RESEARCH-ARTICLE

Multidimensional gesture sensing at the piano keyboard

ANDREW P. MCPHERSON, Drexel University, Philadelphia, PA, United States

YOUNGMOO E KIM, Drexel University, Philadelphia, PA, United States

Published: 07 May 2011

Citation in BibTeX format

CHI '11: CHI Conference on Human Factors in Computing Systems
May 7 - 12, 2011
BC, Vancouver, Canada

Conference Sponsors:
SIGCHI

CHI '11: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (May 2011)
https://doi.org/10.1145/1978942.1979355
ISBN: 9781450302289

Multidimensional Gesture Sensing at the Piano Keyboard

Andrew P. McPherson
Drexel University
Electrical & Computer Engineering
apm@drexel.edu

Youngmoo E. Kim
Drexel University
Electrical & Computer Engineering
ykim@drexel.edu

ABSTRACT
In this paper we present a new keyboard interface for computer music applications. Where traditional keyboard controllers report the velocity of each key-press, our interface senses up to five separate dimensions: velocity, percussiveness, rigidity, weight, and depth. These dimensions, which we identified based on the pedagogical piano literature and pilot studies with professional pianists, together present a rich picture of physical gestures at the keyboard, including information on the performer's motion before, during, and after a note is played. User studies confirm that the sensed dimensions are intuitive and controllable and that mappings between gesture and sound produce novel, playable musical instruments, even for users without prior keyboard experience. The multidimensional sensing capability demonstrated in this paper is also potentially applicable to button interfaces outside the musical domain.

Author Keywords
Piano, keyboard, gesture sensing, multidimensional input, musical interfaces.

ACM Classification Keywords
H.5.5 Sound and Music Computing: Systems; H.5.2 User Interfaces: Input devices and strategies

General Terms
Design, Human Factors

INTRODUCTION
A great many computer music interfaces have been developed over the past decades, but the piano keyboard remains the interface of choice for most digital music tasks. Most interactions between human performer and computer instrument continue to be governed by the MIDI (Musical Instrument Digital Interface) standard [19], now more than 25 years old. MIDI specifies that motion on the keyboard be described as a series of discrete press and release events, with accompanying information on the velocity of each key-press. In this way, the complex mechanical system of the piano keyboard was reduced to a low-bandwidth information stream suitable for processing by 1980s-era computers.

Despite continual efforts by manufacturers to produce controllers closely emulating the sound and feel of the piano keyboard, pianists frequently express dissatisfaction with current interfaces, feeling them to be insufficiently "expressive." In their view, MIDI keyboards inadequately capture the nuances of fine piano playing, failing to replicate the subtle mapping between physical action at the keyboard and musical sound.[1] Since current keyboard technology reduces complex physical gestures to simple velocity metrics, even the most sophisticated synthesizer designer is restricted to an over-simplified picture of the performer's actions.

This paper presents an alternative approach to keyboard controller design, beginning not with the mechanics of the piano but with piano *technique*. Drawing on the extensive pedagogical literature and pilot studies with professional pianists, we have developed a new keyboard interface which measures five distinct gestural dimensions that pianists feel are important. In addition to capturing the subtlety of advanced piano performance, we seek to build an interface playable by a wide community of users, even those without prior piano training. A trio of user studies demonstrate this playability. Specifically, we show our interface possesses three important properties:

1. **Intuition:** The interface makes use of gestures familiar even to untrained users with no keyboard experience.
2. **Controllability:** Users can consciously control the new dimensions with high accuracy.
3. **Mappability:** Gestural parameters can be mapped to sound production in ways that are novel and musically useful.

After presenting the results of our user studies, we discuss applications of the multidimensional keyboard interface to both musical and non-musical tasks.

BACKGROUND

Mechanical Tactile Interfaces
With the recent interest in multi-touch interfaces and virtual on-screen controls, the venerable mechanical button is sometimes overlooked as a platform for future development. Yet mechanical buttons retain certain advantages: they offer natural tactile feedback and are particularly well-suited to

[1] Pianist Boris Berman's advice to students is typical: "Often overlooked is the need to work on an instrument that responds sufficiently to the nuances of touch. (No electronic keyboard will do, I'm afraid.)" [1]

vision-free interaction [11]. These qualities can be particularly advantageous in musical performance, where the user's visual attention is often focused on reading sheet music or interacting with other musicians.

Within the mechanical realm, interest has been growing in adopting pressure sensitivity as an additional input dimension, with recent studies examining finger pressure in the context of mobile phones [23], mice [2], and computer keyboards [3]. Certain MIDI keyboards have long featured "aftertouch" pressure sensitivity [19].

An oft-cited drawback to the mechanical button is its static nature, but this need not be limiting. Harrison [11] has developed a pneumatic interface generating dynamically configurable buttons. The Monome [15] computer music controller consists of a square grid of identical lighted buttons whose function can be dynamically assigned by the user. Even MIDI keyboard instruments, though they make assumptions about musical pitch structure, offer a certain degree of flexibility through patch (sound-set) changes.

Several researchers have developed music keyboards reporting additional information for each key-press. Freed and Avizienis [6] developed a keyboard with continuous key position sensing; Moog [16] presents a keyboard whose keys move in two dimensions and feature touch sensitivity on the surface. The Haken Continuum [10] erases the mechanical distinction between keys, allowing independent horizontal, vertical, and depth control of multiple presses.

The Piano "Touch" Controversy

The current state of the keyboard interface partly reflects a longstanding debate between pianists and acousticians. At the heart of the disagreement is whether, for identical key velocities, the type of "touch" (the quality of a physical key-press gesture) affects the tone of the piano. Acousticians dismiss this notion, arguing that the piano hammer is in free ballistic motion when it strikes the strings, putting it outside the control of the player [5]. Hence, the argument goes, the only meaningful effect of a key-press can be to impart an initial velocity to the hammer. By contrast, pianists continue to swear by a rich variety of keyboard gestures. From the earliest days of the instrument, pianists have been concerned with finding ways to attenuate the instrument's percussive nature in favor of pure, long-lasting tones [1, 7, 21].

In the 1920s, Ortmann showed that piano key motion could be classified into two types of touch: percussive (in which a moving finger strikes the key) and non-percussive (in which the finger begins at rest on the surface) [17, 18]. More recently, Goebl et al. [8] demonstrated that the percussive touch produces a characteristic noise when the finger strikes the key; when this noise was removed from recordings, listeners were unable to distinguish between piano notes with the same velocity, regardless of the touch used.

Since experiments have put to rest the notion that touch affects the timbre of the acoustic piano, computer music researchers have largely lost interest in the expressive nuances of key motion, content to model only the timing and velocity of key-presses. (On the other hand, interest in the broader biomechanical process of piano playing remains strong [9].) Pianists, however, continue to perform and teach using a rich vocabulary of gestures to which they ascribe expressive meaning. Regardless of whether different types of key-press gestures have an effect on the piano sound, they may be resolvable from the key motion itself. If so, then we could build an interface which measures and responds to the touch qualities pianists value, producing a multi-dimensional controller with both musical and pedagogical applications.

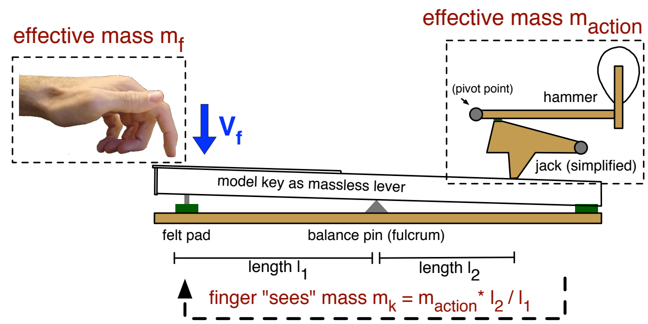

Figure 1. Simplified model of the piano action, approximating the interaction of finger and key as a collision between two simple masses.

DESIGN PRINCIPLES: MODELING THE PIANO KEYBOARD

To obtain the richest possible picture of performer-keyboard interaction, we will examine both the mechanics of the piano and the basic physiological techniques of human players.

Mechanics

Figure 1 shows a simplified diagram of the acoustic grand piano action. The key forms one end of a lever, the opposite end of which operates a series of additional levers culminating in a felt-covered wooden hammer. When the key is pressed, the hammer is thrown upward against the strings. A detailed discussion of piano action can be found in [5]; it is sufficient here to model the key as a massless lever, with the mass of the performer's finger and the hammer action acting on opposite sides. The key travels approximately 9 mm between its resting position and the key-bed, where it impacts a felt disc. Additional force on the key will compress the felt, allowing additional travel of approximately 1 mm. The instantaneous position of the key will thus be somewhere between 0 (resting) and 1 cm (depressed with maximum force).

Suppose that a constant force is exerted on the key, beginning from its resting position. We expect to see a linear increase in velocity (constant acceleration) throughout the stroke. Suppose, on the other hand, that the performer's finger is already in motion when it strikes the key surface. Let us model the finger (plus hand and arm) as a mass m_f with initial velocity v_f. If the collision is perfectly elastic, conservation of momentum tells us that the resulting key velocity will be $v_k = \frac{2m_f}{m_f+m_k}v_f$. In other words, an immediate spike in key velocity will occur, proportional to the momentum of the performer's finger.

After the collision, key and finger will tend to separate, and the key will lose velocity due to the weight of the action. If the performer continues to exert force, the finger will catch up with the key, causing a steady increase in velocity until it reaches the key-bed. The interval between initial impact and "catch-up" depends on a combination of elasticity of collision, force exerted by the performer, and weight of the muscles used (since a loose finger has a smaller effective mass than the whole arm, and thus will be repelled more strongly by the collision [22]).

Elements of Performance Technique

In summarizing his historical survey of pianists and their techniques, Gerig writes, "the pianist with the perfect technique is also a singer, a first-rate vocalist! The singing voice is the ideal tonal model and aid to phrasing, breathing, and interpretation." [7] (p. 520). Gerig divides historical techniques into two schools, those based primarily on the muscular action of rigid fingers and those based on applying the weight of relaxed larger muscles, advocating balance between these approaches. Sandor [21] makes a distinction between notes played by "free fall" versus "thrust" and places particular emphasis on maintaining "resilient" joints: "The essential quality in a singing tone is intensity, and this is true for soft as well as for loud sounds. The sound should carry; it should have body, it should be expressive, and it should have lasting quality. The playing mechanism, therefore, should be neither too hard nor too soft; the joints of the fingers, wrist, and hand must be supple, resilient, and elastic."

Berman [1] identifies five variables of piano touch: weight, mass, speed, perception of depth, and the shape of the fingers (pp. 10-12). He further distinguishes between two approaches to the keyboard: "in" (pouring weight into each note) and "out" (pulling the fingers away from the keys, "as if ... 'grabbing' the sound from the keyboard and bringing it out"). Schultz [22], departing from Ortmann's mechanical models [17, 18], classifies keyboard touch by the use of weight, pressure, or (muscular) fixation. Schultz analyzes the mechanics of the percussive key-press in detail, noting the effects of mass (finger vs. whole arm) and applied force after the collision (p. 42).

Though these authors (and indeed, every pianist) differ somewhat on the ideal technique, they share a goal of transcending the percussive mechanics of the instrument and a sense that musical expression and physical gesture are inextricably linked. Their writings reflect the collected knowledge of millions of pianists, developed over more than a century. For the designer of keyboard-based computer interfaces, it is hard to imagine a richer trove of data on human interaction. To identify the quantitative signatures of each type of playing, we next conducted pilot studies to isolate the important numerical factors of piano key motion.

SENSOR SETUP: QUANTIFYING KEY MOTION

In our previous work [13, 14], we developed a sensor to record the continuous position of each key (rather than traditional MIDI velocity). LEDs and photodiodes mounted above each key measure the amount of light reflected off the key surface, which is inversely related to the distance between key and sensor (Figure 2). Each photodiode is sampled at a rate of 600Hz with a resolution of 12 bits (8-10 bits in practice, given limited signal range). Samples are transmitted by USB to a host computer.

The system is calibrated by measuring the minimum and maximum light values for each key; key positions are subsequently normalized to a range of 0 (resting) to 1 (fully depressed). Continuous key velocity is calculated from the first difference of position. The sample rate is sufficient to capture anywhere from 10 to over 100 samples during the interval that the key is in motion, creating a detailed picture of each press. In our user studies, the sensor is installed on an acoustic grand piano; however, similar sensors could be integrated into an electronic keyboard or indeed any mechanical button interface.

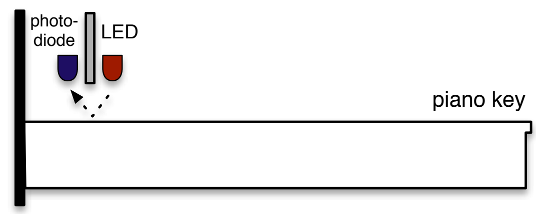

Figure 2. Optical reflectance sensors record the continuous position of each piano key, sampled 600 times per second.

Pilot Study: Identifying Dimensions of a Key-Press

We conducted pilot studies with four professional pianists, who played on a Steinway L grand piano equipped with our key position sensor. Subjects were given excerpts from the piano literature (Mozart, Beethoven, Schubert and Debussy) and asked to play each excerpt with several expressive affects. Subjects were also interviewed about their personal technique. Our goal was to identify the dimensions of a key-press that commonly varied with different expressive modes of playing. Our results identified four principal variables which closely align with the literature:

- **Velocity:** Key velocity controls the speed of the hammer and hence the volume of the tone. Naturally, it was the most important variable in all modes of playing.
- **Percussiveness:** The momentum of the hand in striking the key can vary from near-zero (finger begins resting on the key) to very high (large preparatory motions). The latter was often used in loud, forceful passages and to emphasize musical accents.
- **Rigidity:** For percussively-played notes, the hand muscles could be held loose or tight, and the principal force could come from the finger joints, the wrist, or the whole arm. We designate these low, medium, and high rigidity. For non-percussive notes, the difference was indistinguishable from key motion alone.
- **Weight:** Once the key impacts the key bed, weight on the key can range from just enough to hold it down to an exaggeratedly heavy touch. The latter was often seen in slow but intense music.

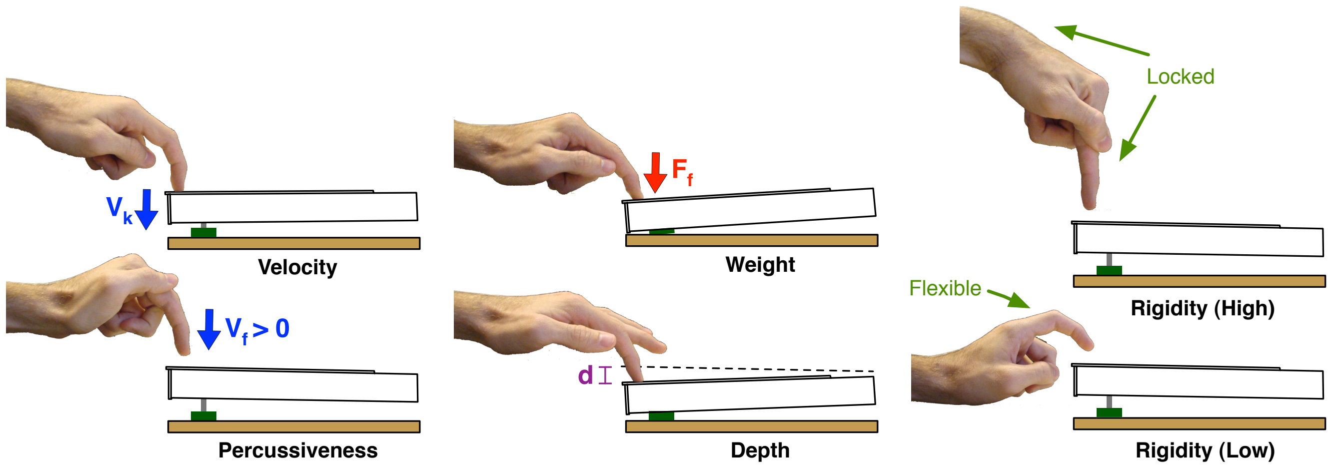

Figure 3. Five dimensions of a piano key press.

To this list we add one additional dimension not found in traditional piano playing, but easily controlled and measured:

- **Depth:** A key can be pressed completely or partially, stopping midway through its range of motion.

Figure 3 illustrates these five dimensions, by which every key-press can be measured.

Feature Extraction: Evaluating Each Dimension

Figure 4 shows position and velocity for two example key-presses. From each press we extract 12 features:

- Group A (1 feature): Overall velocity, measured at "escapement", where hammer flies free of the action (measured to be approximately key position 0.65).
- Group B (6 features): Magnitude, duration, and area under the velocity curve for the first velocity peak and trough.
- Group C (1 feature): Position at time of key-bed impact.
- Group D (4 features): Average positions and velocities for two brief post-impact intervals.

Group A (*velocity*) is self-explanatory. The features in Group B reflect our mechanical model, and can together be used to evaluate the *percussiveness* and *rigidity* of a press: a strongly percussive press will show a large initial velocity spike, where a non-percussive press will show none at all. Rigidity is evaluated by comparing the spike magnitude to its rebound. The features in Groups C and D reflect the reaction of the felt pad to varying key force. Group C directly measures the *depth* of press, where Groups C and D together assess its *weight*: a heavy press will hold the key deeply into the felt, where for a light press, the key will show a slight rebound after impact.

These features together present a detailed view of performer-keyboard interaction, from the preparation before the finger contacts the key to the way the performer responds after the key reaches the key-bed. The features can be used together or in specific combinations, either as continuous variables or as inputs to a discrete classifier system. Our user studies demonstrate the viability of both approaches.

USER STUDIES: OVERVIEW

We conducted three user studies to evaluate whether our interface is intuitive, controllable, and capable of useful musical mappings. Each study included 10 subjects (3 female, mean age 23.8), most of whom had little or no prior piano background. None of our subjects were professional performers or full-time music students; 3 of 10 subjects reported two or more years of piano training, with 5 subjects reporting no formal training at all. Asked to rate their piano familiarity on a scale of 1 (neophyte) to 10 (professional), subjects reported a mean of 3.4 (median 3, range 1-7).

All studies were conducted on a Steinway B grand piano which, like all pianos, provides auditory feedback proportional to key velocity. Subjects were presented each study in the order presented below. The order was chosen because the first study assumes no knowledge of the techniques under investigation, the second teaches and tests a few basic skills, and the third applies the skills to selected musical problems.

USER STUDY 1: GESTURE AND INTUITION

The purpose of this study is to evaluate the *intuitiveness* of the gestures used in our enhanced keyboard. Specifically, we want to resolve between the following hypotheses:

- **Hypothesis 1:** For a naive user, all key-presses differ only by velocity. Percussiveness, rigidity, weight, and depth relate linearly to velocity.
- **Hypothesis 2:** Naive users exhibit a range of values for each parameter, but the additional features can be considered as noise, having no correlation with expressive or gestural intent.
- **Hypothesis 3:** Even without knowledge of the system, naive users naturally demonstrate resolvable patterns along multiple dimensions.

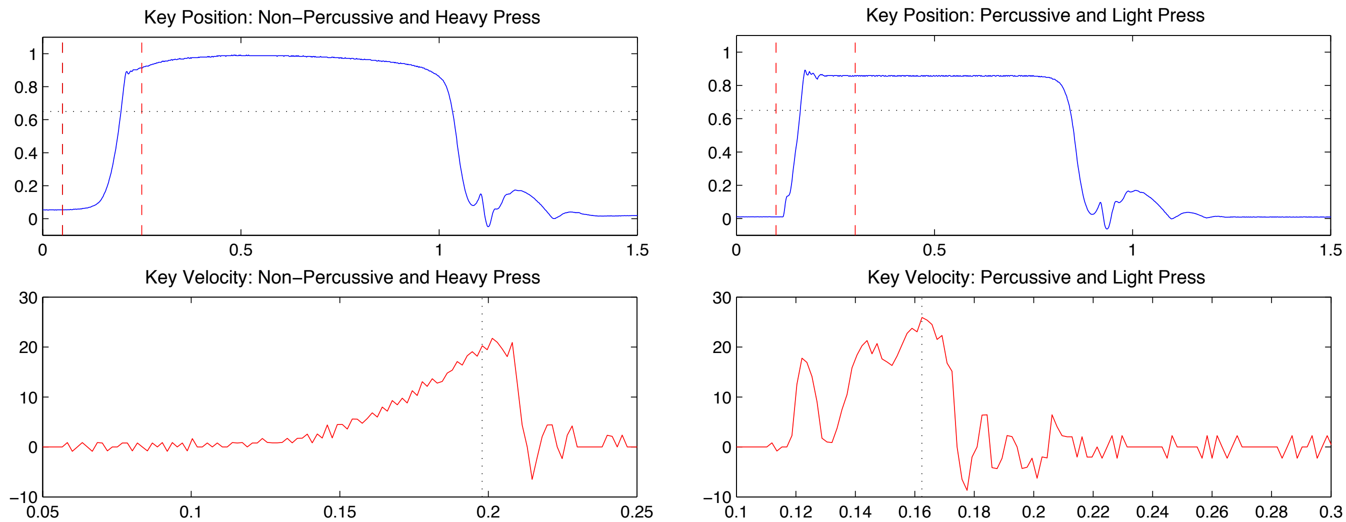

Figure 4. Key position and velocity measurements for two types of key-press. Velocity plots (bottom row) focus on the brief period of key motion (vertical dashed lines). Dotted lines show estimated position of hammer escapement. Times are in seconds, key position normalized 0-1.

Design
Subjects were taught to play a simple melody (Figure 5) consisting of 18 notes (5 distinct). Subjects were free to choose the most comfortable fingering. Once each subject felt comfortable with the melody, he or she was asked to play it in nine different whimsical styles: *normal (no cue)*; *very delicate, as if afraid of being heard*; *like Frankenstein*; *like flowing water*; *as if the keys are extremely hot to the touch*; *as if you're angry at the piano*; *like a bird pecking at the keys*; *as if the keys are very heavy and hard to press*; and *as if there are no bones in your hand*. The descriptions are deliberately chosen not to align with common musical terminology (*espressivo*, *legato*, etc.) so responses reflect intuition rather than acquired training. Although subjects were expected to have varying interpretations, the styles were designed to collectively elicit a broad range of physical behavior at the keyboard. Subjects were not told the purpose of the exercise so as not to bias their responses.

Each key-press was labeled by subject and style and scored according to the 12 aforementioned features. The complete data set thus consisted of $\approx 18 \times 9 \times 10 = 1620$ presses (performance mistakes slightly altered the exact number).

To accept or reject Hypothesis 1, principal component analysis was applied to the aggregate data set (with features normalized to zero mean, unit variance). Hypothesis 1, if correct, implies that most dataset variance should be attributable to a single component. Subsequently, to choose between Hypotheses 2 and 3, classifier learning systems were trained using the features as inputs and the style as output (i.e. a 9-class problem). Classifier performance was compared using 1 feature (Group A, velocity), 3 features (Group A and part of B), 8 features (Groups A-C), and all 12 features. If Hypothesis 3 is correct, the addition of extra features should improve classifier accuracy. All tests were performed both on the aggregate dataset and individually for each subject.

Figure 5. Melody used in User Studies 1 and 3.

Comp.	Score	Total Var.	Feature Group Weights
1	3.06	25.5%	D (.70), B (.70), A (.14)
2	2.21	44.0%	D (.71), B (.70), A (.11)
3	1.81	59.1%	C (.68), B (.68), A (.26)
4	1.74	73.6%	D (.71), B (.65), A (.27)
5	1.30	84.4%	C (.71), B (.60), A (.33)
6	1.00	92.8%	D (.70), B (.66), A (.25)
7	.46	96.5%	B (.90), A (.42), C (.10)
8	.22	98.5%	D (.71), B (.52), A (.48)

Table 1. Principal component analysis of Study 1 aggregate data. 6 components are required to explain 90% of the dataset variance.

Results
Table 1 shows the principal component strengths of the aggregate dataset, as well as the relative contribution of each feature group to each component. To account for 90% of the total variance, 6 components are required. Examining the eigenvectors of the covariance matrix shows that the first six components are heavily dependent on *weight* (Group D) and *percussiveness* (Group B) features, with secondary emphasis on *depth* (Group C). Surprisingly, though *velocity* (Group A) appears in each of the first 8 components, it never appears as the primary contributor to any of them. The high number of components required to explain the dataset variance suggests a rejection of Hypothesis 1.

Three types of classifiers were tested to evaluate Hypotheses 2 and 3: decision tree (with pruning), naive Bayes, and k-nearest neighbor ($k = 10$).[2] The 10-fold cross-validation

[2] Three types were used to minimize bias from any particular classifier on this relatively small dataset.

Aggregate Data				
# Features	1 (A)	3 (A,B)	8 (A-C)	12 (A-D)
Decision Tree	.327	.364	.383	.409
Naive Bayes	.322	.345	.309	.387
10-NN	.308	.359	.352	.399
Improvement	—	11.7%	9.1%	24.9%
Mean of Individual Subjects				
# Features	1 (A)	3 (A,B)	8 (A-C)	12 (A-D)
Decision Tree	.378	.437	.459	.491
Naive Bayes	.377	.441	.421	.461
10-NN	.394	.433	.412	.480
Improvement	—	14.4%	12.6 %	25.3%

Table 2. Study 1 cross-validation accuracy for varying numbers of features. Chance = .11. Letters specify feature groups used by classifier.

accuracy of each classifier is shown in Table 2. Chance accuracy for this problem is 11.1%. The superior classifier performance on per-subject versus aggregate data may reflect either different stylistic interpretations among subjects or an artifact of the small datasets. For both aggregate data and the mean of individual subjects, the inclusion of all 12 features creates a 25% relative improvement in accuracy versus velocity alone. Pairwise t-tests on the per-subject results demonstrate statistically significant differences ($p < .001$) for every pair except 3 and 8 features (p = .28).

Discussion

From these results we conclude that Hypothesis 3 is best: the intuitive keyboard actions of naive users vary independently along multiple dimensions in a way that meaningfully correlates with intent. This conclusion may indicate an easier learning curve for new players since multidimensional gestures are already part of their natural vocabulary.

USER STUDY 2: PERFORMANCE ACCURACY

The purpose of this study is to evaluate the *controllability* of the interface. In this study, each dimension is discretized into two or three classes; the performance of subjects in hitting target classes is evaluated in 5 unidimensional and 3 multidimensional tests:

1. Velocity (3 classes): *low*, *medium*, *high* (corresponding to the musical dynamics *piano*, *mezzo-forte*, *fortissimo*).
2. Percussiveness (2 classes): *non-percussive* (finger begins on key), *percussive* (finger in motion when it strikes key).
3. Rigidity (3 classes): *low* (loose finger), *medium* (rigid finger, loose wrist), *high* (muscles locked).
4. Weight (2 classes): *light*, *heavy* (force into key-bed).
5. Depth (2 classes): *full* (key reaches key-bed), *partial*.
6. Velocity + Percussiveness (2 classes each, 4 total): velocity divided into to only *low* and *high*.
7. Velocity + Weight (2 each, 4 total).
8. Velocity + Percussiveness + Weight (2 each, 8 total).

Because the classifiers are trained with the key-presses of one investigator, this study also evaluates the universality of the interface. In other words, do key-press feature patterns generated by one user generalize to other users, without user-specific training?

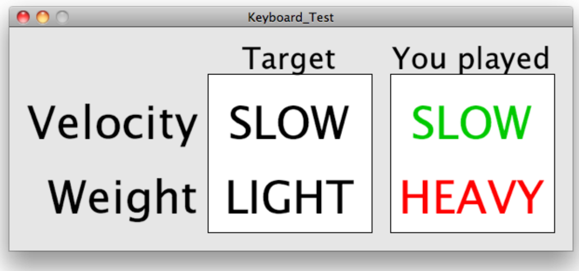

Figure 6. User Study 2 testing environment.

Design

Decision tree classifiers (with pruning) were trained in the Wekinator real-time machine learning environment [4] using 100 key-presses for each target class or combination of classes. All training and testing was performed on a single key (C4). Decision trees were chosen for their high performance with small training sets and for the minimal computational resources needed to evaluate each press in a real-time environment. A test tool was developed using the Processing graphical environment [20] which displayed the target class(es) and the user's actual input (Figure 6).

Each test consisted of 24 presses balanced across the possible targets, with target order randomized within each test. The eight tests were consistently presented in the sequence listed above. Though it is possible that greater familiarity with the piano may improve performance on later tests, several tests have prerequisites: for example, rigidity can only be evaluated in the context of a percussive press, and evaluating multidimensional problems only makes sense after each dimension has been introduced.

At the beginning of each test, the relevant dimension(s) were explained verbally and each target demonstrated by the investigator. Subjects were given up to five minutes to practice, receiving visual feedback on how each press was classified; during practice time, subjects were allowed to request suggestions on how to perform each gesture. Most subjects took 60 seconds or less to practice before each test.

Results

Figure 7 shows mean subject performance for each test. Note that chance accuracy varies with the number of classes. For multidimensional tests, an answer is considered "correct" only if it is correctly classified in every dimension. Subjects performed each unidimensional test except rigidity with better than 75% accuracy. Percussiveness and depth accuracies were above 90%, and we expect that a 2-class velocity problem would show similar results. (Because velocity uniquely provides aural feedback on the piano, and because it is familiar to everyone with even minimal keyboard experience, we chose to evaluate a more challenging problem.)

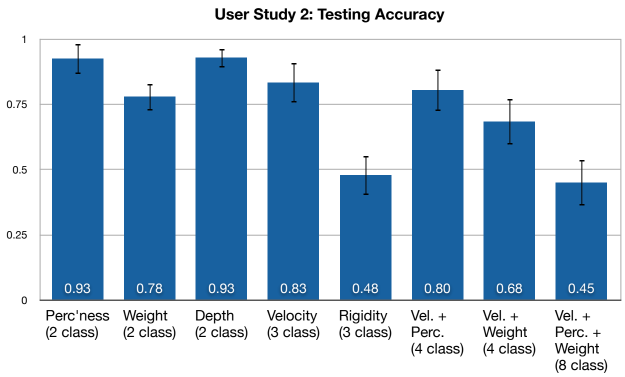

Figure 7. Proportion of key-presses correctly classified, with 95% confidence intervals.

<table>
<tr><td></td><td colspan="2">Velocity + Percussiveness</td><td colspan="2">Velocity + Weight</td></tr>
<tr><td></td><td>Non-Perc.</td><td>Perc.</td><td>Light</td><td>Heavy</td></tr>
<tr><td>Slow</td><td>90.0%</td><td>53.3%</td><td>71.7%</td><td>56.6%</td></tr>
<tr><td>Fast</td><td>83.3%</td><td>95.0%</td><td>63.3%</td><td>81.7%</td></tr>
<tr><td colspan="5">Velocity + Percussiveness + Weight</td></tr>
<tr><td></td><td colspan="2">Non-Perc.</td><td colspan="2">Perc.</td></tr>
<tr><td></td><td>Light</td><td>Heavy</td><td>Light</td><td>Heavy</td></tr>
<tr><td>Slow</td><td>56.7%</td><td>76.7%</td><td>36.7%</td><td>13.3%</td></tr>
<tr><td>Fast</td><td>6.7%</td><td>66.7%</td><td>53.3%</td><td>50.0%</td></tr>
</table>

Table 3. Breakdown of testing accuracy for multidimensional models. Certain combinations of parameters proved difficult to execute.

Subjects performed better in the velocity-percussiveness test than in the velocity-weight test. Average performance was only 45% in the three-dimension problem, though 86% of presses were correctly classified in two or more dimensions. A look at the internals (Table 3) shows that certain combinations were especially difficult. For example, *slow-percussive* presses were correctly classified significantly less often than other types; *slow-heavy* and *fast-light* presses were also less accurate. *Slow-percussive-heavy* and *fast-nonpercussive-light* combinations were almost never classified correctly.

Mechanics and muscular control may explain these results. Certain groupings naturally correlate: *slow-nonpercussive-light* strokes are easily executed together as a careful, controlled motion; *fast-percussive-heavy* strokes can be played by bringing the weight of the whole arm down on the key from above. By contrast, combining slow velocity with a percussive stroke and heavy weight requires the finger to be in motion when it strikes the key, to slow down once the key is set in motion, then to follow through with significant force once the key reaches the key bed. This requires independent awareness of three separate phases of key motion, a non-trivial task for non-expert players.

Discussion

The results of this study show that velocity, percussiveness, weight, and depth are all viable modes of input, since users with only a few minutes of training can accurately control each dimension. Rigidity was much more difficult to control, particularly low rigidity, which was almost never classified correctly (16%). Perhaps this dimension depends on the specific mechanics of an individual player's hand.

Select combinations of dimensions can be used together in discrete classifiers; however, systems with three or more dimensions should be avoided in situations with a high cost of misclassifying a single dimension. We do not attempt to answer whether users with more piano training test better. Evaluating only the three subjects with 2+ years of piano experience shows no trend (better performance in 3 tests, worse in 4, identical in 1), but a larger study would be needed.

This study shows that the interface is consciously controllable and that classifiers trained on one player can accurately respond to another. Like Ortmann [17] and Goebl et al. [8], Study 2 focuses on single key strokes. Our results show that even if the sound of an individual piano note depends solely on key velocity, players are capable of controlling key motion in several independent dimensions. The next study explores selected musical applications, mapping continuous measurements of each dimension to sound production and evaluating user performance playing complete melodies.

USER STUDY 3: SELECTED MUSICAL MAPPINGS

This purpose of this study is to evaluate the *mappability* of the interface: can a deterministic relationship between gestural dimensions and sonic parameters produce a playable musical instrument? On the acoustic piano, the mapping is embedded in the mechanical action: choice of key affects the frequency of a note, and key velocity affects its amplitude and spectrum. There are innumerable possible choices of mapping, and choosing one that is "expressive" is a challenge involving both art and engineering [24]. In this study we demonstrate the usability of two selected mappings.

Study 3A: Keyboard Percussion

Our first musical application generates a ride cymbal sound alongside each piano note. (Pitched instruments are commonly doubled with percussion in many musical styles to add a distinctive attack.) We map the percussiveness of each key-press, measured by the magnitude of the initial velocity spike, to cymbal volume. Below a certain threshold (12 position units per second), the cymbal is muted. In this way, the piano can be played with or without cymbal by choosing percussive or non-percussive presses, and the cymbal can be played alone by tapping firmly on a key without pressing it all the way down.[3] The cymbal is generated by synthesizer and played through speakers atop the piano.

Each subject was explained the mapping and allowed up to three minutes to practice. Subjects were asked to play the melody from Study 1 (Figure 5) in three modes, twice per mode: piano alone, piano and cymbal, and cymbal alone. Subjects were instructed to play the melody using a single finger to eliminate variability from different fingerings.

Controlling the cymbal is arguably more difficult than the

[3]Some MIDI keyboards offer built-in doubling of pitched instruments and percussion; unlike our system, the two are not independently controllable since both relate to key velocity.

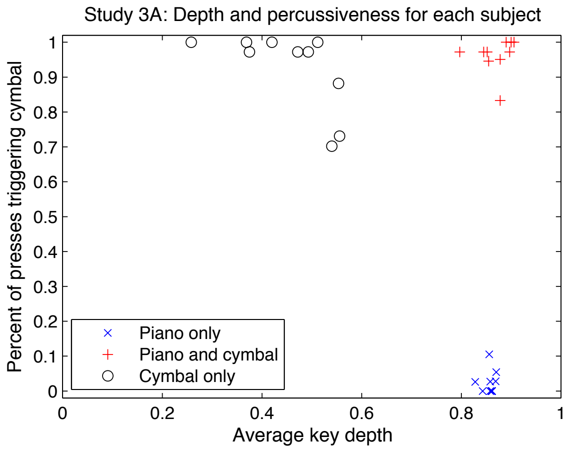

Figure 8. User performance in playing melody with piano alone, piano and cymbal together, and cymbal alone.

percussiveness classifier in Study 2 since multiple keys are played in rapid succession. However, accuracy in percussive versus non-percussive playing was higher than Study 2, with 96% of piano-and-cymbal notes exceeding the percussiveness threshold versus only 2.4% of piano-only notes (Figure 8). Cymbal-only notes were played above the threshold 92% of the time. In the cymbal-only test, 11% of key-presses reached the depth of hammer escapement, a rough estimate of how many notes contained a spurious piano sound.

Our results suggest that aural feedback is an asset to percussive versus non-percussive playing, though greater user familiarity in this study may contribute. Most importantly, this study establishes that percussive playing can add a useful new musical dimension to the traditional keyboard. One subject commented on the fast response time of the cymbal; another subject, an experienced drummer, remarked on the appropriateness of the mapping between percussive playing and cymbal sounds.

Study 3B: Continuous Control of the Acoustic Piano

Our second musical application makes use of our prior work augmenting the acoustic piano with electromagnetic string actuation [12]. Electromagnets placed above the piano strings induce the strings to vibration, allowing continuous modulation of the amplitude and spectrum of each note. In this study, key position is mapped to note volume, where resting position is silent and a fully depressed key produces the loudest tone. The conventional mode of piano playing is unimpeded, but hammer strokes are no longer necessary to initiate sound.

Design

Before the electromagnetic system was enabled, subjects were asked to play the Figure 5 melody in two modes: *softly and continuously, making smooth transitions from one note to the next*; and *lightly and soundlessly, still very connected*. This established a baseline performance against which the electromagnetic mapping could be evaluated.

The electromagnetic mapping was subsequently enabled and

Figure 9. Melody for Study 3B with crescendos on selected notes.

explained to the subject, who was given three minutes to practice. Each subject was again asked to play the melody *softly and continuously, making smooth transitions from one note to the next*, and then asked to play it again *even softer*. The purpose of these tests was to ascertain whether users could readily adapt to an unfamiliar mode of playing by accurately controlling key depth.

Subjects were next asked to practice making a crescendo on a single note (a technique impossible on the traditional piano). Once comfortable, they were asked to play the melody with a crescendo on the long notes (Figure 9). This experiment was repeated twice.

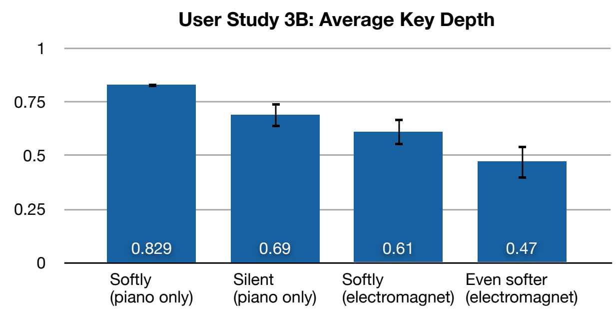

Figure 10. Average key-press depth for four modes of melodic playing, with and without electromagnetic mapping.

Results

Figure 10 compares the average key-press depth for the first four modes of playing (two piano only, two with electromagnets). A one-way, repeated measures ANOVA across subjects confirms these differences to be statistically significant ($p < .001$). A post-hoc pairwise t-test between the "soft" and "even softer" electromagnetic cases confirms the latter to exhibit significantly lower average depth ($p < .001$), which for this mapping indicates softer overall volume.

To evaluate the crescendo performances, we apply a linear regression to key depth versus time for the duration of each note (Figure 11). Notes played with crescendo should exhibit positive slope (increasing volume), where other notes should exhibit slope close to zero (constant volume). Table 4 shows the results. Both trials show significant differences ($p < .01$) in pairwise t-tests, but the second shows greater differentiation between crescendo and non-crescendo notes.

Our results show that a previously unused aspect of keyboard performance (key depth) can be successfully mapped to a musical result (volume). Subjects adjusted immediately to the new mapping when asked to play softly and consistently but required a longer learning period to execute the more

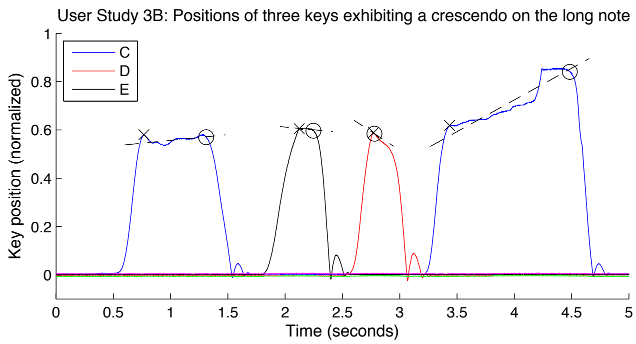

Figure 11. Key depth versus time in Study 3B, with best-fit lines to evaluate the slope of each key-press. (First measure of crescendo test shown.)

Mean slope of key-presses (Δdepth/Δtime)			
	Non-crescendo	Crescendo	Significance
Trial 1	-.015	.169	$p = .004$
Trial 2	-.088	.282	$p = .0013$

Table 4. Study 3B, slope of key depth versus time for crescendo and non-crescendo notes, mean of 10 subjects.

complex effect of shaping volume within a single note.

APPLICATIONS

User Study 3 demonstrated two simple mappings among a broad array of musical applications. We can classify these applications into three categories:

- **Augmented Piano:** One class of musical mappings focuses on the *subtlety* of piano technique, where the goal is to enhance the expressivity of the acoustic piano. Key velocity may remain the primary determinant of sound, but other dimensions map to subtle modulations of tone and timbre. With a synthesizer based on an adjustable physical model of the piano, for example, percussive strokes could be played with firmer felt hammers, enhancing an intuitive correlation between percussive gestures and "bright" sound. The electromagnetic resonator system of Study 3B [12] offers still greater potential by physically manipulating the vibrations of acoustic strings. Mappings between key motion and electromagnetic control can add dimensions to the piano while retaining its acoustic character.
- **Novel Keyboard Instruments:** A second class of applications assigns key-press dimensions to distinctive, independent musical results. Study 3A demonstrates a compound instrument where two classes of sounds can be played from the same controller. This mapping could be expanded to a complete drum kit using multi-finger taps and swipes across the keyboard, allowing a single performer to play both piano and drums without removing her hands from the keyboard. Unusual remappings of each key-press dimension are also possible; for example, key weight could modulate the pitch of the instrument like the 18th-century clavichord.
- **Pedagogy:** The dimensions of each key-press reveal a great deal about a pianist's physical technique. This information could be used in teaching contexts to identify improper motions, excessive stiffness or weight, or imbalanced force among the fingers. Hadjakos [9] has developed a pedagogical piano system based on arm-mounted accelerometers; our work would be a natural complement to produce a comprehensive piano training system.

Implementation Beyond the Piano Keyboard

The interaction techniques in this paper have been demonstrated on a piano keyboard, but they are applicable to any mechanical button interface. The implementation requirements are as follows:

1. Continuous position sensing at 500Hz or higher sampling rate. Sensor can be of any type (optical, resistive, etc.) as long as it provides approximately linear measurements of key position with 8 bits of resolution or more.
2. Buttons should have a non-trivial travel distance, so they are capable of accumulating velocity over the course of their throw.
3. For sensing *weight*, a compressible material (e.g. felt) should be mounted underneath the button so that pressure effects a change in its position.
4. For *depth* to be controllable, the button should be capable of being held steady at any point in its throw. A counterexample is the computer keyboard designed for a "click" feel, where after an initial activation force, the key travels immediately to the bottom of its throw.

An interface meeting these requirements will possess a superset of the capabilities of pressure-sensitive button interfaces, and in comparison to force-sensing resistors, buttons equipped with a compressible base may exhibit superior tactile feedback since finger pressure will produce a perceptible change in button position.

An exploration of the technology's extra-musical possibilities is a topic for another paper, but we point to studies with the Pressure Sensitive Keyboard [3] as a brief survey. Possible applications include:

- **Gaming:** Weight or depth can be mapped to the speed of movement or height of jump. Percussiveness could have particular application in sports games such as golf or baseball where precise control of a collision is required.
- **Editing and CAD:** Low-depth (incomplete) button presses could be used to preview the results of an action (image filter, etc.) before committing to it. Where Apple has introduced momentum-based scrolling on its trackpads, button velocity could be used to scrub through a video or navigate a 3D design with a simulation of momentum, with faster presses traveling greater distances.
- **Affective computing:** Users often express their frustration through excessively heavy, percussive impacts on the keyboard or mouse. The velocity, weight, and percussiveness of keyboard interactions could be revealing of emotional state, and used to either alter the response of a UI

or to transmit emotional information to another human via stylized text communication [3].

- **Computing for the disabled:** Our interface allows a single finger to control multiple simultaneous dimensions of a button-press. For users with the use of only a few muscles, multidimensional button input could enable faster, richer interactions.

Next Steps

We have demonstrated that users with no specialized training can accurately control the interface, a necessary step to its wider adoption. Future work will focus specifically on experienced pianists, for whom multidimensional control of key motion is part of developing a personal technique. In addition to investigating whether experienced pianists exhibit greater accuracy in the classification tasks of User Study 2, we will study the relationship between expressive intention and physical gesture at the piano keyboard. For example, pianists sometimes talk about emulating the sound of orchestral instruments from the keyboard [1]. What can we learn about these types of playing and other subjective musical qualities by studying a rich picture of key motion?

CONCLUSION

We have presented a new approach to a classic interface, demonstrating a musical keyboard which captures not only key velocity, but multiple dimensions of every gesture, including key-press percussiveness, rigidity, weight and depth. These dimensions were identified as important based on the piano pedagogical literature and pilot studies with professional pianists. User studies demonstrate that the new dimensions are intuitive to an untrained user, consciously controllable with limited practice, and have novel musical applications. This work lays a foundation for a new generation of intelligent musical keyboards, and the underlying mechanical principles can be applied to a broad range of button-based interfaces outside the musical realm.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant # 0937060 to the Computing Research Association for the CIFellows Project.

REFERENCES

1. B. Berman. *Notes from the Pianist's Bench*. Yale University Press, New Haven and London, 2000.
2. J. Cechanowicz, P. Irani, and S. Subramanian. Augmenting the mouse with pressure sensitive input. In *Proc. CHI 2007*.
3. P. Dietz, B. Eidelson, J. Westhues, and S. Bathiche. A practical pressure sensitive computer keyboard. In *Proc. UIST 2009*.
4. R. Fiebrink. Real-time interaction with supervised learning. In *Proc. CHI 2010 Extended Abstracts*.
5. N. Fletcher and T. Rossing. *The Physics of Musical Instruments*. Springer-Verlag, New York, 1998.
6. A. Freed and R. Avizienis. A new music keyboard featuring continuous key-position sensing and high-speed communication options. In *Proc. ICMC 2000*.
7. R. Gerig. *Famous Pianists & Their Technique*. Indiana University Press, Bloomington, IN, 2007.
8. W. Goebl, R. Bresin, and A. Galembo. Once again: The perception of piano touch and tone. Can touch audibly change piano sound independently of intensity? In *Proc. ISMA 2004*.
9. A. Hadjakos, E. Aitenbichler, and M. Mühlhauser. Probabilistic model of pianists' arm touch movements. In *Proc. NIME 2009*.
10. Haken Continuum Fingerboard. http://www.cerlsoundgroup.org/Continuum/.
11. C. Harrison and S. Hudson. Providing dynamically changeable physical buttons on a visual display. In *Proc. CHI 2009*.
12. A. McPherson. The magnetic resonator piano: Electronic augmentation of an acoustic grand piano. *Journal of New Music Research*, 39(3):189–202, 2010.
13. A. McPherson and Y. Kim. Augmenting the acoustic piano with electromagnetic string actuation and continuous key position sensing. In *Proc. NIME 2010*.
14. A. McPherson and Y. Kim. Toward a computationally-enhanced acoustic grand piano. In *Proc. CHI 2010 Extended Abstracts*.
15. Monome. http://monome.org.
16. R. A. Moog and T. L. Rhea. Evolution of the keyboard interface: The Bösendorfer 290 SE recording piano and the Moog multiply-touch-sensitive keyboards. *Computer Music Journal*, 14(2):52–60, Summer 1990.
17. O. Ortmann. *The Physical Basis of Piano Touch and Tone*. Kegan Paul, Trenc, Trubner & Co., 1925.
18. O. Ortmann. *The Physiological Mechanics of Piano Technique*. Kegan Paul, Trenc, Trubner & Co., 1929.
19. J. A. Paradiso. Electronic music: new ways to play. *IEEE Spectrum*, 34(12), 1997.
20. Processing. http://processing.org.
21. G. Sandor. *On Piano Playing*. Macmillan Publishing Co., 1981.
22. A. Schultz. *The Riddle of the Pianist's Finger and its Relationship to a Touch-Scheme*. University of Chicago Press, Chicago, 1936.
23. C. Stewart, M. Rohs, S. Kratz, and G. Essl. Characteristics of pressure-based input for mobile devices. In *Proc. CHI 2010*.
24. M. Wanderley and P. Depalle. Gestural control of sound synthesis. *Proceedings of the IEEE*, 92(4):632–644, 2004.