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Evolution of the Keyboard Interface: The Bösendorfer 290 SE Recording Piano and The Moog Multiply-Touch-Sensitive Keyboards

In Alfred Dolge's classic book *Pianos and Their Makers,* we learn that archetypes of the keyboard date to antiquity and that *clavis* (keys) came into use on church organs almost a thousand years ago (Dolge 1911). As a musical interface, the keyboard has enjoyed remarkable longevity. Judging by its popularity on electronic musical instruments, the keyboard shows every sign of thriving for another millennium. The keyboard offers the musician rapid, sensitive articulation of multiple sounds and/or events and provides an arguably effective stand-in for ensemble players, particularly in more informal situations.

Literally millions of amateur and professional musicians have keyboard skills. For this reason, the continuing evolution of the keyboard will doubtless include designs that facilitate and possibly extend idiomatic expression. Less traditional keyboard designs will also be created that require development of new performance techniques. This article discusses recent results that represent these two different directions of development. The Bösendorfer 290 SE recording piano is a powerful system that has its roots in several centuries of player-reproducer piano technology. The Bösendorfer 290 SE senses piano key and pedal movements with very high resolution and stores these data on disk or tape for editing and mechanical playback. The Moog Multiply-Touch-Sensitive keyboard exhibits a design that reports (in two dimensions) the location of the performer's finger on the surface of a key as well as the depth of key depression. This design implies considerable extension of existing keyboard technique.

The Bösendorfer 290 SE Recording Piano

The authors have heard several performances involving the Bösendorfer 290 SE recording piano. Moog attended a special "Live Recital Recording" featuring the music of Mendelssohn and Mussorgsky, performed by Frederick Moyer on the Bösendorfer 290 SE.

Enticed both by the prospect of a first-rate concert and the opportunity to hear a computerized Bösendorfer in action, Moog joined Moyer's audience in Houghton Memorial Chapel at Wellesley College. The event was hosted by Moyer, Gunther Schuller, and John Amuedo for an invited audience of pianists, computer scientists, and musical acousticians, in cooperation with the Boston chapter of the Acoustical Society of America. The opening remarks were made by Gunther Schuller, a well-known composer and conductor who also has produced several of Moyer's recent recordings. Schuller explained that Moyer's concert would be recorded digitally as performance gesture data rather than audio. Weeks later, a digital audio recording system would be set up in the same chapel, and the performance gesture data would be used to play the Bösendorfer, recreating Moyer's performance of that evening. Editing that would normally be done in the analog or digital audio signal domain would be

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carried out on the Bösendorfer performance data directly, before the final audio mastering of the compact disk (CD) was to take place. The CD of Moyer's live concert would then be recorded in an environment free of audience and environmental noise.

John Amuedo, a research scientist from the MIT Artificial Intelligence Laboratory, coordinated the data gathering. Before the performance, he explained in simple technical terms the operation of the Bösendorfer 290 SE. He then took his position at the IBM PC computer system as Frederick Moyer walked on stage. What the audience witnessed was an apparently traditional classical piano recital. There were no microphones, extraneous mechanical noises, or motions to distract from Moyer's splendid performance, which filled the hall with the glorious sound of the Bösendorfer. Anthony Tommasini, music critic of the *Boston Globe,* described Moyer's performance as having "a rich tone, clarity, lyrical sensitivity, and plenty of virtuosic energy."

After Moyer's encore, a curious audience came up to congratulate Moyer and to look inside the piano. Amuedo announced, "now we'll hear some of the music being played back." As the piano's keys began to move, some people gazed at the keyboard, shaking their heads in near disbelief. Others returned to their seats, listening closely to determine just how faithfully the performance was being reproduced. Moog recalls his impressions vividly:

> With my eyes closed, I had no trouble imagining that Moyer was in fact playing the instrument. I could spot no clues whatsoever that I was hearing a playback. The timings of the rapid passages, the variations from soft to loud, and every dynamic marking and pedal movement were exactly as I remembered in the original performance.
>
> While I listened, the engineer side of my brain chugged away, estimating how accurately the playback mechanism must be to recreate Moyer's performance. The dynamic range of Moyer's playing was very wide—perhaps 50 dB. Now, 50 dB is a power ratio of 100,000 : 1, and the system's key solenoids were handling that range. What's more, they were handling it with a timing accuracy of better than 5 msec. And the pedal motions! The controlled releases of the sustain pedal by which Moyer slowly damped the ends of certain phrases were all accurately recreated on playback. Finally, all of this was going on with no thumps, wheezes, hums, or squeaks.
>
> By the end of the evening, it occurred to me that this technology might just be the most dramatic advance in piano recording that we have ever seen. Just as digital audio recording and the CD have brought audio reproduction to a point where the full dynamic range of virtually any audio material can be reproduced with nearly inaudible noise and distortion, the technology within the Bösendorfer 290 SE has brought the reproducing piano to such a state of advanced technical development that a whole gamut of new musical applications is now feasible.

The 290 E system was invented by Wayne Stahnke, a musician-engineer who lives in Woodland Hills, California USA. As a young boy, he fell in love with the player piano, and as a teenager he tried to build an improved version. In 1972, after acquiring the necessary engineering skills in college, he built an electronic interface between a pair of pneumatic reproducing pianos. Next came an all-electronic recorder-player for an upright piano with state-of-the-art features, such as optical sensing of hammer velocity and individual expression per key. That instrument required a year of concentrated effort and evoked considerable interest from the pianists who tried it. It also attracted the attention of the Merle Norman Foundation, which maintains a large museum of automatic musical instruments.

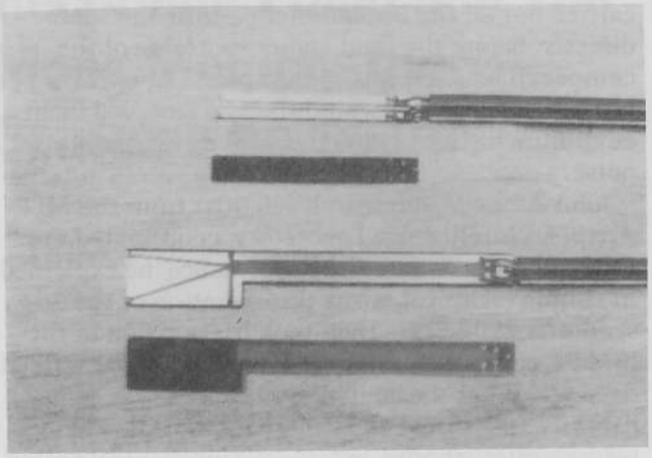
A commission from the owner of the Merle Norman Foundation enabled Stahnke to build his technology into a new Steinway model D grand piano, a project that took nearly three years of full-time effort. By this time, adequately powerful microprocessors had become available, which transformed the project from an exercise in hardware to a need to develop intelligent software. After being shown publicly, the Steinway instrument was donated to the University of Southern California.

Stahnke's next project involved a recording instrument based on a Yamaha grand piano, which he built for his own use. John Amuedo saw the Yamaha-based prototype of Stahnke's technology in 1981 while on a trip to Los Angeles. Shortly thereafter, Amuedo was invited to organize the first MIT Conference on Musical Learning, held September 1982 at the Miramar Sheraton hotel in Los Angeles. This conference brought together a group of musicians, cognitive psychologists, and computer scientists to discuss two aspects of musical learning: the practice strategies that professional musicians use when learning unfamiliar music; and the spontaneous learning that occurs in improvisation, such as jazz ensemble playing. Stahnke made the Yamaha prototype system available for this conference in order to document the musical proceedings. The response of the dozen concert artists who attended the conference was uniformly enthusiastic. Johana Harris recalls:

> The experience of hearing myself play from the vantage point of a listener, rather than a performer, was profound. I think the thing that moved me so about this experience was that the piano preserved all of the emotional qualities of the performance that I had intended to convey. This instrument didn't sound mechanical at all—it was recreating an exact reflection of what I wanted to share.

At the time, Amuedo was consulting for Kimball International, evaluating new computer-based musical technologies. He recommended that Kimball pursue licensing and development of Stahnke's technology for manufacture in the Bösendorfer concert instruments. Amuedo further proposed that Kimball build a prototype Bösendorfer 290 model piano equipped with Stahnke's technology for his project at the MIT Artificial Intelligence Laboratory. That instrument was delivered in February 1985, and Amuedo subsequently provided beta test support for Kimball on issues such as system software and user interface design, signal processing techniques for assessing playback fidelity, and the design of a personal computer interface. Kimball officially announced availability of the 290 SE recording piano in the summer of 1986, and since that time has made Stahnke's technology available in Bösendorfer's 9 ft and 7-1/2 ft concert instruments.

Fig. 1. Resistive key surfaces for sensing finger position. From bottom of photo: Top of white key surface; bottom of white key surface; top of black key surface; bottom of black key surface.



The Bösendorfer 290 SE Technology

The system that Stahnke designed uses optical sensors to detect both key and hammer positions. Each sensor consists of a light-emitting diode (LED) and a phototransistor facing each other across a gap of about 1/8 in. When a key on the piano is struck, a precision-cut aluminum shutter mounted in the shank of that key's hammer moves across this gap; the shutter either blocks the light from the LED or allows it to shine on the phototransistor. The LED-phototransistor sensor assemblies are fixed, while the aluminum shutters are attached to both the keys and the hammer shanks. Each shutter and its tiny mounting screw weigh a small fraction of a gram, contributing negligible mass to the hammer.

A single key shutter is located on the bottom of each key, directly under where the performer's finger would typically strike. The LED-phototransistor assembly for each key is positioned so that an individual key down signal is produced as soon as the key is minutely depressed. The associated hammer shank shutter is located near the base of the hammer. The hammer-shank, LED-phototransistor assembly is positioned so that the hammer's position is reported just as it is about to hit the string. The time between key down and hammer strike is therefore an inverse function of hammer velocity.

All key sensors are scanned 800 times per second. When a key is depressed sufficiently to activate its

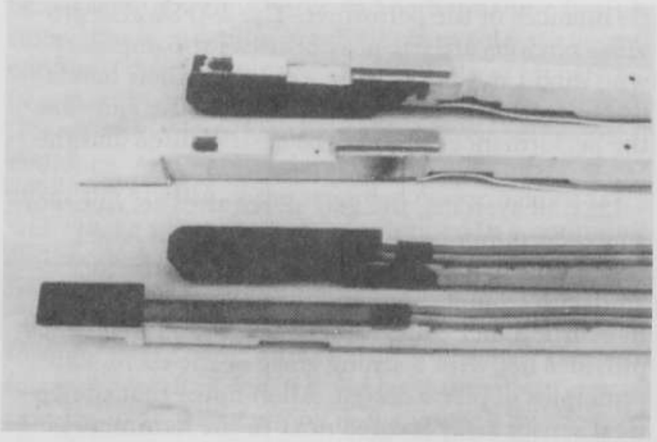


Fig. 2. Keys with resistive surfaces and aluminium vanes in place.

sensor, the scanning circuitry then awaits the signal from the hammer-shank sensor and resolves the timing of the two events to within 40 μm. Thus, the velocity of each hammer is accurately measured when it is about to strike the string. This—and not the velocity of the key—is what is recorded and played back. This design mitigates errors that individual mechanical differences among various keys of the piano action might otherwise contribute.

The Bösendorfer uses linear motors mounted under the key bed to actuate its piano keys. Most electric motors you are familiar with are rotary types. Two types of linear motors that you may be familiar with are the solenoid (e.g., the ones that go "kachunk!" to open a valve in a washing machine) and the driver element of a loudspeaker. Neither of these would be suited to the task of precisely actuating a piano key; most solenoids are designed to push as hard as possible without regard to speed, control, or mechanical noise. On the other hand, speaker drivers can move quickly and accurately but are too large and inefficient to be lined up in a row of 97 (as the Bösendorfer Imperial grand piano has 9 extra notes in the bass).

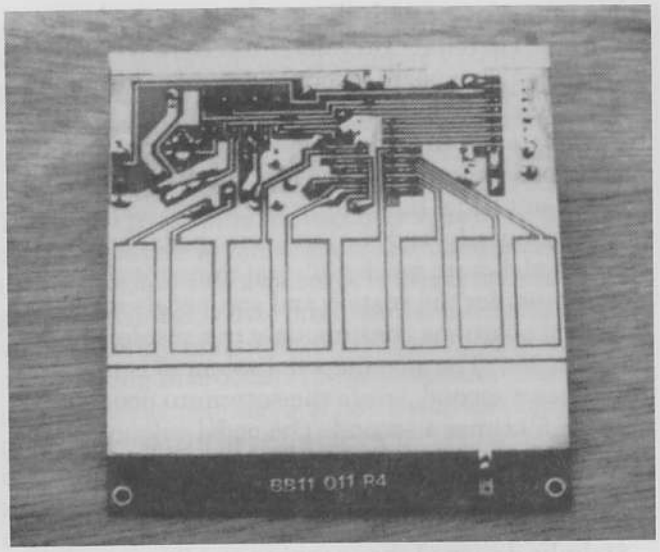
Stahnke designed his key actuator motors to work efficiently over the 1/2 in that they are required to travel and to work quietly, quickly, and precisely. They are shaped like a solenoid, about an inch in diameter and a few inches long. They are mounted under the key bed so that the actuators come into contact with the key levers only during playback. Therefore, they don't interfere with the instrument's keyboard response during performance.

The pedals have their own linear motors, which are much larger than the key actuator motors. The sustain pedal motor must be able to lift all the dampers; the soft pedal has to shift the entire piano action horizontally, and the sostenuto pedal has to actuate an elaborate mechanical latching mechanism. The sensors for the sustain and soft pedals measure the pedal positions continuously to a resolution of 1 part in 256. The sustain pedal solenoid is updated 100 times a second, while the sostenuto pedal is updated 50 times a second. The pedal solenoids are enclosed in a wooden box finished to match the rest of the piano. This box is mounted unobtrusively on the bottom of the piano, in back of the pedals.

Stahnke designed the scanning and linear motor drive electronics to optimize the performance of the sensors and motors. He first built a custom computer to analyze sensor signals, actuate the motors, and store, retrieve, and edit piano performance data. The product manufactured by Bösendorfer uses an IBM PC to manage performance data. Stahnke and the engineering staff of Kimball International (Bösendorfer's parent company in the United States) have spent considerable time developing software that provides an expanding repertoire of musical and support functions for this software-intensive system.

Among the advances of which Stahnke is most proud are the software routines that correct for the piano's time delay and response characteristics. His transport delay correction procedure takes into account the time delay (variable up to 100 msec) between initial actuation of a key during playback and the striking of the string by the hammer. This routine starts the solenoid in anticipation of the time at which a note is actually intended to be heard. *Adaptive calibration* is another routine that enables the system to calibrate itself to match playback velocities to those measured during recording. This routine strikes each of the notes on the piano at eight different dynamic levels, discerns the relationships between hammer velocities and motor currents, and calculates the loudness corrections that must be applied to make the instrument play

Fig. 3. Circuit board for sensing key height.



evenly. The adaptive calibration routine can be run every few days or after the instrument is moved in order to correct for factors such as wear and humidity that would otherwise affect the system's playback response.

Perspectives on the Bösendorfer 290 SE

From an historical viewpoint, the 290 SE can be viewed as the culmination of several centuries of attempts to mechanize and automate the piano by a variety of manufacturers. The use of mechanical devices to play an instrument with a keyboard dates back to 1731 (Dolge 1911). At the beginning of the twentieth century, the *Welte Mignon* reproducing piano and the *Dea* system were used to record the playing of Joseffy, Rosenthal, De Pachman, Busoni, and other piano virtuosos using paper tape (Dolge 1911).

While we recognize that any mechanical recording-playback system for the piano owes something to this evolution, we wonder if the Bösendorfer 290 SE might not be different from its predecessors not only in degree, but in kind. It might reasonably be considered the ultimate development in the long lineage of mechanical piano playback due to its capacity to record and reproduce the exceedingly subtle nuances of the performer. The 290 SE also provides obvious artistic possibilities for composers who might not necessarily ever place their hands on the keyboard of the system due to the fact that the performance data may be easily edited and the MIDI protocol may be implemented.

Like all systems, the 290 SE requires service. For an expert opinion we turned to Kathleen Allen, who enjoys a reputation in the Boston area for her ability to troubleshoot and repair unusual pianos. In addition, her educational background in physics provides her with a strong grasp of the technical principles of piano design. Allen notes that the optical sensor array located next to the hammers is mounted on a monolithic rail suspended above the piano action. This rail may be removed for those maintenance procedures (such as regulation) that may require access to the moving parts of the piano action. She observes that because the key frame has been modified to accommodate the electronics, adjusting the piano for a concert or recording session would take more time than normal. Other than that, the piano part of the 290 SE system is adjusted and tuned like a conventional grand piano.

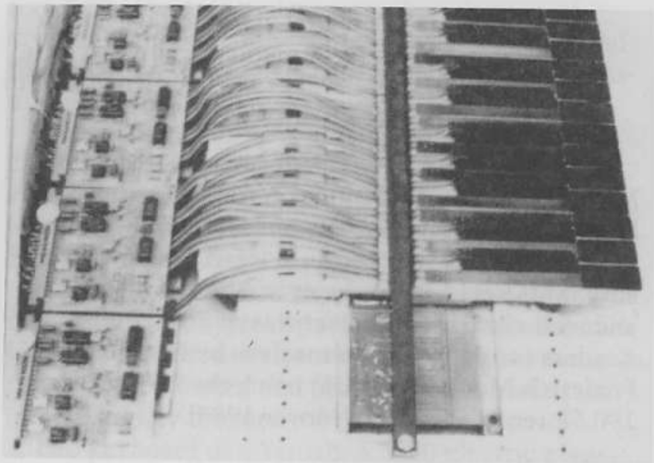
The 290 SE is a new resource that a skilled pianist can explore immediately without having to confront a new technique or being forced to cope with frustrating design deficiencies. Frederick Moyer is ideally suited to explore the 290 SE. He is an experienced concert pianist and an avid computer user as well. Expertise with computers is by no means required to use the 290 SE. This experience can, however, demystify the concepts related to the performance data and its manipulation. For Moyer, the idea that performance is data—data that can be recorded, edited, and made into an audio recording—makes unqualified good sense. As he commented to us, "there's no magic in producing piano tones. If you can duplicate the hammer speeds at the right time, you will essentially have duplicated the performance." Commenting on his motivation for using the 290 SE, Moyer explained, "I've been disappointed by piano recordings that I've done and those that have been done by other pianists." He feels that piano recordings are generally not as spontaneous or inspired as unrecorded live performances. In a live performance, people assume that there will be occasional wrong notes and perhaps some hesitations. These mistakes are difficult to tolerate on recordings, due to their predictability upon repeated hearings. Pianists naturally become more conservative when they are being recorded, even before an audience. Audience and environmental noises may affect the quality of the recorded performances as well; these noises cannot be tolerated in a commercial product. As a result, live concert piano recordings are edited—sometimes extensively.

Moyer feels that traditionally recorded piano performances are compromised in three ways. The performance itself is constrained because artists give priority to avoiding wrong notes, especially those they know cannot be removed by editing. Second, editing often consists of piecing together sections of separate performances, a practice that minimizes the number of mistakes but degrades continuity. Third, ambient noises can also be controlled in a recording studio, but most pianists need the stimulation of responsive listeners in order to play their best. The 290 SE system provides a way of alleviating these problems.

The questions that arise have to do with judgments about musical integrity. What is the point of recording a live performance if the result is sanitized to perfection? Amuedo, who has recorded a number of concert artists on the 290 SE at the MIT Artificial Intelligence Laboratory, offers his perspective. He states that "technical perfection is not the issue. Mistakes in performance that don't contribute to a satisfying musical experience may simply be more readily corrected. In a sense, this may be giving both the listener and the performer exactly what they want." Amuedo found that many notes not on the manuscript creep into performance, especially during fast passages. Most of these so-called brushed notes are soft and are not played deliberately. Their musical effect is often to thicken the texture of the playing. Amuedo and Moyer found that when these notes were taken out, the resulting performances had a strange, steely, mechanical quality. So they were left in. On the other hand, an occasional prominently audible wrong note could be corrected, and that, in their judgment, did improve the musical quality of the recorded performance.

The points that emerge clearly from the comments cited previously are that with the 290 SE system it is easier to obtain an exciting, musically satisfying recording of a concert performance, even before editing; that deciding what to edit and what to leave alone are important musical choices that ideally can be made by the pianist; and that an audio recording of an edited 290 SE performance can be more musically effective than a direct audio recording—whether or not the direct audio recording is edited—both for the pianist and for the listener.

Fig. 4. Side view of an organ-style keyboard with MTS sensor system. X-Y circuitry is seen to the left; Z circuitry is under the keys.



SE instruments have been sold to academic institutions, where they are used for composition and research as well as for recording. Instruments have been permanently located at the Royal Academy of Music in London, Ohio State University, the University of Maryland International Piano Archive, and Yamaha Piano Company's research laboratories in Osaka, Japan. SE instruments have also been made available for extended residencies at the Manhattan School of Music, the Moscow Conservatory, Indiana University, and the University of Southern California.

Will computer-controlled reproducing pianos supplant conventional direct digital audio recording as the standard for piano recording technology? Igor Kipnis' review of Moyer's CD in the July 1989 issue of *Stereophile* comments:

> Does the [Bösendorfer] system make sense? Does it have advantages? It would appear so, at least to achieve the spontaneity of the live con-

> cert minus its peripheral disadvantages of human error and noise. A pianist is not only able to respond interpretively to his audience, but to the acoustics of the hall as well.

Kipnis praises Moyer's performance of the seven Mendelssohn compositions on the CD as having been "played with warmth and sensitivity." Kipnis further suggests that Moyer's "searching musicianship is also evident in the evocative, thoughtful, and well-characterized *Pictures at an Exhibition.*" Readers can judge for themselves by listening to Frederick Moyer's first CD using the Bösendorfer 290 SE recording piano (Moyer 1988).

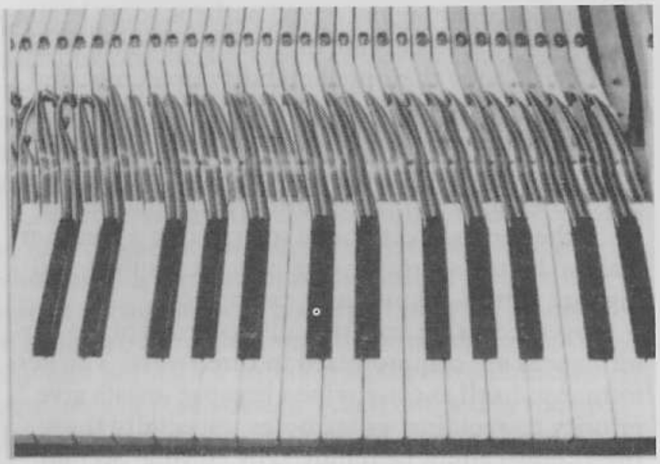
The Moog Multiply-Touch-Sensitive Keyboards

The development of the Moog Multiply-Touch-Sensitive (MTS) keyboards began with a research contract between the Indiana School of Music and Moog Music, Inc. The immediate predecessor of the the current design was described in a paper by Moog (1982) at the 1982 International Computer Music Conference in Venice, Italy.

The MTS keyboards are a family of keyboard controllers. Each model features individual sensors for each key that allow real-time, continuous control of up to three musical parameters. The key levers and keybed are standard wooden organ or piano keyboards. The sensors on each key continuously detect the up-down position of the key and the position in two dimensions of the musician's finger on the key surface. In terms of the feel that performers perceive as they depress a key, the sensors are completely transparent; the keys move and feel exactly like those of a conventional clavier.

Each MTS keyboard is equipped with scanning, processing, and logic circuitry that generates a digital data stream that periodically reports the status of the sensors of each active key. Software to convert this data stream to MIDI information is executed on a dedicated small computer external to the keyboard. The musical parameters controlled by a given MTS keyboard are determined by the capabilities of the tone-producing devices to which it is connected and by the operating software that relates the keyboard's output to the tone-producer's control inputs.

Fig. 5. A portion of a Yamaha CP-80 Piano keyboard, showing the X-Y key surface sensors. Note that white key surfaces are coated with white epoxy in this example.



Moog MTS Keyboard Technology

The sensors of each active MTS key continuously report three positions: the left-right position of the player's finger on the key surface (X axis), the front-back position of the player's finger on the key surface (Y axis), and the up-down position of the key itself (Z-axis). The X and Y signals are sensed by a resistive film on the playing surface of the key. The substrate is made of thin, epoxy-glass circuit board material, with a conductive pattern on one side and the resistive film on the other side. The film forms one plate of a capacitor. The player's finger is on the other capacitor plate and is grounded (at high frequencies) by virtue of its connection to the rest of the performer's body. A description of the electrical characteristics of the human finger has been provided elsewhere. A thin layer of urethane over the resistive film provides the insulating dielectric of the capacitor. A ribbon cable connects the four corners of the resistive film to circuitry that excites the corners with the same high-frequency, alternating voltage and measures the current flow from each of the corners. This circuitry computes the differences between the film's corner currents, then divides these differences by the total film current. This gives two analog output signals, one of which is proportional to the left-right (X) position of the finger, while the other is proportional to the front-back (Y) position.

The circuit board material that comprises the key surface is glued, resistive film-side-up, to the top of a standard wooden organ or piano key. White keys are painted white with epoxy paint. A specially cut fallboard covers the termination portions of the key surfaces. Figures 1 and 2 show the elements of the resistive key surfaces and their construction into piano-style keyboard.

Yet another variable capacitance scheme is used to measure the key's vertical (Z) position. An aluminum vane, attached to the bottom of each key, forms a capacitor with a portion of the pattern of a circuit board that is mounted below the key. Since the dielectric of the Z-measuring capacitor is air, the capacitor's output depends almost entirely on the spacing of the vane and the circuit board. In addition to this, a force-measuring (F) sensor for each key is positioned under the front rail felt punching. This sensor is an electrically resistive film that is placed in contact with a closely spaced conductive grid on a thin circuit board. With no force on the sensor, the resistance across the grid is very high. When the key bottoms out on the front rail, the resistance across the grid drops in roughly inverse proportion to the force on the key.

The resistances of the force sensors are measured and scanned at the same rate as the Z-axis sensors. The scaling of the sensor outputs is adjusted by the keyboard's operating software, so that the Z output goes from its minimum to its maximum value when the key bumps into the felt punching. From this point the F output starts from its minimum value and approaches its maximum value asymptotically as the key is pressed further into the felt. Figure 3 shows one of the Z-axis sensor circuit boards.

Each MTS keyboard has its own microprocessor-based operating system that performs scanning and data formatting functions. A single connector incorporates both an 8-bit parallel output and an 8-bit parallel input. The number of each active key, plus the key's sensor outputs, are loaded into a queue (FIFO) register in the keyboard, ready to be read by the external computer. The keyboard's input is used by the external computer to select operating system options and to run calibration and diagnostic software on the keyboard. Typical operating system options include: the maximum number of active keys, the data update rate, the selection of criteria for determining which keys are active, and the selection of which sensor outputs will be transmitted to the MIDI output.

The MTS sensor system has been installed in organ- and piano-style keyboards. Typically, the keys are spring-loaded. Circuitry associated with the X-Y sensors is located behind the keys, while circuitry associated with the Z and F sensors is located in the key bed itself, under the keys. One octave of keys are typically removed to make room for a left-hand controller—a panel of global controls that will be scanned and processed along with the individual key sensors.

The keyboard of a Yamaha CP-80 electric piano has also been fitted with the MTS sensor system. Ribbon cables from the keys are dressed along the sides of the keys and down to the X-Y circuitry that is located in a well at the bottom of the instrument case. Thus, the existing piano action and strings are not disturbed. Figures 4 and 5 show the MTS system installed in organ- and piano-style keyboards respectively.

Summary

The advent of electronic musical instruments by no means signals an end to the evolution of the clavier, or keyboard controller. This evolution will bifurcate generally into designs that embrace traditional piano or organ techniques and those that require extension of clavier technique with attendant extension of our understanding of what is idiomatic to the keyboard.

The two systems we have described in this article represent examples of these two directions of development. The first uses recent developments in electromechanical and computer technology to extend the usefulness of the traditional piano instrument and performance technique by providing high-fidelity gesture recording and playback built into concert quality instruments. The second system we presented represents an example of the current directions for the extension of the range and dimensionality of control available in the keyboard-style of performance interface beyond that of current organ, piano, or synthesizer keyboards.

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