# The vBow: a virtual violin bow controller for mapping gesture to synthesis with haptic feedback

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**The vBow, a virtual violin bow musical controller, has been designed to provide the computer musician with most of the gestural freedom of a bow on a violin string. Four cable and servomotor systems allow for four degrees of freedom, including the lateral motion of a bow stroke across a string, the rotational motion of a bow crossing strings, the vertical motion of a bow approaching and pushing into a string, and the longitudinal motion of a bow travelling along the length of a string. Encoders, attached to the shaft of the servomotors, sense the gesture of the performer, through the rotation of the servomotor shafts, turned by the motion of the cables. The data from each encoder is mapped to a parameter in synthesis software of a bowed-string physical model. The software also sends control voltages to the servomotors, engaging them and the cables attached to them with a haptic feedback simulation of friction, vibration, detents and elasticity.**

## 1. MOTIVATION

The vBow was developed in response to the need for a reliable, expressive human computer interface, based on the paradigm of the violin. As a composer and performer of interactive computer music, I found using a MIDI violin as a controller problematic. The translation of the signal from a violin string vibrating on a piezoelectric sensor into MIDI pitch and velocity data was prone to error, and the latency of the system caused a disconnect between my performance on the instrument and the audible musical result.

My original idea, to design a controller that solely mapped the violinist's gesture to synthesis parameters, was challenged by my learning of the experiments in haptic feedback conducted by Sile O'Modhrain and Chris Chafe at Stanford University's CCRMA. Through their experiments, they discovered that the inclusion of haptic or kinesthetic feedback in a performance system improves playability and quickens the performer's response to the system (Chafe and O'Modhrain 1996, O'Modhrain and Chafe 2000a, b).

With this new understanding of the importance to performers of the haptic feedback of an instrument, I decided to design the vBow to provide the player kinesthetic cues similar to those received from bowing an acoustic violin string. The vBow would map haptic cues to the kinesthesia of the performer in parallel with mapping the bowing gesture to sound synthesis parameters.

## 2. BACKGROUND

Other research has also explored the importance of force-feedback for musical performance. Anders Askenfelt and Erik Jansson, from the Royal Institute of Technology in Stockholm, studied the vibrations of several acoustic stringed instruments, concluding that the kinesthetic feedback of these vibrations assist with intonation and timing during performance. In the specific case of the violin bow, measurements were taken from the bottom and back of the frog, and the transverse and longitudinal vibrations were found to be within the limits of perception, for the lowest two strings. Also, the catch and release of the string, due to the friction between the bow and string, was found to help with timing, for accented notes and at bow changes (Askenfelt and Jansson 1992).

In other related work, four researchers, Jean-Loup Florens, Aime Razafindrakoto, Annie Luciani and Claude Cadoz, working for the Association pour la Crèation et la Recherche sur les Outils d'Expression (ACROE) and the Laboratoire d'Informatique Fondamentale et d'Intelligence Artificielle (LIFIA), developed an interface which sensed the transverse velocity and vertical force of a bowing gesture. This sensor data was used to simulate the acoustics of a vibrating string, according to a friction model, which related bow velocity to bow force, in a nonlinear function (Florens *et al.* 1986).

This research was continued by Jean-Loup Florens and Cyrille Henry, in the development of the CORDIS-ANIMA system, which uses a force-feedback interface, comprising a multi-axis actuator and two-axis joystick, to drive a bowed-string physical model. The physical model is constructed from a bow mass and a string made of twenty-five to sixty masses, which are coupled with a nonlinear stick-slip friction model. In addition to mapping bow stroke and pressure from the interface to the bowed-string physical model, the system produces the force feedback of pulses, resulting from the bowing force, through the interface (Florens and Henry 2001).

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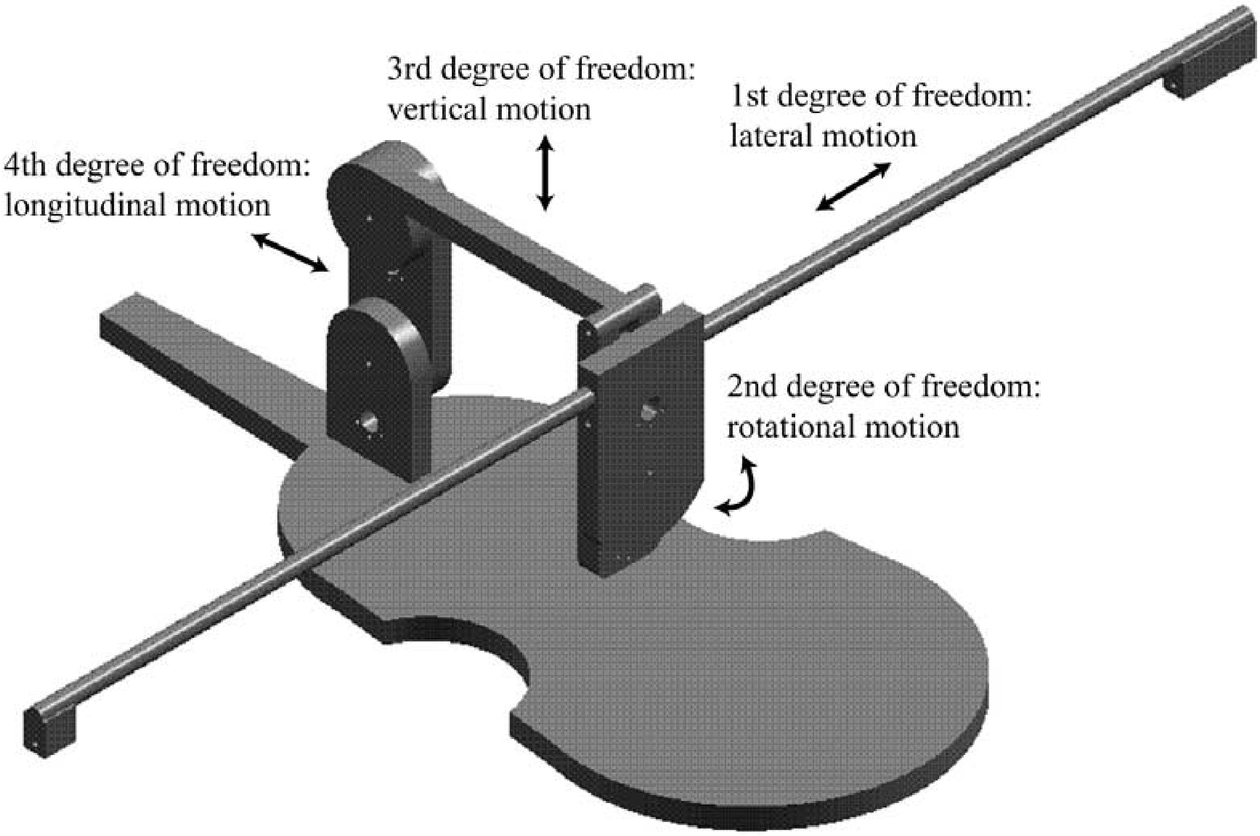


**Figure 1.** The vBow: degrees of freedom.

## 3. CONSTRUCTION

The vBow is constructed from acrylic and fibreglass pieces, servomotors, aluminium capstans, nylon-coated stainless steel cable, and various fasteners. Each acrylic piece was laser cut and further machined with a mill. The capstans were turned on a lathe from an aluminium rod, and attached to the shafts of the servomotors with setscrews. The Maxon Precision Motors (http://www.maxonmotor.com/) servomotors were selected for their torque, and the encoders were chosen for their precision. The Sava Industries (http://www.savacable.com/) cable was selected for its strength and small diameter (Nichols 2000).

The instrument is assembled from eight acrylic pieces and one fibreglass stick. At the base of the vBow is a violin-shaped body, with holes drilled through its height, through which screws secure the rest of the instrument to the body. Attached to the body is a base, which houses the servomotor with encoder that senses longitudinal motion, and provides the haptic feedback of friction, as the bow travels along the length of the virtual string.

Fastened with a threaded pin to the base is the longitudinal piece, which rides along its curved edge over the capstan attached to the servomotor below. A cable, secured at the ends of the curved edge with two screws, lies along the curved edge and wraps around the adjacent capstan. The longitudinal piece moves back and forth, travelling the distance equal to that of a bow moving from *sul ponticello* to *sul tasto* in relation to the violin bridge, while turning the capstan and servomotor with the cable. The servomotor with encoder that senses vertical motion above and into the virtual string, and provides the haptic cue of bow pressure and string elasticity, is also attached to this longitudinal piece.

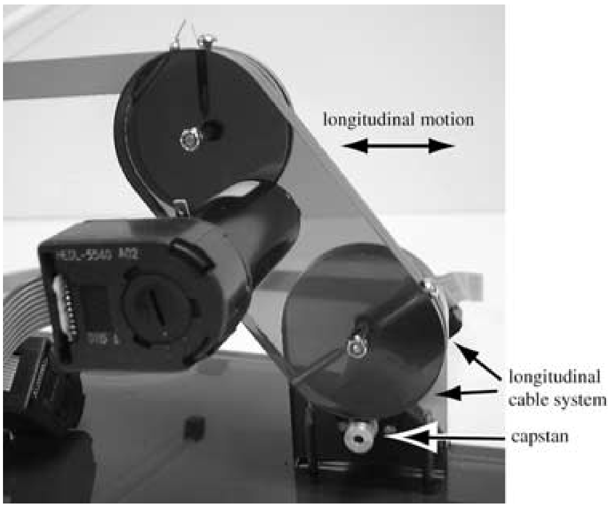


**Figure 2.** Longitudinal motion.

Similarly, an arm that extends over the violin-shaped

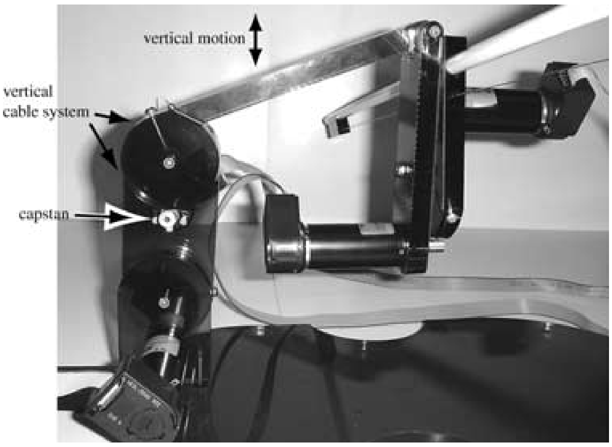


**Figure 3.** Vertical motion.

body is attached with a threaded pin to the longitudinal piece, and holds the cable that wraps around the capstan attached to the servomotor below. The cable is terminated at one end of the curved edge with a ball and shank in a hole drilled through the depth of the arm, and is secured at the other end with a screw. As the arm is lifted above the body, the curved edge rides atop the capstan, the attached cable spins the capstan and servomotor below, and the encoder senses the vertical position of the virtual bow.

The rotational piece is attached to the end of the arm with another threaded pin in such a way that it swings freely. This rotational piece holds the servomotor and encoder that senses the rotation of string crossings and provides the haptic feedback of the bow making contact with each virtual string. The housing is attached to the rotational piece with a threaded pin, so that it swivels freely at the radius of the top curve of a violin bridge. Its cable is secured at either end of this curve with two screws, and wraps around the capstan attached to the servomotor below. As the housing swivels, the curved edge rides along the top of the capstan, the cable spins the capstan and servomotor shaft, and the encoder reads bow position across the four virtual strings.

Two holes drilled through the width of the housing serve as a cable guide hole and a smooth bore through which the fibreglass stick passes. Secured to the housing, just below the cable guide hole, is the servomotor with encoder that senses bow stroke velocity and direction, and provides the haptic feedback of friction and vibration, as the vBow is drawn across the virtual string.

At either end of the fibreglass stick is an acrylic tip and frog. The tip is fastened to the stick with two screws, while the frog is attached to the stick with a standard bow-tightening screw and eyelet. The bow-tightening screw fits into a hole drilled through the length of the stick, while the eyelet rests in a groove carved out of the bottom edge of the stick. A length of cable is terminated at the tip with a ball and shank, runs through the length of the tip and through the cable guide hole in the housing, wraps around the capstan attached to the housing servomotor, runs through the length of the frog, and is terminated at the frog with another ball and shank. As the stick is drawn back and forth through the housing, the cable spins the capstan attached to the housing servomotor, and the encoder senses bow velocity and direction.

## 4. APPLICATION

The previous version of the vBow, a one-degree-of-freedom device, comprised the same stick, tip and frog, and a variation of the housing of the current version (Nichols 2000). It was used to test the expressivity of a bowed-string physical model, and the efficacy of the haptic feedback of friction and vibration (Nichols 2001). The current version of the vBow will be used both as an expressive controller to perform interactive computer music, and as an instrument to experiment with various synthesis and force-feedback models. The software for the current version of the vBow provides for mapping the encoder readings to synthesis parameters, and mapping the haptic cues associated with the different kinds of motion to the servomotors.

The vBow was developed with specific mappings in mind. Each degree of freedom of the interface was designed to emulate a component movement of the bowing gesture. Lateral, rotational, vertical and longitudinal motions were intended to provide data to synthesis parameters, imitating the acoustic response produced by a violin bow moving similarly on a string. Likewise, the mapping of haptic feedback to the degrees of freedom of the interface were intended to imitate the kinesthetic feedback produced by a violin bow moving analogously on a string.

The synthesis software for the vBow was written using the Synthesis ToolKit (STK) (http://www-ccrma.stanford.edu/software/stk/), a collection of C++ objects for computer generated sound (Cook and Scavone 1999). The bowed-string physical model used was based on research by Michael McIntyre, Robert Schumacher, Julius Smith and James Woodhouse, was coded as an STK object by Perry Cook, and developed further by Stefania Serafin.

These developments of the bowed-string physical model came out of research conducted by Stefania Serafin, Christophe Vergez and Xavier Rodet, in which a hyperbolic friction model, a function of bow force and transverse string velocity minus bow velocity, is used to represent the bow–string interaction (Serafin, Vergez and Rodet 1999).

Because both the bowed-string physical model and the vBow were developed according to the physical position and motion of the bow, as it interacts with the string, mapping the different types of motion of the vBow to the synthesis parameters of the physical model was a natural fit.

The control software was also written in C++, using

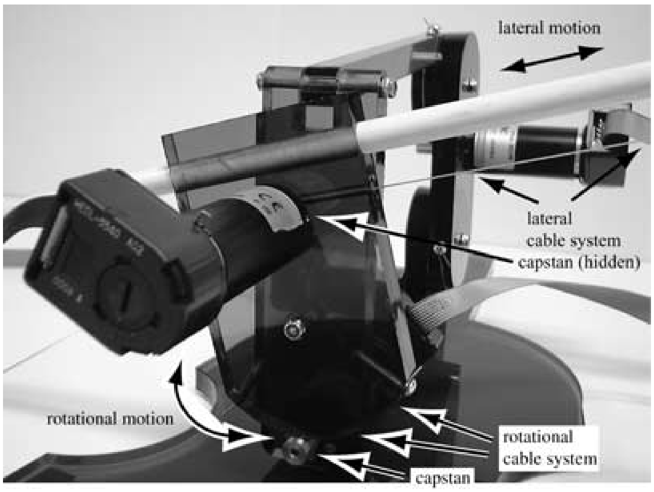


**Figure 4.** Rotational and lateral motion.

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

The stick-slip-slide friction model, used for the haptic feedback for both the lateral and longitudinal motion, was developed by Vincent Hayward and Brian Armstrong, from the Dahl friction model. For both friction models, position $w$ of an adhesion point is subtracted from position $x$ of a moving mass, producing value $z$, which can be understood as the strain of a spring connecting $x$ and $w$. When $z$ reaches maximum strain, $w$ breaks from its stuck position, and slides in parallel with $x$. In the case of the Hayward and Armstrong model, variable alpha, which is a function of $z$, is added to the equation, allowing for $z$ to exceed maximum strain, causing $w$ to slip and stick again (Hayward and Armstrong 2000).

The software maps the sampled encoder readings for lateral motion to the string velocity parameter of the bowed-string physical model. As the user draws the vBow, the cable attached to the stick turns the capstan attached to the servomotor shaft, and the encoder reads the shaft rotations. These sampled encoder readings are then used as bow velocity data for the hyperbolic friction model used to represent bow–string interaction in the bowed-string physical model.

The brightness of the bowed-string timbre produced by the physical model varies with the speed of the virtual bow. As the user draws the vBow slowly, the synthesis software produces a dark and scratchy sound similar to that produced by drawing a bow over a violin string too slowly to produce a steady-state tone. As the user draws the vBow quickly, the synthesis software produces a thin and fuzzy sound similar to *flautando*. And, as the user draws the vBow at a steady, optimal velocity, the synthesis software produces a clear bowed-string timbre.

The software also maps the stick-slip-slide friction model mentioned above to the servomotor for lateral motion. As the user draws the vBow, the sampled encoder readings are used as position $x$ of the moving mass in the friction model. The feel of the friction model can be adjusted by choosing different values for the point of maximum strain for $z$, and the point where $z$ causes adhesion point $w$ to slip, essentially changing the size of the spring. The stiffness of spring $z$ can also be adjusted, scaling the overall frictional force.

The output of the bowed-string physical model is also mapped to the servomotor for lateral motion, providing a haptic feedback of vibration that relates directly to the sound synthesis. Because the vibration can be applied to the servomotor independent of the friction model, both can be studied and tuned separately. Similarly, the software maps the encoder count for rotational motion to the frequency parameter of the bowed-string physical model. As the vBow rotates through four regions, the bowed-string sound synthesis changes pitch, playing each of the four frequencies of the open strings of the violin.

The haptic feedback of detents is mapped to the servomotor for rotational motion, simulating the feel of a bow rolling over the round surface of a violin string, as it crosses strings. This force feedback of detents is produced by applying an opposing force to the servomotor and cable system, that increases to maximum halfway up the slope of the round surface, decreases to the top, reverses direction increasing to maximum halfway down the slope, and decreases to the bottom.

Likewise, the software maps the data from the encoder that senses vertical motion to the bow force parameter of the bowed-string physical model. As the vBow moves downward towards the violin-shaped body, the increasing sampled encoder count is used as the bow

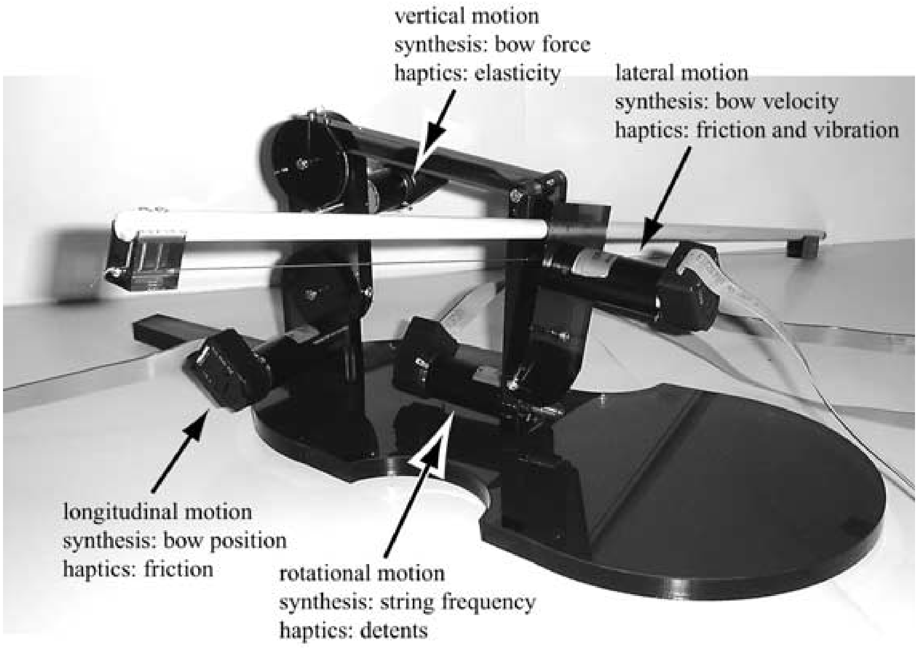


**Figure 5.** The vBow: servomotor and encoder mapping.

force value for the hyperbolic friction model of the bowed-string physical model. As bow force increases, the strength and loudness of the bowed-string timbre grows, until the force is great enough to stop the vibration of the virtual string in the sound synthesis software.

The haptic feedback of elasticity is mapped to the corresponding servomotor for vertical motion, simulating the resilience of a bow pushing into a violin string. As the vBow is pushed down toward the body, the force feedback of elastic resistance is simulated by applying a continually increasing opposing force to the servomotor and cable system for vertical motion.

Finally, the software maps the encoder count for longitudinal motion to the bow position parameter of the bowed-string physical model, producing *sul ponticello* and *sul tasto* effects. These sampled encoder readings imitate bow position in relation to the bridge, changing the lengths of the delay lines, which represent the string vibrations on either side of the bow, in the physical model.

The control software maps longitudinal friction to the corresponding servomotor, using the same Hayward and Armstrong friction model discussed above. As the vBow moves longitudinally, the sampled encoder count is again used as position $x$ of the moving mass in the friction model, which is used to calculate frictional force.

In addition to the vBow imitating the sound and feel of an acoustic violin, it will be used as a controller of different types of synthesis and haptic feedback. Since the reading from each encoder can be mapped to any synthesis parameter, and any kind of haptic cue can be mapped to each servomotor, the vBow is an especially versatile computer music instrument. The expressivity of the vBow is limited only by the kinds and range of motion sensed and the types of synthesis and force-feedback cues programmed.

Because of the ease with which variations in programming can change the haptic response of the vBow, kinesthetic feedback can be used as a compositional element. The force feedback of the instrument can change throughout the piece, providing the performer with a variety of haptic responses to their physical gestures.

## 5. IMPROVEMENT

Improvements to the hardware include two new pieces which have been designed to compensate for the weight of the servomotors, allowing for the vBow to move more freely. A new arm piece extends in two directions, so that a counterweight can counterbalance the rotation and housing pieces and servomotors, while the vBow moves vertically. In addition, a hole drilled in a protrusion has been added to the longitudinal piece, to hold a spring which will counterbalance the longitudinal motion of the vBow. The spring will be fastened at the other end to a post, which extends up through a hole drilled through the violin-shaped body.

Additions to the software will include improvements to the multi-threading of encoder reading, real-time audio output, and servomotor control. I have also begun experiments porting the vBow software, which currently runs under the Windows operating system, to RTLinux (http://www.fsmlabs.com/), a real-time variation of the popular Unix-based operating system, in order to avoid latency and ensure near real-time response of the instrument.

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