Spherical Radiation From Stringed Instruments: Measured, Modeled, and Reproduced

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Abstract: Directional impulse responses were collected for six stringed instruments, including two classical acoustic guitars, an archtop jazz acoustic/electric guitar, a mandolin, a violin, and a Hardanger (Norwegian folk) fiddle. Impulse responses were recorded simultaneously from 12 microphones spaced uniformly at the vertices of an icosahedron. Data was collected for all instruments with a human player holding the instrument, and for some instruments also with the instrument suspended without being held by the player. For one guitar, the violin, and the mandolin, the position was adjusted by small angles, and a total of 72 impulse responses (six sets of 12 microphones) were collected. Various signal processing techniques were used to investigate, factor, store, and implement the collected impulse responses. A software workbench was created which allows virtual microphones to be placed around a virtual instrument, and then allows signals to be processed through the resulting derived transfer functions. Signal sources for the application include plucked and bowed string physical synthesis models, or any external sound source. Instrument body transfer characteristics can be parametrically edited, adjusting body size, main resonances, etc. Applications of the database and application software have included adding directional radiation models to physical models for virtual reality and composition, and adding more realistic body resonances to electronic stringed instruments for real-time performance.

Introduction

Musical instruments radiate sound in directional, frequency dependent spatial patterns. For some instruments such as brass, the patterns are fairly predictable from the known properties of horns. For other instruments such as woodwinds, the patterns are more complex due to a number of toneholes which can radiate sound, and the configurations of these tonehole radiation sources vary with different fingerings (Caussé et al 1992).

For stringed instruments, the radiators are wooden boxes whose shapes, materials, and techniques of construction vary greatly between families, and from instrument to instrument within a sub-family. Players of electric stringed instruments are aware of the benefits of solid bodied instruments with magnetic pickups, such as increased sustain times, decreased problems with feedback when amplifying the instrument, and the ability to process the sound of the instrument without the natural sound being heard. However, performers using solid body electric stringed instruments often find that these instruments lack the "warmth" associated with acoustic instruments, and using loudspeakers to amplify the electronic instrument does not provide a satisfactory dispersion of sound in performance spaces.

In recent years, synthesis by physical modeling has become more possible and popular (CMJ 1992/3). To synthesize stringed instrument sounds using physical modeling, models of the bodies of these instruments are required which are efficient, realistic, and parametrically controllable. The latter is important to composers and interactive performers wishing to exploit the flexibility of parametric body models, allowing for dynamic changes in the parameters to be used as compositional and performance gestures. Another application area is virtual reality and 3D sound, which has brought a need for data and algorithms for implementing the directional radiation properties of musical instruments, the human voice, and other sound sources (Hiipakka et al 1997).

In the project described in this paper (dubbed the “NBody Project”), directional impulse responses were collected for six stringed instruments, including three guitars, a mandolin, a violin, and a Hardanger (Norwegian folk) fiddle. Various researchers have investigated the radiation properties of the violin (Weinreich 1997)(Bissinger 1995)(Bissinger and Bailey 1997)(Bailey and Bissinger 1997), but the primary purpose of the NBody project is to obtain a set of useable filters for implementing realistic spatial radiation patterns of a variety of stringed instruments for simulation and performance. This paper will describe the data collection methods, the instruments which were investigated, some acoustic results from inspecting the collected data, and some applications and systems which were constructed to use the collected data for synthesis and live performance.

Data Collection Equipment and Methods

An icosahedral (20 faces, 12 vertices) grid was constructed of ½" dowel rods, with a microphone mounting flange located at each vertex. Figure 1 shows a photograph of the microphone array, with a researcher outside, a mandolin suspended inside the array, and the twelve microphone positions labeled . The total diameter of the sphere bounded by the microphone elements was approximately 4'. Twelve identical AKG C3000 cardioid microphones were positioned at the vertices of the icosahedron, pointing directly inward. All microphone positions were adjusted so that there was exactly 21" between any two adjacent microphone elements, and each principal microphone axis was aimed toward the opposite vertex in the array. The array was suspended in the center (near the floor) of a 48' x 60' x 70' concert hall. An enclosed chamber 8' in diameter was constructed of 2" acoustic foam, suspended around the icosadron in the center of the auditorium. Extra layers of acoustic foam were placed on the floor of the constructed chamber. The microphones were routed through preamps with flat frequency response to two Tascam DA-88 digital audio tape recorders. All microphone signal paths were normalized to within 1 dB, using a test tone generator.

The stringed instruments were excited using a Modal Shop Model 086C80 miniature force hammer, designed for maximum impacts of 50 pounds, and with a factory calibrated sensitivity of 96.6 mV/g. The hammer signal was routed through a PCB Piezotronics Model 480E09 power supply, through an active op-amp impedance matching circuit to an audio preamp, and routed to one channel on each DA-88 digital audio tape recorder. Due to care exercised during recording setup and alignment, no force hammer or microphone signals were found to have overloaded the electronics during the recording process. Inspection of the force hammer excitation signals revealed that the data collected is valid up to approximately 10KHz, consistent with the published frequency response specifications from the force hammer manufacturer. Sets of "good" impulse responses were selected based on the excitation signal. This was done by eliminating any double hammer hits, eliminating any recordings where the researcher commented during the experiment that it was a bad hit, then finally choosing from the remaining possibilities the force hammer impulse with the narrowest and highest peak. Selected signals were transferred digitally to computer for analysis.

Instruments Investigated in This Study

Three guitars were investigated, a Sam Dunlap 1988 classical guitar, a Sergio Abreu (Brazil, 1997) classical guitar, and a Fender Elite (d'Aquisto 1987) arch-top acoustic/electric jazz guitar. For the arch-top guitar, an extra channel was recorded from the electric pickup, with the tone control set to maximum brightness. Other instruments investigated include a 1987 Kentucky KM1605 F-hole mandolin, a David Folland 1989 violin, and a Hauk Buen (Norway, 1993) Hardanger fiddle.

All instruments were prepared by placing felt beneath and around the strings along the fingerboard, in the tuning heads/pegs, and in the tailpiece where necessary to damp any string vibrations. Only the amount of felt required to damp string resonance was used, and no felt was allowed to touch the bridge or body of the instrument. Strings were tensioned to their normal tunings. In the case of the Hardanger fiddle, which has a set of 5 sympathetic strings beneath the bridge, a set of measurements was collected with the sympathetic strings damped, and another set of measurements was collected with the sympathetic strings undamped.

For all instruments, impulse data was collected with the instrument being held by a player in the normal playing position. For the Dunlap guitar, the mandolin, and the violin, an additional set of data was collected with the instrument suspended without being held by a player. Care was taken to put the instrument into the same position and angle within the microphone array in both the player-held and non-held case. The principal instrument position was with the top plate of the instrument directly facing microphone 1 (in the case of the guitars and mandolin, or facing microphone 2 in the case of the violin and fiddle). The instruments were excited by striking the bridge at the point where each string crosses the bridge.

Since humans were performing the striking, multiple strikes (a dozen or so) for each string were recorded. Inspection of the hammer force signals were used to determine a "good hit." After collection of data from the principle position, the Dunlap guitar, the mandolin, the violin, and the Hardanger fiddle were rotated 30 degrees upward, aiming the top plate directly between microphones 1 and 2 (2 and 11 for the violin and fiddle), and another set of impulses was collected. An additional set was collected with the top plate aimed between microphones 1 and 3 (2 and 4 for the violin and fiddle). Three additional sets of data were collected with the instrument facing microphone 1 but rotated 30 degrees around an axis running normal to the top plate, rotated similarly facing between microphones 1 and 2, and finally rotated facing between microphones 1 and 3. Figure 2 shows the 6 positions for a guitar. This resulted in a total of 6 sets of 12 simultaneously collected impulse responses, for a total of 72 positions around the instrument.

Because of limitations of time, expense of the instruments, etc., the Abreu classical guitar and the arch-top jazz guitar were subjected only to collection conditions of player-held, principal position (12 microphones only), one string impulse responses.

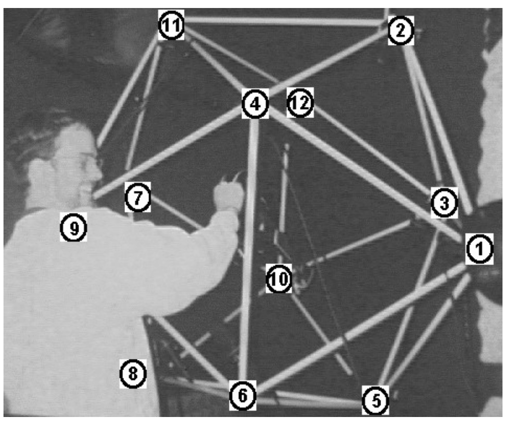

FIGURE 1. Microphone array structure.

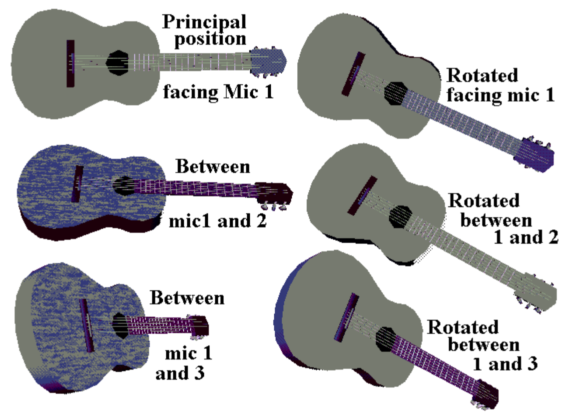

FIGURE 2. Instrument positions for recording.

Some Results and Comparisons

The impulse responses from different strings on the same instrument proved to be significantly different only for the violin and Hardanger fiddle. Figure 3 shows raw data magnitude spectra of the microphone 1-6 signals for the principal player-held position from the four strings of the Hardanger fiddle. The Hardanger fiddle is said by some to exhibit a "shimmering" quality on the higher strings, which is easily explained by the differences in filter functions in proceeding from the lower to the higher strings.

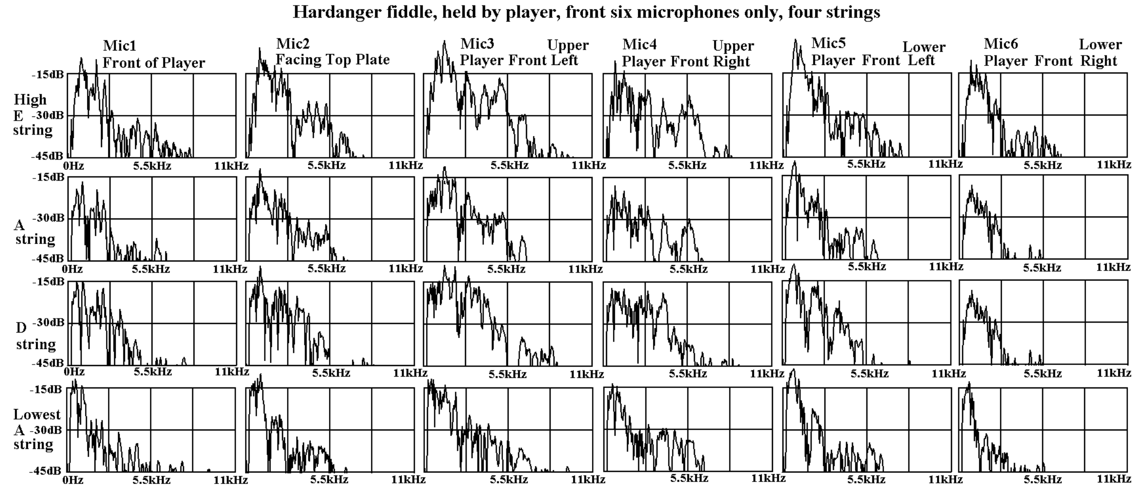

FIGURE 3. Hardanger fiddle responses for the front six microphones, four different string excitations.

The mandolin was selected for more extensive analysis in this paper. Figure 4 shows magnitude spectra of the microphone 1-12 principle player-held position, with the hammer impulse excitation deconvolved (division in the frequency domain). Figure 5 shows magnitude spectra of the microphone 1-12 principle position raw data, comparing the player-held (upper plots) and non-held (lower plots) cases. There are many differences, but most obvious is the attenuation in the rear channels 7, 8, etc, in the player-held case, along with an overall attenuation in the 3-4kHz region in all spatial directions, when the instrument is held by the player.

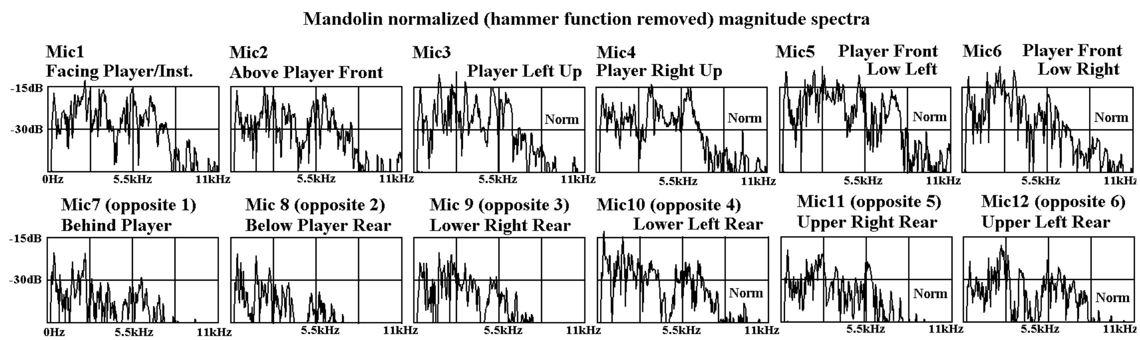

FIGURE 4. Normalized (excitation function deconvolved) mandolin magnitude spectra for all 12 microphones, player held case.

Principle components analysis was performed on the 72 player-held mandolin signals, both on magnitude spectra, and log magnitude spectra. As shown in Figure 6, the results were not as promising as was hoped. For the magnitude spectrum case, ten principal components explain only 84% of the variation, and twenty explain 93%. The performance is slightly better for few principal components in the log magnitude spectrum space, but even if magnitude is reconstructed, there is still the question of how to reconstruct phase. Surface spherical harmonics (Evans, Angus and Tew 1998) are being investigated as an interpolation method, and show promise because of the nature of the principal spatial modes of musical instrument bodies.

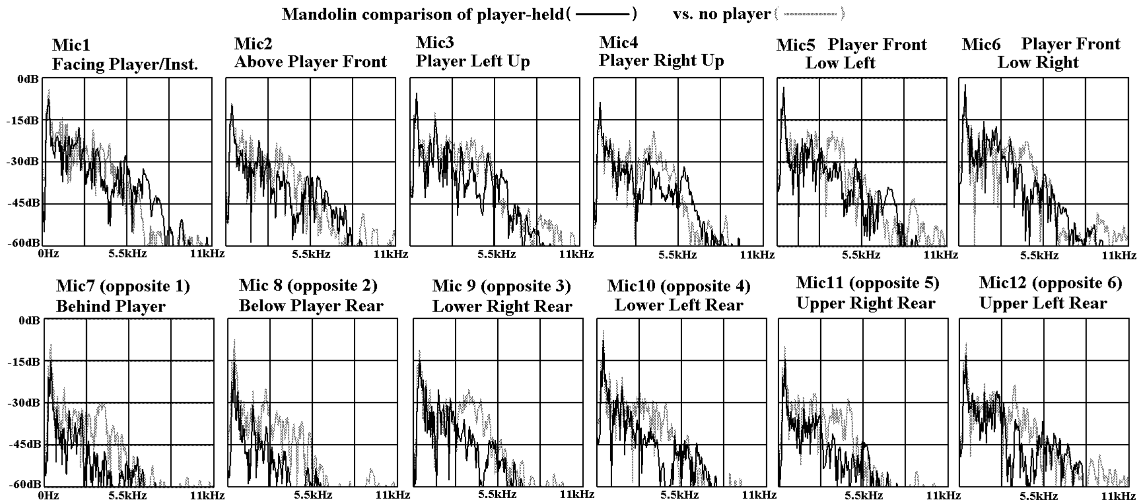

FIGURE 5. Raw data magnitude spectra for mandolin, player-held vs. non-player conditions.

Signal Processing, Building the Filter Database

Using parametric information derived using system identification techniques, the main resonances of stringed instruments can be efficiently modeled using Infinite Impulse Response (IIR) digital filters. The residual is significantly shortened as compared to the original impulse response, allowing for more efficient Finite Impulse Response (or pole-zero IIR) implementation of the residual, and often the residual can be eliminated entirely.

Measured Nbody signals were factored into bands covering 0 - 2.75 kHz, 2.75 - 5.5 kHz, 0 - 5.5 kHz., 5.5 - 11.025 kHz, and 11.025 - 22.05kHz., using half-band filters with a stop-band rejection of 80 dB. Low order warped linear prediction (Steiglitz 1981)(Karjalainen 1996) was performed on the 0-2.75kHz. band for the guitars, and on the 0 - 5.5 kHz. band for the mandolin, violin, and fiddle. The main low frequency LPC resonances for the Dunlap classical guitar were 219, 498, 859, 1273, and 1562 Hz. The main low frequency LPC resonances for the Abreu classical guitar were 220, 587, 860, 1030, 1223 Hz., with many more densely packed significant resonances above. The main low frequency LPC resonances for the arch-top guitar were 320, 574, 922, 1718 Hz (and with a very weak resonance in the 200 Hz range only detectable in the pickup channel). The main low-frequency LPC resonances for the violin were 524, 1156, 1870, 2302, 2836, and 3758 Hz. The main low-frequency LPC resonances for the Hardanger fiddle were 580, 987, 1894, 2234, 2584, and 3465 Hz. The main low frequency LPC resonances for the mandolin were 388, 1002, 1749, 2354, 3557, and 4354 Hz.

For the first version of the Nbody database, the filter parameters of the low-frequency portions of the impulse responses are stored as parameters of filter center frequency and resonance. The residuals are stored in oversampled halfband form (original sampling rate), in the frequency domain, with bands from 0 to 2.75 kHz, 0 to 5.5 kHz, 2.75 to 5.5 kHz., 5.5 to 11.025 kHz, and 11.025 - 22.05 kHz. Storing the samples in this way allows for scaling (body size modification) and flexible implementation at somewhat arbitrary sample rates. Original full-bandwidth versions of all impulses are also stored in the time domain.

Computer Applications: Accessing and Using the Database

Applications of the NBody database and application software have included adding directional radiation models to physical models for virtual reality and composition, and adding more realistic body resonances to electronic stringed instruments for real-time performance. The positioning system currently runs in real time, but only for static microphone positions. Fast methods for spatial interpolation and convolution are being investigated to make feasible a system which can efficiently support time-varying microphone positions.

As shown in Figure 7, a software workbench has been created which allows the user to be positioned at any point around a virtual instrument. Signals can then be synthesized or processed using the resulting derived transfer function. Signal sources for the basic NBody application include MIDI and scorefile controlled plucked and bowed string physical models, and any external sound source. Any of the directly measured body transfer characteristics can be called up instantly and parametrically edited, adjusting individual filter resonances, etc.

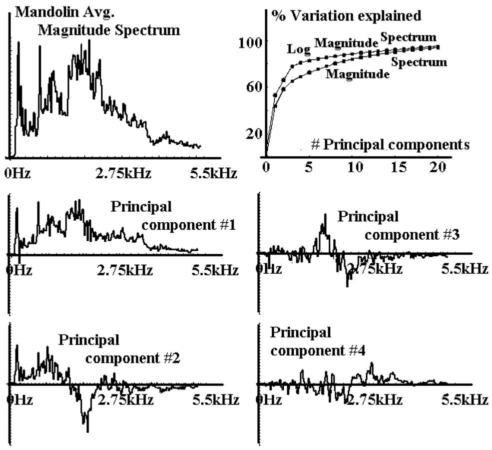

FIGURE 6. Principal components analysis of mandolin.

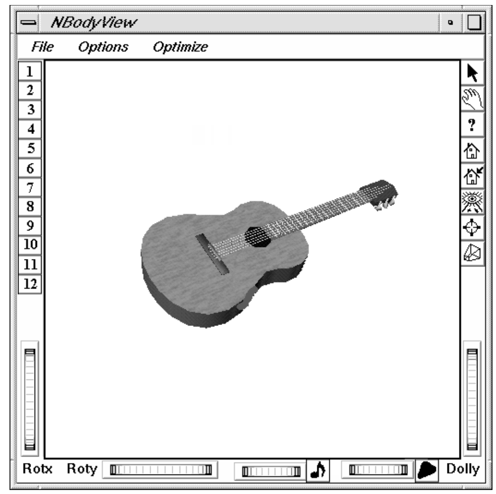

FIGURE 7. Nbody application interface.

Spherical Speaker Arrays, and a New Instrument

Four multi-speaker display devices (nicknamed “the Boulder,” “the Bomb,” “R2,” and “The Critter”) have been constructed, and are shown in Figure 8. In these devices, 12 speakers are arranged in an evenly-spaced array, facing outward. These speakers are essentially the dodecahedral dual display devices for the icosahedral microphone data collection array shown in Figure 1. Any sound that was incident on a given microphone in the microphone array can be played back on the matching speaker in the speaker array, resulting in a fairly faithful reconstruction of the original spherical wavefront emitted by the instrument. Fast, multi-channel convolution has been implemented to allow any sound source, such as a solid body electric violin signal, to be filtered by the directional radiation impulse responses measured in the NBody data collection project.

FIGURE 8. Left: The Boulder 12 speaker array. Right: The Bomb

We have also built a new instrument that includes elements of both the violin's physical performance interface and its spatial filtering audio diffuser, yet eliminates both the resonating body and the strings. The instrument, BoSSA (Bowed-Sensor-Speaker-Array), is an amalgamation and extension of our previous work with violin interfaces, physical models, and the directional tonal radiation studies described here. It includes a sensor-bow (the R-Bow), a sensor-fingerboard (the Fangerbored), an array of bowed sensor-sponges (the Bonge), and a 12-channel spherical speaker array (“The Critter”) (see Figures 9-10). Sensors used include force-sensing resistors (FSRs), linear position sensors, and accelerometers. When combined with various real-time synthesis and signal processing techniques, BoSSA offers the possibility for a new kind of *electronic chamber music* (Trueman and Cook 1999)(Trueman 1999).

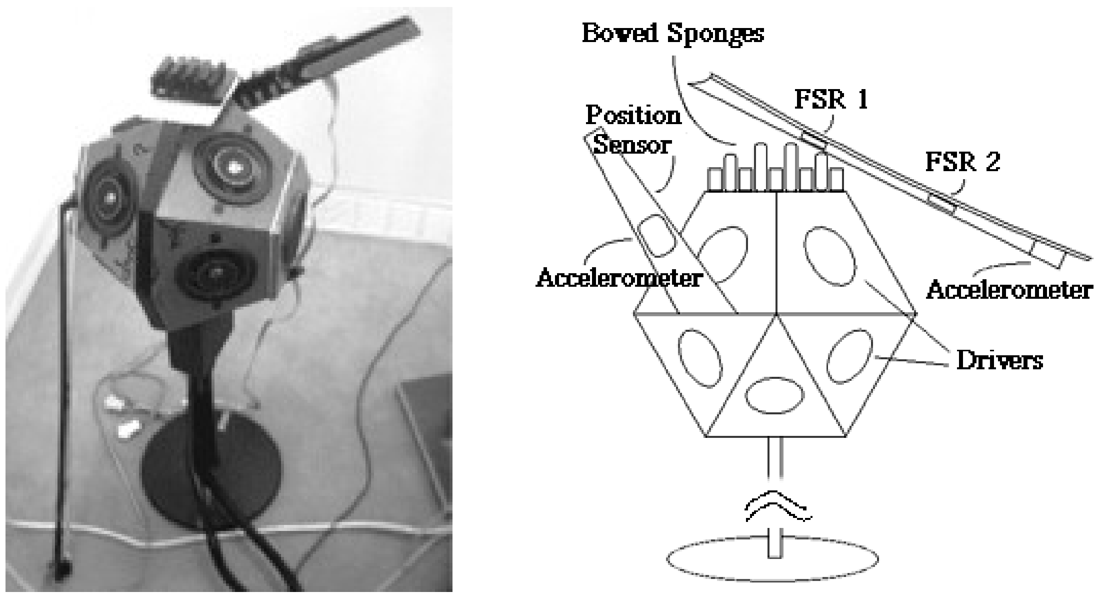

FIGURE 9. BoSSA (Bowed-Sensor-Speaker-Array).

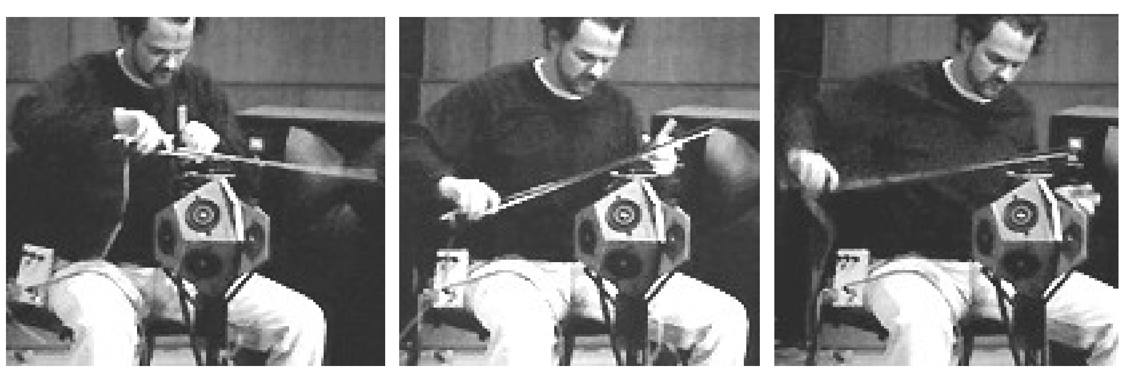

FIGURE 10. Three frames from the first performance with the BoSSA.

Conclusions

Data collected from multiple stringed instruments was analyzed and used to construct computer applications which allow directional filter functions to be imposed on arbitrary sound sources, such as physical models and solid body electric instruments. Much more work remains to be done in analyzing the large amount of collected data, in investigating interpolation schemes, and investigating factorizations of the directional filter responses for fast convolutions and flexible parametric manipulations. Both interpolation in space and interpolations between different instruments would be of interest. More instruments should be recorded and added to the database, including cello, double bass, and various folk instruments. The data from this project is publicly available in both raw and processed forms, allowing researchers to use it for various purposes, including verification of theories about the radiation properties of instruments.

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