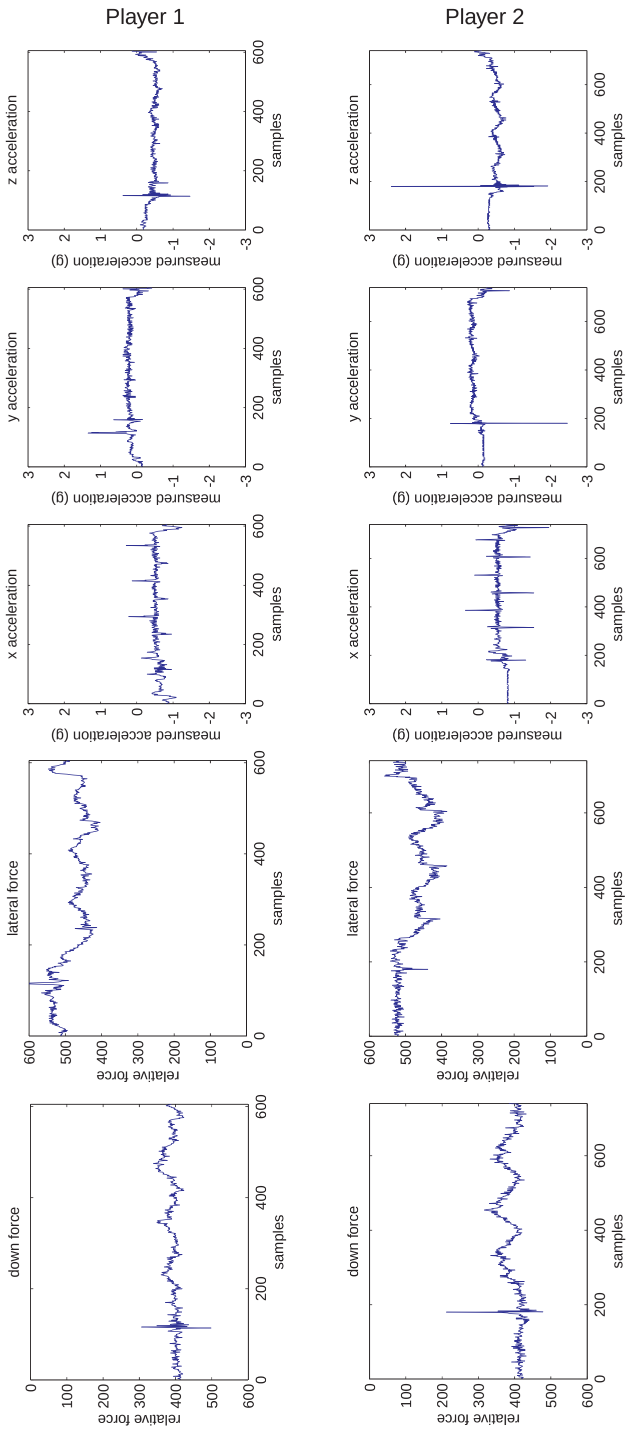


Figure 4.2: The legato bowstroke is performed by drawing the bow to sound a succession of notes. Here, the bowstroke is repeated in alternating pattern with notes G and A on the D string (third position) with two notes per beat (and per stroke) at a rate of 72 beats per minute. The start of the legato repetition is preceded by the sharp spike seen most easily in the downward force measurement before sample 200. The behaviors of all five sensors are similar for both players. As expected, the changes in acceleration for the legato are much more subtle than for the detache.

measurement is extractable from the audio, but this exercise must be accomplished in the future.

## 4.3 User Feedback

Because of the rapid deterioration of the strain sensors in the first experimental bow, very little testing was performed on it. The author as well as Joshua Bell tested the second version of the *Hyperbow*. The performance of the acceleration and strain sensors was determined to be sufficient, both in terms of range and sensitivity, but the physical feel of the interface itself called for improvement.

Though the increase in weight of the bow was considerable, the bow was determined to be manageable, though of course quite different in feel to a traditional bow. After a period of bowing while growing accustomed to the addition of the various wires, it was determined that the attempt to maintain the balance point of the bow, by placing the bow board toward the tip of the bow, rather than on the frog end, as had been done before (*Digital Stradivarius* project), yielded no measurable advantage. The balance point was moved from approximately 25.5cm from the frog end of the bow stick to around 30.3cm after the addition of the bow board, battery, and wires. Because the right hand acts as a kind of lever, with the thumb as the fulcrum, balancing between the forefinger and fourth finger, all of the tasks of control are made more arduous by the addition of weight to the left of the forefinger. Given the choice to add weight at the precise location of the balance point or to the frog end of the bow, under the right hand, it is better to choose the latter so as to reduce excess strain on the right hand.

In the third version of the *Hyperbow*, the bow board was relocated and re-fashioned to fit the frog of the bow. Six players, including the author, tested the third version of the *Hyperbow* and evaluated the comfort of the interface for the left hand. The addition of weight to this bow was reduced from that of the earlier versions of the *Hyperbow*, due to the reduction in the number strain gauge channels and the incorporation of the smaller ceramic package ADXL202E accelerometers, but the weight increase is still marked. However, because of the placement of the board on the frog, the bow was determined to be much less tiring over longer periods of play than the previous version. In this case, the balance point of the bow moved from 10.004 cm from the frog end of the bow stick to 19.8cm. Unfortunately, there was no alternative found to the largest contributor to the weight of the bow, the battery. The sensors on this bow showed no appreciable loss in sensitivity and were deemed quite satisfactory in their response to physical gesture.

The presence of the bow board on the frog was easily tolerated, as the fingers of the right hand have no cause to come into contact with the side of the frog closest to the player. It was noted that special care had to be taken in order to avoid contact between the wires that join the strain gauges in their Wheatstone Bridge configuration and the strings of the violin while bowing. In general this was not a detriment, as the only danger is that the connections of the wires will be broken through direct scraping against the strings, an action that is only likely to occur with extreme pressure on the bow coupled with a larger angle of the right hand wrist than is present under regular bowing conditions. Still, the presence of wires on the bow is one of the greatest disadvantages to this sensing system, as they represent possible points of vulnerability of the system as well discomfort for the player.

## 4.4 Next Steps

The data from the *Hyperbow* has been shown to be repeatable and reliable. The different types of data also span a fairly large range of description of the bowing gestures of a violinist. Together, the rather macroscopic view of bowing described by the position measurements, the illustration of the acceleration forces, and the subtle strain measurements detailing the underlying immediate, physical experiences of the bow stick created by the careful bowing articulations of a violinist, provide several different perspectives from which to view right hand violin technique.

Additionally, it is critical to note that not all of the data produced by the *Hyperbow* can be extracted from the audio, as the lateral force measurement is not generally considered when inspecting oscillations of violin strings. This measurement has also never been incorporated in a violin controller before. The angle of the player's wrist corresponds quite strongly to the value of the lateral force on the bow, and indeed is an important element of any violinist's right hand technique. It is an assertion of this work that this measurement may prove an extremely valuable method of control when designing custom music applications, as a violinist has ready command over it at all times and may also mindfully alter the volume of sound emitted from the violin while independently controlling wrist angle.

# Chapter 5

# Extended Example/Applications

## 5.1 Toy Symphony

The original performance goal for the *Hyperbow* was its inclusion in the Toy Symphony program, as the physical interface of the *Hyperviolin* for soloist Joshua Bell. As such, it was designed to maintain the sophistication of an acoustic violin while exploiting aspects of physical performance made possible only with technological embellishments on the classic design of the violin.

As its name would suggest, the performance of Toy Symphony will feature the playing of toy interfaces. The primary goal of this project is to establish a paradigm in which children can make music with interfaces better suited to them than standard traditional instruments, contributing to the sophisticated performance in a meaningful way, while playing new music toys created specifically for their use.

Because Toy Symphony also aims to introduce children to the world of new music, the inclusion of the *Hyperbow* is furthers this goal. The sensing system might even enable a virtuoso to share or guide the music created by the children, as it could be used to transmit aspects of the violin's music to the toys as starting material. This possibility might allow for new ways of sharing music and mentoring inexperienced players.

Because the position sensing subsystem is a revision of an earlier project, new music applications for this feature were not explored in this project. Instead, emphasis was placed on the creation of new scenarios in which to present the new musical possibilities enabled by the addition of strain and acceleration measurements.

## 5.2 Nord Modular Demo

The initial music application developed for the demonstration of this project utilized the Nord Modular synthesizer, manufactured by Clavia DMI of Stockholm, Sweden. As this device is equipped with MIDI input and output ports, an audio input port, and the ability to download patches from a computer with either a Windows or Macintosh platform, it was ideally suited for the development of simple, portable demonstrations and experimentation.

The audio signal from the RAAD violin was connected directly to the audio input port of the Nord Modular so that the direct sound produced by the instrument while bowed with the *Hyperbow* could be altered with the gesture data extracted from the player's bowing. Communication between the Nord Modular and a Dell Inspiron 3800 laptop for the purpose of creating custom patches was established by means of a USB to MIDI converter, the USB MIDISport 2x2 from Midiman, Inc. of Arcadia, CA (see Fig. 5.1). Creating the interface between the *Hyperbow* and the Nord Modular so that the gesture data could be assigned to MIDI controllers within the patch was more complicated.

The data from the bow was transmitted at a baud rate of 19200bps with a resolution of 10 bits for the strain data and 8 bits for the accelerometer data (see §3.1.2). Because MIDI data must be transferred at a baud rate of 31250bps and may have a resolution of only 7 bits, the bow data had to be translated accordingly (see Fig. 5.2). The level of the signal from the serial cable carrying the bow data was reduced by means of a MAX232 chip (manufactured by Maxim Integrated Products, Inc., of Sunnyvale, CA.) from the 0-9 Volt range to 0-5 Volt range. The task of translation was accomplished by a PIC16F877–the high-voltage version of the PIC on the bow board. The firmware for this microprocessor was written to receive the data from the strain and acceleration sensors, truncate it, and

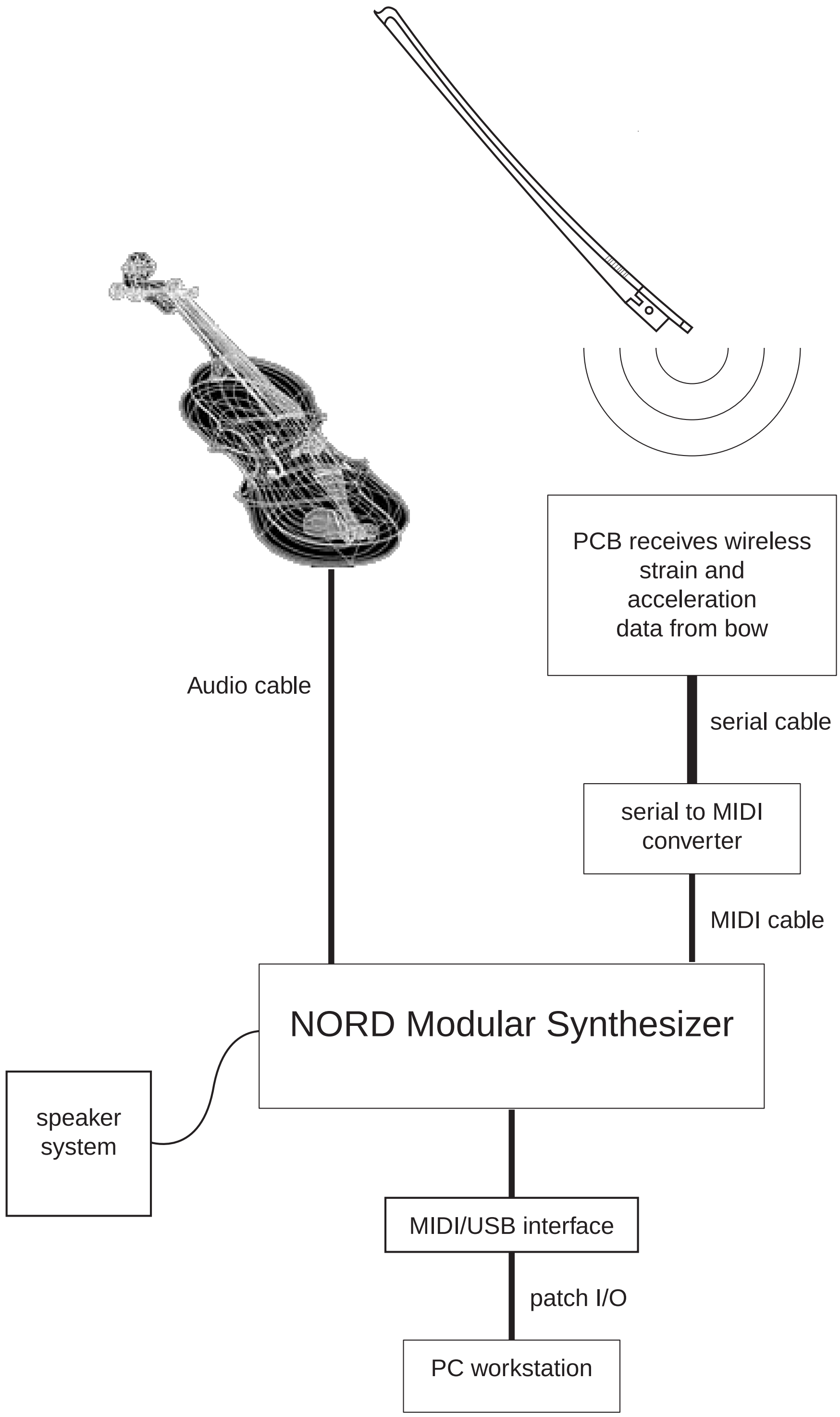


Figure 5.1: The Nord Modular demo system was constructed by connected the audio output of the RAAD violin to the audio input of the Nord Modular. The patch was designed on a PC workstation that communicates with the Nord Modular via a USB MIDISport Midiman MIDI/USB interface. The serial data from the *Hyperbow* was converted to MIDI data by a simple breadboarded circuit and then sent to the MIDI input port of the Nord Modular. The *Hyperbow* was therefore able to manipulate the sound of the audio of the RAAD violin in real-time using 5 MIDI controllers that were mapped to its 5 channels of acceleration and strain data.

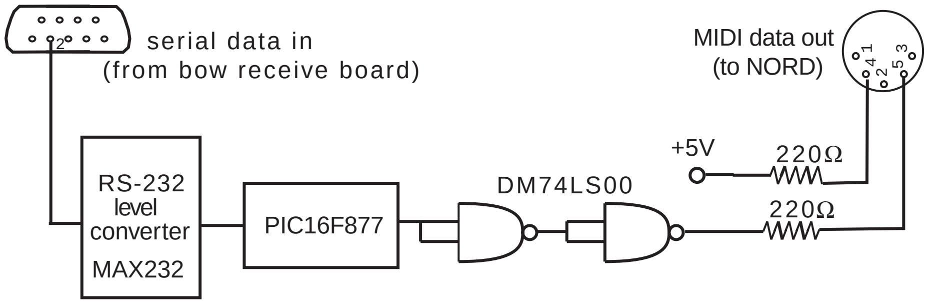


Figure 5.2: The serial to MIDI converter used in the Nord Modular demo setup was constructed with a MAX232 RS-232 level converter (to bring the serial signal down to the 0-5V range); a PIC16F877 microprocessor that read the serial data, truncated it to the 7-bit MIDI range, and sent it out in MIDI format; and a DM74LS00 NAND gate chip used to buffer the signal before sending it through the MIDI port.

scale it down so that it fell within the range of 0-127. The data was then sent out at the rate of 31250bps through a MIDI cable to the MIDI input port of the Nord Modular.

It is important to note that the truncation and scaling of this data was possible without diminishing the range of the sensors, as they were each only active within a 7-bit range. However, it was still an advantage to have the high resolution of the 8-bit digital accelerometer data and the 10-bit strain data (given by the A/D converter in the PIC16LF877), as the 7 bits used to describe each sensor value in the MIDI protocol represented a value at higher resolution.

This music demonstration incorporated very simple transformations of the original violin sound, such as delays, filters, and equalization. As it was a very preliminary experiment, focus was first placed on functionality. There remains much to do to develop this music application.

## 5.3 Deeper Exploration/New Modes of Expression

Though it was designed to be an interface for a virtuoso violinist with a traditional classical music background, the *Hyperbow* is meant to be an alternative for any violinist, or indeed, for any player of a bowed string instrument. By offering possibilities for the real-time alteration of acoustic or electric sound though gestures familiar and learned by the player, the *Hyperbow* offers an endless supply of new sounds and musical options. The *Hyperbow* enables players to view, inspect, and exploit the subtlety of their bowing.

The acceleration measurements allow the possibility to affect the sound of the violin while the bow is not in contact with an open string. For instance, a player might use the bow in air to perturb the music.

The new sensing system described in this thesis offers many new performance scenarios to a violinist. For instance, a traditional acoustic violin may be played with the use of the enhanced bow to control parameters in a sound synthesis engine. This may produce the sound of a different instrument by altering the raw material of the audio signal generated by the resonance of the violin and amplifying the transformed signal in real-time. As the player makes the changes in the acceleration and the pressure of the bow on the strings that result in the differences in the amplitude and attack of the violin's sound, she may not only affect the same elements of the new synthesized sound (amplified above the vibration of the actual string sound), but may also use the bow as a means of switching between sounds and adding additional effects (i.e. reverberation). So, one may play a transcription of a violin piece, such as an unaccompanied Bach sonata, that is composed for more than one "voice".

Similarly, one may also imagine an opportunity to articulate selected components of the harmonic content of the violin's sound by use of this enhanced bow. For instance, one may use the strokes of the bow to amplify, individually or in small groups, the harmonics sounded above any pitch played so as to subtly shape the timbre of the music. In fact, one may amplify certain harmonics to such a degree that they are perceived as additional pitches, so that with great care a player may induce with her bow melodies above that which she is fingering on the strings.

The greatest hope for this bow lies in the value of the strain measurements, as they provide a much different perspective of bowing technique than has been incorporated into any similar music controller in the past. Though other types of data, such as position measurement are interesting to employ in music applications, and indeed incredibly useful for analysis, they may present obstacles for the creation of new and unique music applications. For instance, position data, which allows one to inspect the movement of the bow across the strings between the tip and the frog, can often encourage one to consider the bow as a slider on a mixing board. This analogy works brilliantly, for a player can immediately understand the aural consequence of the physical gestures of the movement back and forth of the bow. Also, this movement is very controllable and readily separable from the primary functions of bowing to determine volume of sound, rhythm, etc. However, it often becomes difficult to create new kinds of sound manipulation when the technique used to generate the changes remains so linear.

As the *Hyperbow* is a new instrument, with different capabilities than a tradition bow, it is hoped that future experimentation with the *Hyperbow* may lead to altogether new bowing techniques.

# Chapter 6

# Future Work

There is much that remains to be done in the progress of the interface described in this thesis and in the expansion of this work into related projects.

Some of the simplest tasks that could be completed in order to extend the work documented in this thesis include merging the position sensing subsystem with the acceleration and strain subsystems, as well as adding bow-bridge distance measurements (essentially the second component of position sensing). Also, the sensing system of the *Hyperbow* could be adapted to be used with the viola, cello, or double bass.

More can be done to analyze the data collected by the *Hyperbow* in order to better describe and classify given bowstrokes and differences in playing styles between violinists. Such knowledge may even be used to enhance teaching tools and techniques.

There is much exciting progress to be made in improving the interface of the *Hyperbow* in order to make it more comfortable to play, to reduce the vulnerability of the sensing system, and to better accommodate the technological enhancements within the form of the bow. The construction of a custom designed bow that better houses the sensing system may also necessitate the design of custom devices, such as strain sensors, whose form factor and material properties are better suited to this application.

Research may be done to exploit the sensing techniques to help create models of bow gestures. The two strain sensors currently present can be consciously controlled by the player somewhat independently of those actions essential for producing sound on the violin. Therefore, these sensors are extremely valuable as music controllers. However, from a scientific viewpoint, there is value in investigating the manner in which the bow flexes and strains along its length during play. Additional strain sensors may be added to the bow stick in order to measure these behaviors.

Also, the possibility of using the *Hyperbow* to play already existing models of bowed strings, or indeed models of altogether different sounds, may be pursued. This might enable a person who has particular skill playing a violin to play other instruments in a style that is somewhat violinistic.

Just as the *Hyperbow* project centered on the desire to capture the smallest articulations of the violin bow to develop new avenues of expression for a player, the concept of accomplishing the same task for the articulations of the left hand fingers on the violin fingerboard is clear. By building a fingerboard that may be incorporated into the design of an acoustic or electric violin (most likely an electric violin, due the fragility of the wood in an acoustic instrument) that measures multi-point position and pressure, one might begin to see the corresponding details of musical expression found in the study of the bow gestures. Perhaps this would enable the development of new left hand violin technique and new fingerboard interfaces separable from the violin itself.

One might also hope that the design and construction of new bows would inspire the development of new stringed instruments. New instruments that perhaps require less proficiency of the left hand, or even no left hand technique whatsoever, may be built to compliment the complexity of new bowing techniques.

The future of the violin is wide open. The possibilities to make new music in ways that are idiomatic to this classic instrument, its technique, and its sound are seemingly endless. One of the most important features of violin performances to maintain though, is the emphasis on the performer and her mastery of the instrument.

# Chapter 7

# Conclusion

The work outlined in this thesis endeavored to reveal the sophistication of physical gestures necessary to play a bowed string instrument, capture descriptions of these gestures through measurement, and show the possibilities for exploiting these individual degrees of control in order to manipulate the sound of a violin in new ways.

The *Hyperbow* project successfully incorporated the three sensing subsystems for bow position, acceleration, and strain. However, special focus was given to the acceleration and strain sensors throughout the development of this work. Improvements were made in the implementation of the overall system as only the most controllable strain measurements were maintained, downward and lateral strain, reducing the total number of strain sensors from the initial number of six. This change, in addition to various changes in chip size, board design, and mounting techniques, improved the physical interface of the *Hyperbow*.

Examinations of data taken for six different bowstrokes indicated that the acceleration and strain measurements were reliable. That is, they were consistent and repeatable and different for each bowstroke. In studying the data, it was also observed that the two types of strain data exhibit behaviors that are not easily inferred by the audio sound of the strings. Especially in the case of the lateral strain sensor, these force measurements were extremely interesting as they offered two degrees of control that are easily separable from the minimal action necessary to produce sound on the violin.

The sensing system of the *Hyperbow* illuminated the tactile nature of playing with the violin bow and the physical interactions between a player and an instrument. These physical interactions are fundamental to music, for music cannot be understood simply through audio analysis. As proven by the continued interest in hearing and seeing live music performances in person despite the proliferation of music media, the remaining admiration for noisy recordings of the past and present day, and the desire of many to make music themselves, there is an essential physicality to music. This important aspect of physicality, of forces applied to an instrument that are naturally musical, was an ideal embraced by the creation of the *Hyperbow*.

One of the most important beliefs motivating this work was that fine instrument-making should continue to evolve. The goal was not to in any way replace beloved traditional instruments, but rather to try to further exploit the features that make them so compelling, with respect to the quality of the sounds they produce and the physical interfaces they provide. The *Hyperbow* was designed to be a new type of bow, offering possibilities not available from a traditional violin bow, while of course losing some of the traits of the classical model as well. Throughout its progress however, the *Hyperbow* maintained the features of the natural violin sound and how it is produced and the intricacy of right hand bowing technique.

The *Hyperbow* project signals the beginning of a new level of expressive measurement in violin controllers that may help to better describe the musicality inherent in violinistic gestures. The creation of such new musical instruments that may begin to approach the sophistication in sound production and physical technique essential to the violin may not only lead to the creation of new music, but also to new ways for performers and audience members to share in it.

# Bibliography

[AJ92] Anders G. Askenfelt and Erik V. Jansson. On vibration sensation and finger touch in stringed instrument playing. *Music Perception*, 9(3):311–349, 1992.

[Ask86] A. Askenfelt. Measurement of bow motion and bow force in violin playing. *Journal of the Acoustical Society of America*, 80(4):1007–15, Oct. 1986.

[Ask89] A. Askenfelt. Measurement of the bowing parameters in violin playing. II. bow-bridge distance, dynamic range, and limits of bow force. *Journal of the Acoustical Society of America*, 86(2):503–16, Aug. 1989.

[Ask91] A. Askenfelt. Voices and strings: Close cousins or not? In Johan Sundberg, Lennart Nord, and Rolf Carlson, editors, *Music, Language, Speech and Brain*, pages 243–255, Wenner-Gren Center, Stockholm, September 1991. Dept. of Speech Communication and Music Acoustics, Royal Institute of Technology, Stockholm, Sweeden, Macmillan Press.

[Aue80] Leopold Auer. *Violin Playing As I Teach It*. Dover Publications, New York, reprint edition, 1980.

[Bea97] James Beament. *The Violin Explained: Components, Mechanism, and Sound*. Clarendon Press, Oxford, U.K., 1997.

[Bis93] G. Bissinger. Merging microphone and accelerometer hammer-impact modal analysis measurements: Working example–the violin bow. In *Proceedings of the 11th International Modal Analysis Conference*, pages 850–854, 1993.

[BW99] X. Boutillon and G. Weinreich. Three-dimensional mechanical admittance: Theory and new measurement method applied to the violin bridge. *Journal of the Acoustical Society of America*, 105(6):3524–33, June 1999.

[Cha88] Chris Chafe. Simulating performance on a bowed instrument. Technical Report STAN-M-48, Center for Computer Research in Music and Acoustics (CCRMA), Department of Music, Stanford University, May 1988.

[Cre84] Lothar Cremer. *The Physics of the Violin*. MIT Press, Cambridge, MA, 1984.

[GA97] K. Guettler and A. Askenfelt. Acceptance limits for the duration of pre-helmholtz transients in bowed string attacks. *Journal of the Acoustical Society of America*, 101(5):2903–13, May 1997.

[Gal62] Ivan Galamian. *Principles of violin: playing and teaching*. Prentice-Hall, Englewood Cliffs, N.J., 1962.

[Lip94] Richard Lipkin. To build a better violin: Can science determine why some instruments sound great? *Science News*, 146:152–153, September 1994.

[Mac85] Tod Machover, editor. *Musical Thought at IRCAM (Contemporary Music Review, Volume 1, Part 1)*. Harwood Academic, April 1985.

[Mac92] Tod Machover. Hyperinstruments: A progress report 1987-1991. Technical report, MIT Media Laboratory, 1992.

[Mat86] Max Matthews. Electronic violin: A research tool. *Violin Society of America*, VIII(1):70–88, 1986.

[MC89] Tod Machover and Joe Chung. Hyperinstruments: Musically intelligent and interactive performance and creativity systems. In *Proceedings of the 1989 International Computer Music Conference*, pages 186–190, San Francisco, CA, 1989. Computer Music Association.

[MG00] Inc. Measurements Group. Interactive guide to strain measurement technology. http://www.measurementsgroup.com/guide/guide.htm, October 2000.

[MK73] M. V. Matthews and J. Kohut. Electronic simulation of violin resonances. *Journal of the Acoustical Society of America*, 53(6):1620–1626, 1973.

[MSW83] M.E. McIntyre, R.T. Schumacher, and J. Woodhouse. On the oscillations of musical instruments. *Journal of the Acoustical Society of America*, 74(5):1325–45, Nov. 1983.

[Nak00] Teresa Marrin Nakra. *Inside the Conductor's Jacket: Analysis, Interpretation and Musical Synthesis of Expressive Gesture*. PhD thesis, MIT, Cambridge, MA, February 2000.

[Nic00] Charles Nichols. The vBow: A haptic musical controller human-computer interface. In *ICMC Proceedings*, 2000.

[Nic01] Charles Nichols. The vBow: Two versions of a virtual violin bow controller. In *ISMA Proceedings*, 2001.

[O'M00] C. C. Sile O'Modhrain. *Playing by feel: Incoroprating haptic feedback into computer based musical instruments*. PhD thesis, Stanford University, 2000.

[OSCSI00] S. O'Modhrain, S. Serafin, C. Chafe, and J. O. Smith III. Qualitative and quantitative assessment on the playability of a virtual bowed-string instrument. In *Proceedings of the 2000 International Computer Music Conference (ICMC2000)*, pages 66–69, Berlin, 2000.

[OSSI00] C. C. Sile O'Modhrain, Stefania Serafin, and J. O. Smith III. Influence of attack parameters on the playability of a virtual bowed string instrument: Tuning the model. In *Proceedings of the 2000 International Computer Music Conference*, Berlin, August 2000.

[Par97] Joe Paradiso. Electronic music interfaces: New ways to play. *IEEE Spectrum*, 34(12):18–30, 1997.

[PG97] Joseph Paradiso and Neil Gershenfeld. Musical applications of electric field sensing. *Computer Music Journal*, 21(3):69–89, 1997.

[Pic91] N. C. Pickering. A new light on bow action. *J. Violin Soc. America*, 11:83–92, 1991.

[RM69] Jean-Claude Risset and Max Matthews. Analysis of musical-instrument tones. *Physics Today*, XXII(2):23–30, February 1969.

[Roa98] Curtis Roads. *The Computer Music Tutorial*. MIT Press, Cambridge, MA, 1998.

[SAF83] J. Sundberg, A. Askenfelt, and L. Fryden. Musical performance: a synthesis-by-rule approach. *Computer Music Journal*, 7(1):37–43, Spring 1983.

[Sch73] J. C. Schelleng. The bowed string and the player. *Journal of the Acoustical Society of America*, 53:26–41, 1973.

[Sch75] R. T. Schumacher. Some aspects of the bow. *Catgut Acoustical Society Newsletter*, 24:5–8, 1975.

[Sch00] Bernd Schoner. *Probabilistic Characterization and Synthesis of complex Driven Systems*. PhD thesis, MIT, 2000.

[SSIW99] S. Serafin, J.O. Smith III, and J. Woodhouse. An investigation of the impact of torsion waves and friction characteristics on the playability of virtual bowed strings. *Proceedings of 1999 Workshop on Applications of Signal Processing to Audio and Acoustics*, pages 87–90, 1999.

[Sto92] Robin Stowell, editor. *The Cambridge Companion to the Violin*. Cambridge University Press, Cambridge, U.K., 1992.

[SW00] J.H. Smith and J. Woodhouse. The tribology of rosin. *Journal of the Mechanics and Physics of Solids*, 48(8):1633–81, Aug. 2000.

[TC99] Dan Trueman and Perry R. Cook. Bossa: The deconstructed violin reconstructed. In *Proceedings of the ICMC*, Beijing, 1999.

[vH54] H. von Helmholtz. *On the Sensations of Tone*. Dover Publications, reprint edition, 1954.

[WC91] G. Weinreich and R. Causse. Elementary stability considerations for bowed-string motion. *Journal of the Acoustical Society of America*, 89(2):887–95, Feb. 1991.

[Wei93] G. Weinreich. Klopsteg memorial lecture (august, 1992): What science knows about violins-and what it does not know. *American Journal of Physics*, 61(12):1067–77, Dec. 1993.

[Woo92] J. Woodhouse. Physical modeling of bowed strings. *Computer Music Journal*, 16(4):43–56, Winter 1992.

[WSG00] J. Woodhouse, R.T. Schumacher, and S. Garoff. Reconstruction of bowing point friction force in a bowed string. *Journal of the Acoustical Society of America*, 108(1):357–68, July 2000.