
Andrew McPherson

Centre for Digital Music
Queen Mary University of London
Mile End Road, London E1 4NS, UK
a.mcpherson@qmul.ac.uk

Buttons, Handles, and Keys: Advances in Continuous-Control Keyboard Instruments

Abstract: The keyboard is one of the most popular and enduring musical interfaces ever created. Today, the keyboard is most closely associated with the acoustic piano and the electronic keyboards inspired by it, which share the essential feature of being discrete: Notes are defined temporally by their onset and release only, with little control over each note beyond velocity and timing. Many keyboard instruments have been invented, however, that let the player continuously shape each note. This article provides a review of keyboards whose keys allow continuous control, from early mechanical origins to the latest digital controllers and augmented instruments. Two of the author's own contributions will be described in detail: a portable optical scanner that can measure continuous key angle on any acoustic piano, and the TouchKeys capacitive multi-touch sensors, which measure the position of fingers on the key surfaces. These two instrument technologies share the trait that they transform the keys of existing keyboards into fully continuous controllers. In addition to their ability to shape the sound of a sustaining note, both technologies also give the keyboardist new dimensions of articulation beyond key velocity. Even in an era of new and imaginative musical interfaces, the keyboard is likely to remain with us for the foreseeable future, and the incorporation of continuous control can bring new levels of richness and nuance to a performance.

In his "Interaction Design Sketchbook," Bill Verplank divides user interface controls into *buttons* for discrete actions and *handles* for continuous actions:

When I press a button (e.g., ON) the machine takes over. . . . Handles can be "analogic." With buttons, I am more often faced with a sequence of presses. With a handle a sequence becomes a gesture. I use buttons for precision, handles for expression (Verplank 2009, p. 7).

The musical keyboard presents an interesting cross between buttons and handles. On the one hand, familiar keyboard instruments like the piano, harpsichord, and organ are essentially discrete, a row of buttons. Key presses are temporally and dynamically defined by their onset and release; key motion after onset is irrelevant to the sound. On the other hand, the physical motions of the human performer are necessarily continuous. The precise qualities of hand and finger movement, commonly known as "touch," hold great importance for expert performers and teachers. Moreover, the listener typically hears a keyboard performance not as sequences of isolated events, but as continuous lines

and phrases, just as a violinist or vocalist might perform.

Nonetheless, for all the expressive capabilities of the keyboard, instrument designers have long wanted more, pursuing what Dolan (2008, p. 4) describes as "an age-old musical problem: the creation of an instrument that combined the dynamic nuance and sustaining power available to bowed-string instruments with the convenience of a keyboard instrument." In other words, could the keyboard instead consist of a series of handles, each one capable of continuously shaping its note, while retaining the advantages of polyphony and familiarity? Proposed solutions to this problem date back as far as Leonardo da Vinci's sketches for the "viola organista" from 1488–1489, but more than five hundred years later, there is still no single agreed-upon approach.

This article explores advances in the design of keyboards featuring continuous control of one or more musical dimensions, from early mechanical origins to digital instruments of the past three decades. The focus is placed on the keyboard interface itself rather than the associated means of sound production. When discussing digital instruments, the scope of the article is also limited to interfaces that resemble the familiar keyboard, rather than the large and active research area of novel continuous controllers. A general review is followed by

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discussions in greater detail of two of the author's recent interfaces: a continuous optical scanner for the acoustic piano keyboard (McPherson 2013b), and the TouchKeys capacitive touch-sensor system, which measures finger position on the key surfaces (McPherson and Kim 2011a). A recurring theme throughout this article is "playability," exploring how design decisions can affect the performer's experience.

Gesture and Touch at the Keyboard

Playing any keyboard instrument places stringent cognitive and biomechanical demands on the player, and accordingly, studying the movements of pianists has long held interest for psychologists and musicologists. In the 1920s, Otto Ortmann studied the mechanics of piano performance from the perspectives of the instrument (Ortmann 1925) and the player's body (Ortmann 1929). Recent studies have examined the details of finger motion as it relates to tempo and timing accuracy (Goebel and Palmer 2008; Dalla Bella and Palmer 2011; Goebel and Palmer 2013). Force between finger and key has been studied in relation to dynamic level (Kinoshita et al. 2007) and movement efficiency (Parlitz, Peschel, and Altenmüller 1998). Other research has explored the kinematics of the hand (Furuya, Flanders, and Soechting 2011), the upper limbs (Furuya and Kinoshita 2008), and the torso and head (Castellano et al. 2008; Thompson and Luck 2012). Studies often compare expert pianists with amateurs, with experts demonstrating better use of the innate connectivity between fingers (Winges and Furuya 2014), more economical use of finger force (Parlitz, Peschel, and Altenmüller 1998) and more efficient coordination of upper limb motion (Furuya and Kinoshita 2008). Further review of the biomechanics of musical performance has been documented by Metcalf et al. (2014).

The essential discreteness of the acoustic piano has been a subject of a longstanding debate: Is it possible to alter the sound of a piano note independently of its loudness? Hart, Fuller, and Lusby (1934) showed that the velocity of hammer-string collisions was exclusively responsible for

the sound of a note: Every change in tone was accompanied by a change in loudness and vice versa. Nonetheless, pianists often describe their touch in rich, multidimensional terms, which go far beyond this simple velocity-based model.

In part, the musical importance of touch can be explained by its effect on the timing and velocities of longer musical phrases. Goebel, Bresin, and Fujinaga (2014) showed that auxiliary impact noises between finger and key or between key and key bed influence the perception of a single tone, and that these noises allow a listener to discriminate between pressed (non-percussive) and struck (percussive) touches. In my own previous work (McPherson and Kim 2011b), I found that, regardless of the acoustic effects, a pianist can control the continuous motion of the key in several simultaneous dimensions besides velocity. These dimensions include percussiveness, weight, and depth. Bernays and Traube (2014) also found meaningful variations in continuous key-motion profiles across four pianists, dependent both on individual style and their intended timbre in performance.

These studies offer instrument designers cause for both optimism and caution. Keyboard technique, even on essentially discrete instruments, consists of meaningful, reproducible patterns of continuous motion that could be adapted for new musical ends. At the same time, the complexity of existing keyboard practice means that any new continuous controls should be introduced carefully to avoid overburdening the performer.

Aspects of Discrete and Continuous Technique

Before considering specific instruments, it is worth clarifying the ways in which a keyboard might be classified as continuous or discrete. I will leave aside the complex issue of phrasing across successive notes to consider three aspects of a single note: *onset*, *sustain*, and *release*.

Onset concerns the brief period when the note begins. Though velocity (dynamic control) is the most familiar feature of piano note onset, this is only one possible feature of the broader quality of articulation. The many types of note onset possible

on bowed string instruments show that there is considerable space left to explore in this area (for an overview of string articulations, see Schoonderwaldt and Demoucron 2009). One subtle example can be found on mechanical tracker organs, where the speed of key onset allows control over the initial transients when the pipe speaks. Another example is the classic Hammond B3 organ, where each key had nine electrical contacts, one for each drawbar. This system was responsible for the “key click” sound musicians came to prize, and in fact the click can be subtly varied in length and loudness by altering the speed of the key, causing different drawbars to engage at slightly different times. These effects were deemed sufficiently important that the 2003 digital recreation of the Hammond B3 replicated the original multi-contact keyboard (Robjohns 2003). Further possibilities for note articulation will be explored in the TouchKeys section later in this article.

Sustain covers the middle of the note between onset and release. In the instrument design literature, “continuous control” is often shorthand for the ability to modulate the sustain of the note, changing its pitch, volume, or timbre. In particular, the ability to change dynamics or add vibrato from the keyboard have long been sources of inspiration for designers. This article will focus on ways of shaping a note’s sustain from the keyboard itself, leaving aside supplementary controls (e.g., the organ swell pedal or the synthesizer pitch wheel).

Release can be as simple as stopping a note abruptly, but variations are possible. Perhaps surprisingly, the acoustic piano keyboard offers a degree of continuous control at release, since the damper can be brought in contact with the string gradually or abruptly. Jazz brass instrument technique suggests other musical possibilities on note release, including *falls* (dropping pitch on release) and *doits* (upward glissando on release). The TouchKeys section in this article will explore how these techniques can be adapted to the keyboard.

Historical Continuous-Control Keyboards

The earliest sketches for a continuous-control keyboard instrument are found in da Vinci’s notebooks

from 1488–1489, depicting an instrument with a rosined wheel to bow a series of strings (Dolan 2008). A keyboard pushes each string into contact with the wheel, causing the note to speak. The instrument was apparently never built by da Vinci himself, but it has been recreated in modern times (Zubrzycki 2013). The earliest similar instrument to be constructed was Hans Haiden’s *Geigenwerk* in 1575. This instrument and most subsequent attempts at sustaining keyboard instruments were based on the same principle of strings bowed by rosined wheels (Dolan 2008).

New instrument technologies flourished in the 18th century; Dolan (2008) explores the motivations and creations of this period. Perhaps the most famous invention combining polyphony with continuous note shaping was Benjamin Franklin’s glass harmonica (1761), consisting of a rotating spindle of glasses, which are induced to vibration by moistened fingers placed on the rims. Subsequent inventors sought to improve the instrument by replacing direct finger-glass contact with a keyboard, showing even in that era the allure of the keyboard as a convenient and versatile interface. Unfortunately, keyboard variants tended to reduce the subtlety of control, and modern recreations of the glass harmonica typically follow Franklin’s original approach.

Among keyboard instruments, the most celebrated example of continuous sustain shaping can be found on the clavichord. Pressing the keys causes a metal *tangent* to strike the string; the tangent remains in contact with the string, forming one of its termination points. Pressure on the key alters the string tension, giving rise to the characteristic *Bebung* vibrato effect (Kirkpatrick 1981). The delicate sound of the clavichord was too soft for use in chamber music, and in the 18th century it was supplanted by the harpsichord and later the piano. It would take until the electronic instruments of the 20th century for this vibrato capability to return to keyboard instruments.

Early Electronic Instruments

Continuous pitch control was a prominent feature of early electronic instruments. Reviews of early

electronic instruments have been presented by Curtis Roads (1996) and Joseph Paradiso (1997). The theremin (1920) controlled pitch and volume using electric field sensing of the player's hands in the air. On the Trautonium (1929), the performer controlled pitch and volume by changing the position and pressure of the finger on a metal wire (Galpin 1937). The Ondes Martenot (1928) is well known for controlling pitch either from a sliding ring worn on the finger or from a keyboard, which slid from side to side to allow vibrato. In fact, the first version of the instrument had only the ring controller; the keyboard was a later addition (Paradiso 1997).

The Ondes Martenot used a separate pressure control, played by the left hand, to regulate the volume (Quartier and Meurisse 2014). The Ondioline (1941) combined side-to-side vibrato from the keyboard with the ability to control volume through key pressure. The Electronic Sackbut (1948) added a third dimension of timbre, controlled with the left hand (Young 1989). These instruments were all monophonic, but in fact the first polyphonic electronic keyboard predates them all: Thaddeus Cahill's polyphonic Telharmonium was first invented in 1901 and redesigned several times. The third version, introduced 1910, featured a pressure-sensitive keyboard to control the volume of each note (Weidenaar 1995). Weighing in at 200 tons and requiring over 600 kilowatts of power, however, the Telharmonium was soon supplanted by cheaper electric organs.

In 1973, keyboard vibrato reappeared on the polyphonic Yamaha GX-1, an analog synthesizer whose keyboard could be slid from side to side to alter the pitch (Paradiso 1997). Some early polyphonic synthesizers, for example the Yamaha CS-80 (1976), featured polyphonic aftertouch, which allows independent modulation of the volume or timbre of each sustaining note through key pressure. Polyphonic aftertouch is part of the standard MIDI specification, and was featured in early MIDI controllers such as the Kurzweil Midiboard (Moog 1987), although it is less often found on current keyboards. Aftertouch is limited in two ways: (1) it becomes active only during the sustain of the note, when the key is down, and hence cannot affect the onset or release; and (2) it has a single direction

of control (increasing pressure, with key release necessarily passing through minimum pressure). Prolonged heavy pressure on the keys also risks fatiguing the player.

Two novel prototypes developed over the 1970s and 1980s added entirely new dimensions to the standard keyboard. The Key Concepts Notebender (1978–84) had keys that could mechanically slide forwards and backwards to bend the pitch up or down (Moog 1987). The Moog Multiply Touch-Sensitive Keyboard (1972–90, cf. Moog and Rhea 1990) sensed the finger position in two dimensions on the surface of each key, letting the player control several parameters simultaneously. The prototype instrument was used by composer John Eaton (Eaton and Moog 2005) but was never commercially produced.

Recent Developments

Since the 1990s, many new extensions to the keyboard have been developed. Some of these involve sensor technology embedded into the keyboard itself, whereas others add extra sensors to capture hand and finger motion while the performer plays. I will leave aside systems that add new dimensions to the keyboard by using separate modes of interaction (e.g., foot pedals) or that involve automated processes not under the control of the performer.

Measurement Systems for Performance Analysis

In addition to general-purpose optical motion-tracking systems often used in performance analysis, several sensor technologies have been developed specifically for the keyboard. The systems in this section appear to be designed primarily to generate data for later offline analysis rather than for new modes of real-time musical control, although the systems could presumably be adapted to the latter purpose.

The Bösendorfer 290SE reproducing grand piano features a measurement system for continuous key angle as well as MIDI (Moog and Rhea 1990);

this feature is also present on the successor CEUS system. Bernays and Traube (2012) have developed a software toolbox for extracting subtle gestural detail from CEUS key angle data. Aristotelis Hadjakos developed several sensor systems for motion capture at the piano, including ones that use accelerometers (Hadjakos, Aitenbichler, and Mühlhauser 2009) and the Kinect depth camera (Hadjakos 2012). MacRitchie and Bailey (2013) developed a piano-specific system for tracking the fingers and wrists using a high-speed camera and painted dots on the knuckles. Grosshauser and Tröster (2013) explored attaching custom force-sensing resistors onto the keyboard surface to measure location and pressure. For a general review of musical instrument sensor techniques, see Medeiros and Wanderley (2014).

Keyboards Integrating Continuous Control

Following the development of the Moog Multiply Touch-Sensitive keyboard in the 1970s and 1980s (Moog and Rhea 1990), several other instruments have been created that incorporate continuous measurement. Freed and Avizienis (2000) created a keyboard controller that measured the continuous angle of each key and that could stream data over a digital audio or Ethernet link. My own TouchKeys system (McPherson and Kim 2011a; McPherson 2012) added capacitive touch sensing to the surface of the keys, providing two-dimensional measurement of each finger position. This system, which is further described later in this article, is designed to attach to any existing keyboard. Data from each dimension can be flexibly mapped to MIDI or Open Sound Control (OSC) messages. Jeff Snyder's JD-1 synthesizer controller (Snyder and McPherson 2012) also uses capacitive sensing, measuring the continuous contact area of the fingers on fixed aluminum keys.

Recent commercial examples include the Endeavour EVO (Kirn 2012), which used capacitive sensing on one axis to measure finger position along a portion of the key, and the Keith McMillen QuNexus (www.keithmcmillen.com/qunexus), a miniature pressure pad controller in a keyboard layout that features

polyphonic aftertouch. Roger Linn's Linnstrument (www.rogerlinndesign.com/linnstrument.html), the Keith McMillen QuNeo (www.keithmcmillen.com/QuNeo), and the Eigen Labs Eigenharp (www.eigenlabs.com) include pressure pads that sense tilt in two axes, though the pads are organized in a grid rather than a keyboard layout.

Some instruments have taken continuity a step further by replacing discrete keys with a single continuous control surface. Lippold Haken's Continuum Fingerboard (Haken, Tellman, and Wolfe 1998) presents the performer with a continuous pressure-sensitive control surface that measures the three-dimensional position of each finger. The horizontal axis is commonly used to control pitch, and printed patterns on the surface indicate where the black and white notes might be found.

The ROLI Seaboard (Lamb and Robertson 2011) also uses a continuous pressure-sensitive control surface shaped into raised "keywaves" resembling the black and white keys. Both the Continuum and the Seaboard allow the performer to glide between notes by dragging a finger horizontally. To address the challenge of starting a note in tune on a continuous surface, both instruments have options to guide the starting pitch toward the nearest semitone. The desire for finer control over pitch has also prompted the development of microtonal keyboards (Keislar 1987) with more than 12 keys to the octave, though each key tends to be a discrete control (onset and release only).

Augmented Instruments with Continuous-Control Keyboards

In 2009, I developed the magnetic resonator piano (McPherson 2010), which manipulates the vibrations of the acoustic piano using electromagnets (see also the Electromagnetically-Prepared Piano, Bloland 2007). The electromagnets induce vibrations in the strings independently of the hammers, enabling infinite sustain and crescendos from silence. Initially the instrument was controlled by two MIDI keyboards, but to achieve the full potential of continuous note shaping, control from the keyboard

with more detail was needed. In 2010 I modified a Moog PianoBar (described subsequently) to measure continuous key angle at a rate of 600 Hz per key (McPherson and Kim 2010). Multidimensional mappings between key motion and magnet signals allow continuous shaping of the volume, pitch, timbre, and even individual harmonics of each note. This work laid the foundation for the later redesign of the keyboard scanner presented in the following section.

In a similar vein, Shear and Wright (2012) augmented the Fender Rhodes electric piano to manipulate the vibrations of the metal tines using electromagnets, with continuous key angle used to alter their volume. Other augmented keyboards have taken a different approach, adding external sensors that are aimed at the hands while they play the keys. Yang and Essl (2012) use a Kinect above a MIDI keyboard to create a three-dimensional control space above and around the keys; Gillian and Nicolls (2012) and Van Zandt-Escobar, Caramiaux, and Tanaka (2014) use Kinect tracking with gesture recognition to control audio processing of the acoustic piano sound. William Brent's Gesturally Extended Piano (Brent 2012) uses IR camera blob tracking to track the hands and forearms, controlling real-time audio processing. Hadjakos and Waloschek (2014) demonstrated the use of wrist-worn accelerometers to add vibrato to a MIDI keyboard by shaking a hand back and forth.

Active Haptic Control

A final class of continuous-control keyboards focuses not on the sound production, but on the feel of the key action. Tactile feedback is important for expert performance (Goebel and Palmer 2008), but a limitation of MIDI keyboards is that their action feels identical regardless of sound setting. Cadoz, Lisowski, and Florens (1990) created a high-bandwidth active-force feedback system using a specially designed motor whose goal was to recreate the feel of familiar keyboard actions including the piano and harpsichord. A similar concept was patented by Richard Baker (1990). This work was further extended in Brent Gillespie's Touchback

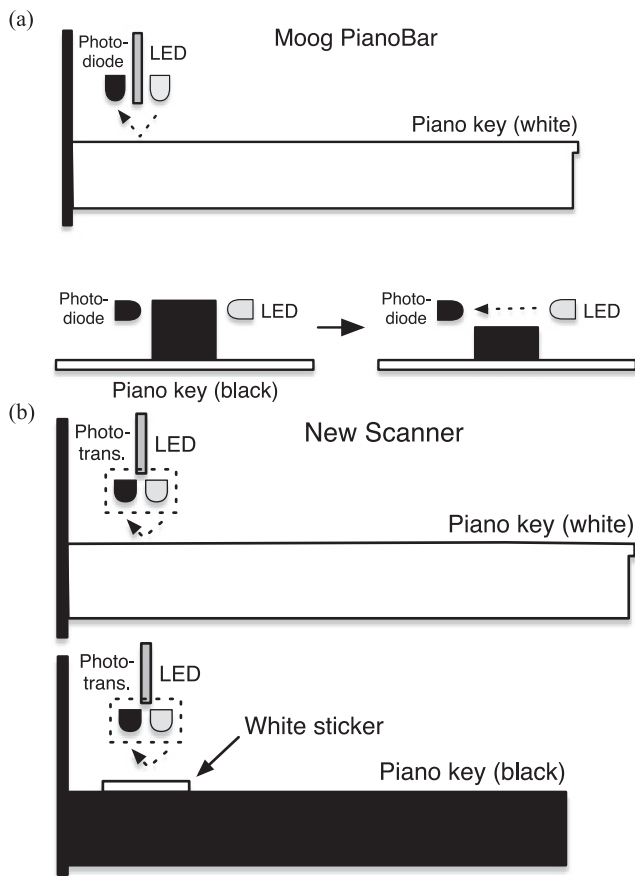
Keyboard (Gillespie 1996; Gillespie et al. 2011) and Oboe and De Poli's MIKEY (multi-instrument virtual keyboard, cf. Oboe and De Poli 2002; Oboe 2006). Lozada, Hafez, and Boutillon (2007) use magneto-rheological fluid to achieve similar force feedback. Bill Verplank's "Plank" allows force-feedback keys to be built from voice-coil motors taken from surplus hard drives (Verplank, Gurevich, and Mathews 2002).

Discussion

Many new keyboard instruments have been invented over the centuries, but few have caught on. In the past decade, new controllers have flourished in both the academical and commercial worlds, so perhaps we will see a greater adoption of new keyboard instruments in the coming years. Still, two impediments to wider use stand out. First, most new instruments have been expensive and many were heavy or unwieldy, limiting their appeal to the most dedicated performers. Second, keyboard technique is already challenging, and continuous polyphonic control is harder still. In an interview (*New Jersey Star-Ledger*, 13 March 2006), John Eaton reflected on the Moog Multiply Touch-Sensitive Keyboard: "It's very difficult to play. But an instrument should be difficult to play. That's the only way to master musical materials, by overcoming these difficulties."

With widespread, low-cost sensor technology and few limitations on real-time audio synthesis, current challenges for continuous-control keyboards are not technical but human. The capabilities of the player—including the lengths of the fingers, the constraints of traditional technique, and the sensorimotor processes developed through years of practice—must become explicit considerations in the design of new instruments. In many cases, a new sensor dimension is only as useful as the mapping that is applied to it (for a discussion of playing new interfaces, see Paradiso and O'Modhrain 2003). When working with an established interface like the keyboard, it is particularly important that new mappings do not interfere with familiar technique (McPherson, Gierakowski, and Stark 2013).

Figure 1. Optical sensing architecture for the Moog PianoBar, with a side view of white key and a front view of black key (a) and new scanner, with a side view (b). The PianoBar uses beam-interruption sensing on the black keys, which does not allow measurement of continuous key angle.



Measuring and Mapping Continuous Key Angle

Though note onset on the acoustic piano is essentially a discrete process defined by the instant when the hammer, flying freely, strikes the string, the hand and finger motions used in playing the piano are continuous and multidimensional. Whether or not these extra dimensions have any direct acoustic effect, they can be reliably controlled by the performer (Goebel, Bresin, and Galembo 2005; McPherson and Kim 2011b) and thus they can be used for augmented piano performance (McPherson and Kim 2010).

The Bösendorfer 290SE and CEUS acoustic pianos incorporate sensors measuring the continuous angle of each key (500 Hz, 8-bit sampling on the CEUS; see Bernays and Traube 2014). The cost and scarcity

The new design uses identical reflectance sensors on each key, each sensor containing an LED and phototransistor in a single package.

of these instruments mean that few composers will make use of this capability, however. Indeed, any electroacoustic music involving acoustic piano can face barriers to performance. Few venues have MIDI-enabled acoustic pianos, so when performance data from the keyboard is needed, electronic keyboards are often used even if an excellent acoustic instrument is available.

This section presents a new hardware solution for portable, detailed sensing of continuous key angle on any acoustic piano, featuring communication and mapping options specifically aimed at electroacoustic and augmented instrument performance.

Moog PianoBar

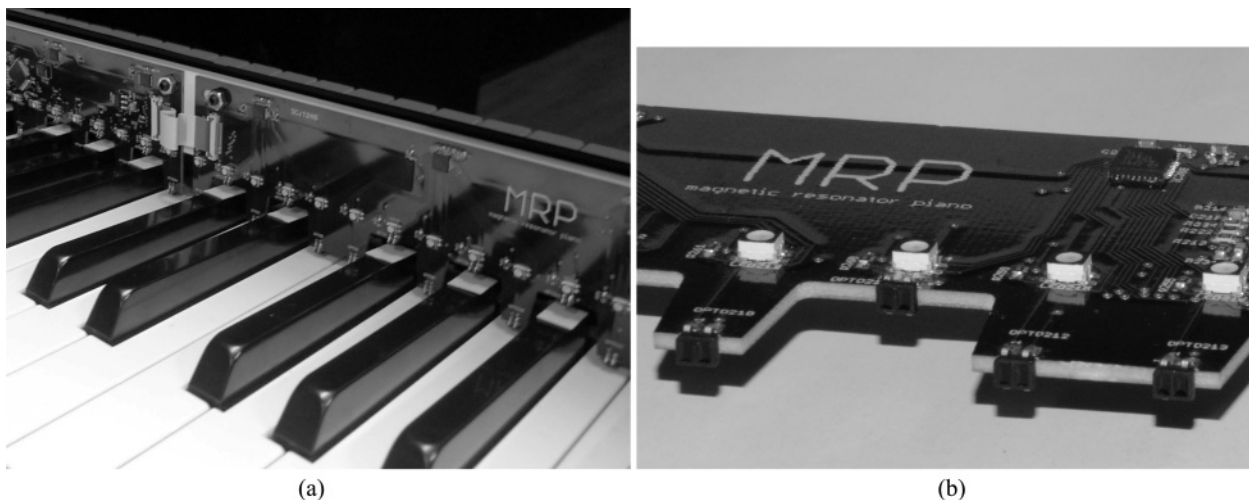
The PianoBar, designed by Donald Buchla in 2001 and sold by Moog Music from 2003 to 2007, is a popular accessory for combining piano with electronics. An optical sensor strip rests at the back of the keyboard, generating MIDI data in response to key motion. Discontinued for several years, the PianoBar has now become increasingly scarce but remains in demand as one of the few convenient, practical options for adding MIDI capability to any acoustic piano.

Internally, the PianoBar uses optical reflectance sensing to measure the white keys and beam-interruption sensing on the black keys (see Figure 1a). A separate magnetic proximity sensor measures the position of the left (*una corda*) and right (damper) pedals. LEDs within the keyboard sensor bar indicate active notes, with orange LEDs used for the white keys and green LEDs for the black keys. Unlike most systems, which are tied to a specific instrument or require lengthy setup and calibration, the PianoBar can be deployed in less than five minutes.

Motivation: Beyond the PianoBar

The scanner system described here aims to address the void left by the discontinuation of the PianoBar, while adding new capabilities for performance and research that go beyond any existing key-angle measurement system. Goals include:

Figure 2. Optical scanner hardware. Optical sensors, each containing an infrared LED and phototransistor in a compact package (b). White stickers are attached to the black keys to increase their reflectance. View of reflectance sensors, each containing an infrared LED and phototransistor in a compact package (b).



1. Continuous key angle at high temporal and spatial resolution, from which MIDI data can be derived as needed.
2. Real-time extraction of key-touch features associated with aspects of keyboard technique that go beyond velocity. These include percussiveness (pressed versus struck keys, see Goebel, Bresin, and Galemba 2005) and aftertouch (key pressure).
3. Flexible mapping options from key motion to sound, building on standard protocols, such as OSC (Wright and Freed 1997), and augmented instruments, such as the magnetic resonator piano (McPherson and Kim 2010).
4. Rich visual feedback from RGB LEDs above each key, providing contextual information beyond MIDI note on and note off.
5. Physical portability, including the ability to pack down in pieces.

Direct hammer measurement (as found in the Bösendorfer instruments) and extended sensing capabilities (capacitive, video, etc.) were impractical within the setup and portability constraints. Hardware audio synthesis (as found in the PianoBar) was not a priority. The height of the PianoBar scanner can be accidentally changed when bumped, so a more secure adjustment mechanism was desired,

even if this required a somewhat longer setup time. Finally, because most current practice uses computer processing rather than hardware MIDI synthesis, a USB connection was preferred to the MIDI ports found on many systems.

Hardware Design

Figure 2 shows the scanner design, which features four circuit boards attached to an acrylic mounting bracket. Each board covers roughly two octaves of sensors (25 sensors for the top board, which includes the high C, and only 15 for the bottom board).

Optical Sensors and Communication

Near-field optical reflectance sensing is used to measure the position of each key. Fairchild QRE1113 sensors, which include an LED and a phototransistor in a compact package, are mounted across the bottom edge of each board (see Figure 2). A schematic of the circuit and analysis of its operation can be found in an earlier publication (McPherson 2013b). Sensor data is reported at a 1-kHz sample rate for each key, with 12-bit resolution. To reduce noise and interference from ambient light, each sample is the average of eight differential measurements.

Each differential measurement is the difference between the reading with LED on and the reading with LED off; thus, each 1-msec sample contains 16 analog-to-digital conversions.

An important difference from the Moog PianoBar concerns the treatment of the black keys. On the PianoBar, the emitter and detector are placed on opposite sides of the key, such that the key interrupts the beam when at rest (see Figure 1a). Although this is sufficient for MIDI note-on and note-off data, the arrangement cannot sense continuous key position over the entire key range. My previous work modified the PianoBar to extract continuous sensor values (McPherson and Kim 2010), but many of the novel mappings, which depended on full-range key position, were only possible on the white keys. By contrast, the new scanner uses identical reflectance sensors on every key. Because the black keys do not reflect enough light to be reliably measured, removable white stickers are affixed to them before the scanner is installed (see Figure 1b). The stickers can be small, using residue-free adhesive, and they do not shorten the playable length of the black keys beyond the space already taken up by the scanner. The process of affixing stickers adds two to three minutes to the setup time, but the higher data quality easily outweighs this drawback.

Measurements of key position are sent to a computer via USB (Communication Device Class), using a custom binary protocol. In practice, data rates of approximately 2 Mbps are required to fully sample an 88-note keyboard, comfortably within the 12-Mbps capability of full-speed USB.

RGB LEDs

The PianoBar included orange or green LEDs over each key. When I used the PianoBar on the magnetic resonator piano (see the earlier *Augmented Instruments* section; also, McPherson and Kim 2010), performers often asked what the colors meant, suggesting that multicolored LED feedback could provide useful additional information. The new scanner includes RGB LEDs above each key that can be set to arbitrary hue, saturation, and brightness. The *Mappings* section, later in this article, discusses possible relationships between key motion and

LED color; ultimately, any relationship is possible, including driving the LEDs independently of the keys.

Real-Time Data Analysis

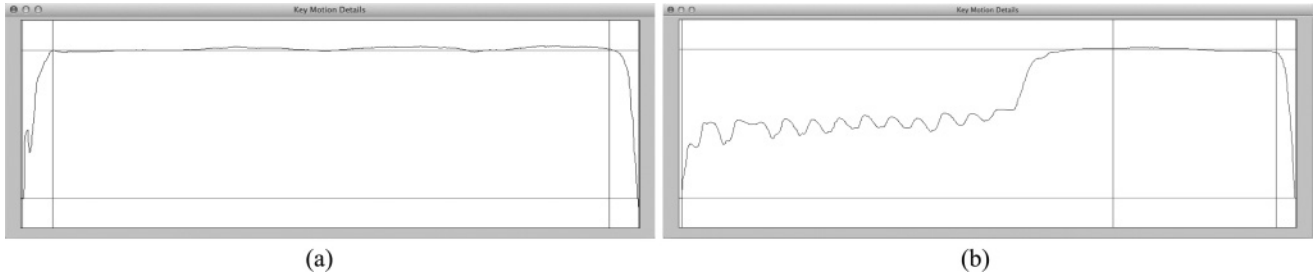
This scanner is intended to provide multidimensional key-gesture sensing on any piano. Continuous key angle data significantly exceeds the level of detail provided by MIDI, and it can be used to derive several features of each key press (McPherson and Kim 2011b). Prior to use, the scanner is calibrated by pressing each key to set the minimum and maximum values. From this point, in addition to raw sensor data, each new note onset generates several features:

1. Velocity, similar to MIDI, but the point of measurement (“escapement point”) can be changed programmatically, unlike other scanners. For example, a shallower escapement point will respond more quickly to new key presses. Resolution of the measurement is not limited by 7-bit MIDI.
2. Percussiveness, which includes several features related to the initial velocity spike that struck keys exhibit. This includes magnitude and location of the initial velocity spike and the relative amount that the key position changed before and after the spike. An overall percussiveness score is also calculated, which can be mapped to an independent dimension of sound production. Previous work showed that performers can control percussiveness and velocity independently (McPherson and Kim 2011b).
3. Aftertouch, or weight, which measures the amount of force the player exerts on the key bed. This can be a single score, immediately following note onset (the deepest point of the key throw), or it can be measured continuously throughout a key press.
4. Release velocity, supported by the MIDI standard but rarely implemented, measures the speed of key release. This is calculated identically to onset velocity at a

Figure 3. Continuous key position for two notes. A note played percussively with aftertouch (a). Note the spike at beginning and position variations at full

press. Vertical lines indicate beginning and end of onset and release phases. A vibrato gesture played by shaking the key between thumb and

forefinger (b), which produces a harmonic glissando on the magnetic resonator piano.



user-definable position threshold. Alternatively, with careful calibration, continuous key position can identify the point at which the damper first lightly touches the string during a slow release, and also when the damper fully rests on the string.

Figure 3 shows two plots of key motion with these features; these plots are generated in real time from the controller software. Internally, the software operates a state machine, which tracks the minima and maxima of the key position, segmenting each note into onset, sustain, and release phases. The software also captures partial key presses and taps that would fall below the traditional note onset threshold.

Mappings

The scanner is intended to be a flexible device for capturing the expressive details of keyboard technique. This section describes two approaches to mapping, one that generates MIDI data, and another that applies to the magnetic resonator piano (McPherson and Kim 2010). Users are also free to develop their own mappings based on raw data or features communicated by OSC.

MIDI Mappings

MIDI onset and release, with velocities, can be derived from continuous position. Key pressure, as detected by subtle variations in position when the key is fully pressed, is transmitted as polyphonic aftertouch. The software can act as a virtual MIDI source for other programs.

A novel MIDI mapping is the use of the percussiveness feature to trigger a second instrument. In this mode, each key press generates MIDI notes on two channels. The first channel retains the standard behavior, whereas on the second, the onset velocity corresponds to the percussiveness of the note. An example musical application uses a sustained voice with slow attack (e.g., strings) on the main channel and a short, percussive sound (e.g., marimba) on the percussiveness channel. In this way, the type of key touch creates a readily apparent variation in the output sound quality.

In MIDI mode, the RGB LED over a key lights up green on the initial touch. When the key reaches the key bed, further pressure (aftertouch) alters the hue of the LED, moving toward red at maximum pressure. Notes played percussively begin with a blue flash to indicate the different touch.

Magnetic Resonator Piano

The magnetic resonator piano (MRP) is an electromagnetically augmented acoustic piano (see the Augmented Instruments section of this article). In 2011, the MRP underwent a complete redesign and several rounds of polishing in response to collaborations with composers and performers (McPherson and Kim 2012). Continuous key motion is foundational to MRP technique, and this is the first scanner to enable the use of a full complement of extended techniques on both black and white keys. Several mappings have been developed that depend on key position, velocity, and the state of the detection system.

Key position, before it reaches the key bed, determines the *intensity* of the note. Intensity is an

intermediate parameter that can, in turn, be mapped to changes in amplitude and spectral content. Lightly touching the keys without pressing them all the way down can thus produce soft, subtle tones. When the key is down, key pressure engages as a second *brightness* dimension that is mapped to the spectral centroid of the electromagnet waveform, pushing the energy higher up the harmonic series for a brighter sound. On release, intensity again scales with position, enabling gradual releases. Because piano keys bounce slightly after release, a post-release state suppresses any sound from these unwanted motions.

Key vibrato is an extended technique made possible by the scanner (see Figure 3b). When the low-pass filtered key velocity exhibits periodic positive and negative peaks spaced less than 300 msec apart, the vibrato mapping is engaged. A vibrato motion causes a progressive increase in the pitch of the note, which moves stepwise up the harmonic series of the string. In this way, tapping repeatedly on the key, or oscillating it between thumb and forefinger, causes a shimmering effect as the string rings at each of its harmonics.

Other mappings break down the traditional independence of the keys. On non-keyboard instruments, the sound of a note is strongly affected by what preceded it and what else sounds simultaneously. On the MRP, when one key is held down and a second key one or two semitones away is touched lightly, the partially pressed key bends the pitch of the original note. The bend is proportional to key position, with a full press bending the note to the pitch of the second key. This enables detailed control of portamento effects.

In MRP mode, the RGB LEDs scale in brightness with key position for partial presses. Pitch-bend gestures, which always involve two or more keys, shift the hue toward the blue end of the spectrum, with green indicating no bend and violet indicating a bend of over one full semitone. Harmonics produced by vibrating the key cycle rapidly through the hues with a lower color saturation (i.e., a whitish tint). These visual mappings highlight the activation of the extended techniques and help the performer regulate their execution.

Observations on Performance

Two interesting observations have emerged from using the new scanner with the MRP as opposed to the earlier modified PianoBar. First, the MRP sounds slightly different, depending on which scanner is used, even though both support the same techniques (on the white keys) and the electromagnetic hardware is identical. The response to key motion on the new scanner tends to sound smoother and more predictable, probably because its ground-up design for continuous angle eliminates some subtle timing and resolution problems on the modified PianoBar. This shows that the keyboard, even when it is mechanically independent of the sound production, can play a crucial role in establishing an instrument's character.

Second, for some musicians, the limitations of the PianoBar and the subtle artifacts it introduces into the strings became a crucial part of the MRP's musical character. It may therefore be necessary to emulate some of the apparent failures of the original technology (especially certain forms of sensor noise) in order to capture the original sound. The experience here mirrors the "key click" effect on the Hammond organ, which was a byproduct of routing audio signals through mechanical contacts on each key. Originally considered a design flaw, it became a cherished part of the Hammond sound that all modern synthetic recreations must emulate.

TouchKeys

Beyond continuous key angle, a promising source of continuous control from the keyboard is the location and motion of the fingers on the key surfaces. Sliding or rocking the fingers on the keys are gestures that are easy to understand, but historically they have been hard to detect. Robert Moog's Multiply Touch-Sensitive keyboard (Moog and Rhea 1990) is perhaps the only previous instrument that allowed polyphonic, two-dimensional measurements of finger position on the key surface, but it never moved beyond the prototype stage.

Figure 4. TouchKeys sensor overlays installed on the surface of a keyboard. The surface of each overlay contains 26 capacitive sensor pads.



This section presents the TouchKeys, capacitive touch-sensor overlays that attach to the surface of any keyboard, transforming each key into a continuous multi-touch control surface. An introduction to the TouchKeys idea was presented in McPherson and Kim (2011a), and further details on the capacitive sensing hardware have been documented in an earlier publication (McPherson 2012). A mapping approach to add vibrato and pitch bends is described by McPherson, Gierakowski, and Stark (2013), and an experimental approach to controlling a physically modeled guitar is described by Heinrichs and McPherson (2012). After a brief overview of the sensors and their integration into the keyboard, this article introduces three new mappings that add new effects during note onset and release.

Hardware

Figure 4 shows the TouchKeys sensor hardware. Each sensor consists of a circuit board with 26 capacitive sensor pads on the top and a microcontroller on the bottom. The sensors attach to any full-sized keyboard using strong but removable adhesive. The board and adhesive together are 1.6 mm thick and weigh 5 g (white) or 2 g (black). The added height is the same for every key, and the weight does not significantly alter the keyboard action. Controller boards placed inside the instrument gather data from the sensors via flexible ribbon cables and stream it

to a computer via USB. The modular design allows for any keyboard size from one to eight octaves.

The sensors measure finger position along two axes at a sampling rate of 200 Hz, with 8-bit resolution in the narrow (horizontal) axis and more than 10-bit resolution in the long (vertical) axis. Up to three fingers per key can be sensed, and the contact area of each touch is also measured, differentiating fingertip from the pad of the finger. These capabilities have evolved over several design iterations in response to feedback from performers. For example, the initial design had only a single sensor dimension on the black keys (McPherson 2012), but in response to a study on vibrato (McPherson, Gierakowski, and Stark 2013), the sensors were redesigned to support two-dimensional control like the white keys.

Integration and Mapping

The TouchKeys are intended to be used with a MIDI keyboard, as the capacitive sensors do not measure key motion. Cross-platform, open-source software (code.soundsoftware.ac.uk/projects/touchkeys) integrates MIDI and touch data, generating MIDI or OSC output messages that can control any synthesizer. The key to this process is a set of modular mappings (see Figure 5) that support a variety of flexible relationships between finger motion and sound.

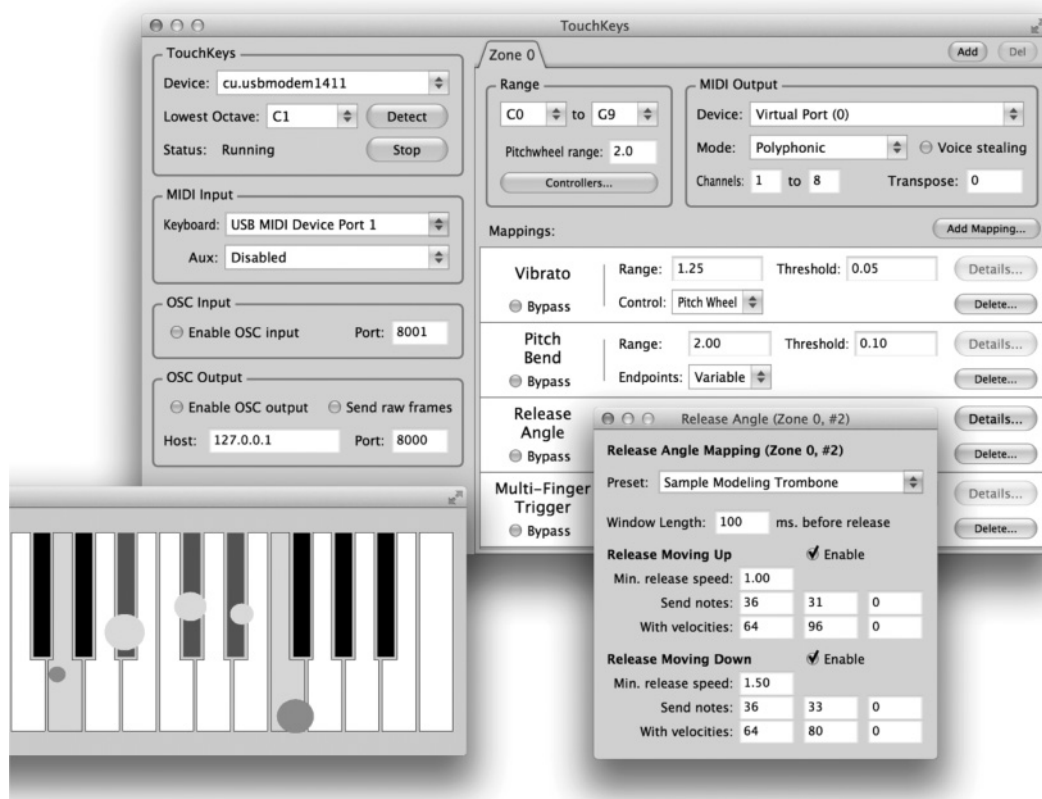
Sustain Shaping: Simple Mappings

Any touch dimension (x or y position, contact area, distance between multiple touches) can be assigned to any MIDI continuous-control parameter, including pitch bend or aftertouch. Touch data can be used either raw or relative to their value at note onset, and the ranges are adjustable. These mappings allow the player to shape the sustain of the note, and they are well suited for timbre effects.

Vibrato and Pitch Bend

Controlling pitch presents a number of subtleties if the instrument is to avoid interfering with traditional technique. One mapping allows the player to add vibrato by rocking a finger horizontally

Figure 5. TouchKeys software interface, including touch display (left), general settings with list of mappings (center), and detailed settings for the release angle mapping (right).



on the key surface. Horizontal motion on the keys is common when relocating the hand, however, so a back-and-forth motion is required before the vibrato engages.

Another mapping creates a pitch bend when the finger slides back and forth on the long axis of the key. To maintain playability, the initial contact location always produces the expected pitch, and only by moving the finger beyond a specified threshold (e.g., 10% of the key length) does the pitch bend engage. The pitches at the endpoints of the keys can be “variable” (pitch bend depends directly on the distance moved) or “fixed” (reaching the end of the key in either direction always produces a known bend, e.g., two semitones up or down). In previous work, we also experimented with automatically snapping the note into the nearest semitone when the bend stops (McPherson, Gierakowski, and Stark 2013).

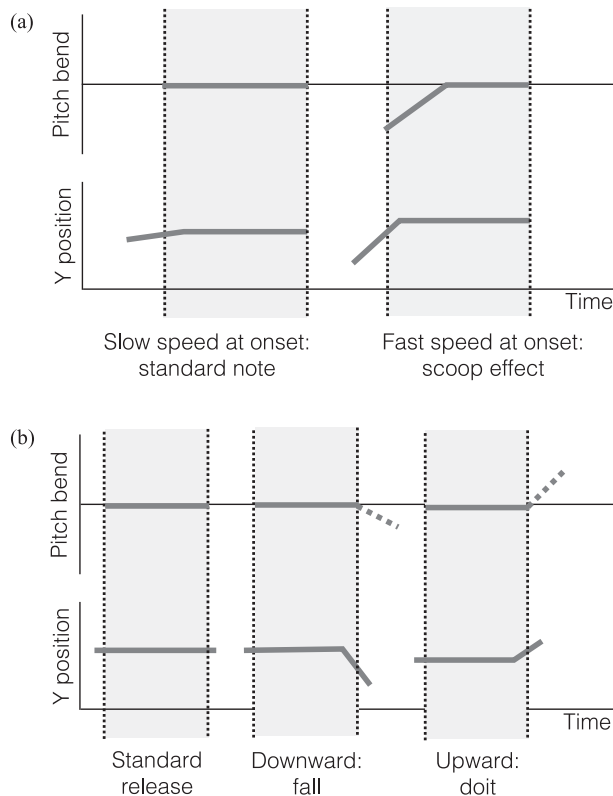
Onset Shaping

The mappings presented thus far shape the sustain of the note between its onset and release. As discussed earlier in this article, however, onset and release also have possibilities for continuous control beyond the simple MIDI-velocity model.

In jazz saxophone technique, a *scoop* is a note that begins below its intended pitch and rises into it. The TouchKeys software includes an “onset angle” mapping, which can add a scoop at the beginning of a note. Figure 6a shows its operation. To trigger a scoop, the key is pressed with the finger already in motion along the y-axis (i.e., sliding away from the performer). When the MIDI note-on message from the key is received, the mapping looks back through the preceding frames of touch data to calculate the speed of the finger. If the speed exceeds a threshold (chosen to avoid interference with traditional playing), the scoop is triggered. The

Figure 6. Onset angle mapping adds a scoop effect when finger is in motion at note-on (a). Release angle mapping

adds falls, doits, or other configurable effects for finger motion at note-off (b).



note begins the pitch bend one or two semitones below its normal value. The pitch then linearly ramps up to its normal value over a short time (50 to 200 msec). Faster finger speed produces a larger and longer scoop, although in principle these two dimensions could be controlled independently.

Alternatively, the same measurement of finger speed could control other effects at onset.

Special Release Effects

Finger speed can also be measured on note release. In the “release angle” mapping, when a MIDI note-off message is received, the mapping looks back through preceding touch data to calculate finger speed along the y-axis (see Figure 6b). In standard technique, this speed is typically low, with the finger lifting straight off the key rather than sliding along it. Therefore, a deliberate motion in either direction can be mapped to new effects.

In the current system, the mapping is designed for use with wind and brass synthesis, where it triggers fall and doit effects. These are jazz techniques where the pitch of the note drops or rises, respectively, as the note is released. The mapping uses key switches provided by the synthesizer: When a particular MIDI note is received outside the sounding range of the instrument, the fall or doit is executed by the synthesizer.

These onset and release mappings introduce an important principle in keyboard gesture mapping: The timescale of the sound effect need not match the timescale of the physical gesture. Digital musical instruments often take a frame-by-frame approach to mapping, where the current frame of sensor data controls the current sound-synthesis parameters. By contrast, the finger motion here precedes the audible effect, and the length of time the finger is in motion may differ from the length of the scoop or fall. In my experience, these mappings do not feel any less immediate to play than the frame-by-frame mappings during a note’s sustain. After all, any keyboard playing already involves preparatory gestures before the sound.

Rapid Retrigger

On the keyboard, unlike many other instruments, fast repetitions of the same note are difficult. The multiple finger sensing of the TouchKeys can be used to bypass this limitation: When a second finger is added to a held note, a new onset message can be generated. Optionally, onset messages can also be generated when the second finger is removed, making rapid tremolo effects easy to play.

Distribution via Kickstarter

As discussed earlier, many new keyboards have been invented, but few achieve widespread use. Impediments include cost, inconvenience, and general availability. To get the TouchKeys into the hands of musicians, I launched a Kickstarter crowd-funding campaign (www.kickstarter.com/projects/instrumentslab/touchkeys-multi-touch-musical-keyboard) in 2013. The campaign successfully

supported the distribution of instruments and self-install sensor kits to musicians around the world. Further discussion on this campaign and the value of crowd funding for the instrument design community can be found in McPherson (2013a).

Conclusion: Beyond “Beyond the Keyboard”?

Inexpensive, ubiquitous computing power has enabled a huge variety of new instruments offering “control and interaction beyond the keyboard paradigm” (Miranda and Wanderley 2006, p. xx). The real and exciting promise of radically new forms of musical interaction can create a temptation to see the keyboard as a throwback, an engineering necessity of previous eras or an easy default for designers who could find more creative solutions. History suggests otherwise. Not only have keyboards been used for over 500 years, surviving many generations of new technology, they have also been incorporated into instruments that were already fully functional without them, including glass harmonica derivatives and the Ondes Martenot. Fundamentally, musical instruments depend at least as much on human factors as on technology. Whether because of something inherent in its design, or simply because of the inertia of previous training, generations of players have found the keyboard to be conducive to their musical ends.

Nonetheless, not all keyboards are equivalent, and there is good reason to believe that the discrete control offered by typical MIDI keyboards imposes unnecessary limitations on current digital instruments. For most of the instruments mentioned in this article, their characteristic sounds would not be possible with only discrete onsets and releases. Moreover, the harpsichord, clavichord, pipe organ, Ondes Martenot, and Hammond B3 are all keyboard instruments, but no two feel or behave alike. Yet all will be at least passingly familiar to a trained pianist. New continuous-control keyboards have the potential to connect with the expertise of millions of performers, while offering new ways to shape the sound.

The Value of Imperfection

In the early days of electronic music, its proponents cited the tantalizing promise of being able to create any sound imaginable, freed from the constraints of mechanical acoustic instruments. But an essay by J. A. Fuller-Maitland, written over 90 years ago, seems prescient, pointing out that precisely because of the interest in creating “perfect” instruments, that “it seems worth while to point out what value there may be in the inherent defects of the various instruments, and in how large a measure their character is due to these very shortcomings” (Fuller-Maitland 1920, p. 91).

Perhaps we are in a similar situation today with the control of musical sounds. Dolan (2013, p. 11) suggests that the keyboard has, historically, been associated with a vision of complete technological control of music, and more fundamentally, “that the basic idea of what we think of as music is bound up with the interface of the keyboard.” Dolan’s suggestion refers not only to keyboard music, but to the Western musical canon at large. The idea that the organization of music is inherently tied to the tools for making it is echoed in a different form by Miranda and Wanderley (2006, p. xx): “those musicians interested in musical innovation are increasingly choosing to design their own new digital musical instruments as part of their quest for new musical composition and performance practices.”

In other words, the creation of new forms of control is perhaps a way to stretch the boundaries of music itself. There can follow a temptation to see the ideal instrument as one that allows as many degrees of freedom as possible, to control the widest possible artistic space. Tanaka (2000, p. 396), however, observes the tendency to control ever-increasing numbers of synthesis parameters, perhaps even across multiple media, cautioning that “the danger is in ending up not with a *Gesamtkunstwerk*, but with a kind of theme park ‘one-man band’.” Following Fuller-Maitland’s argument, the essential value of a musical controller may also be in its limitations as much as in its capabilities.

In closing, consider again the most famous of continuous-control keyboard instruments, the

clavichord. Kirkpatrick (1981, p. 295) provides a personal account of playing clavichord, talking not only of learning to control vibrato, but in learning when not to use it: "In later years, I was to use less and less of the kind of vibrato that obtrudes itself upon the attention of the hearer, reserving it only for the most subtle colouration of sound, and in my later recordings I eliminated it almost entirely." Even as new instruments change the way we interact with sound, the keyboard is likely to remain with us. There is much still to be developed and refined, but perhaps the greatest contributions will come not from complex multidimensional controls, but from new levels of nuance and subtlety.

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