HACHIStack: Dual-Layer Photo Touch Sensing for Haptic and Auditory Tapping Interaction

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ABSTRACT

We present a novel photo touch sensing architecture, HACHIStack. It can measure the approaching velocity of an object and predict its contact time with the touch screen using two optical sensing layers above the surface. Our photo sensing layers have three unique capabilities: high-speed sampling, velocity acquisition, and contact time prediction. This work quantitatively examines these capabilities through two laboratory experiments, and confirms that the capabilities of HACHIStack are sufficient for multimodal interaction, in particular, touch-based interaction with haptic enhancement. We then present three applications with HACHIStack: 1) chromatic percussions (xylophone and glockenspiel) with haptic feedback; 2) no-delay haptic feedback with the sensation of tapping on various simulated materials (e.g., rubber, wood and aluminum); and 3) a virtual piano instrument that allows players to perform weak and strong strokes by changing the tapping velocity.

Author Keywords

Approaching velocity; HACHIStack; multimodal interaction; touch sensor.

ACM Classification Keywords

H.5.2. [Information Interfaces and Presentation]: User Interfaces —*Input Devices*

General Terms

Design; Measurement.

INTRODUCTION

Interactions with touch screens can be greatly enhanced by combining auditory and haptic feedback with visual feedback, improving the efficacy and realism of a virtual environment. For example, clicking sounds of a button on can well inform the user of her press. As the touch screen does not require physical widgets for interaction, a music entertainment system can offer different types of musical instruments by simply changing the interface displayed on the screen, and the user can interact with them by direct

touch. Realistic haptic sensation of pressing a key on the piano, for example, would enhance the user experience on such virtual musical instruments.

Research in the field of Human-Computer Interaction and haptics has explored techniques and systems to offer the user realistic haptic sensations of virtual widgets from clicking sensation [12, 30, 43] to friction [3], stiffness [25], and bumpiness [39]. Haptic feedback like friction [27], clicking sensation [29], and reactive force [47] can also be provided through tools the user is holding to interact with the touch screen, such as a pen. These projects demonstrate that haptic technologies can offer a wide range of feedback on interaction with a flat interactive surface.

One important technical consideration to achieve well-designed haptic feedback is delay. Prior work has shown that even a delay of 5 ms on haptic feedback can impact on the perceived stiffness of pressing interaction [36]. To this end, measuring how the user is approaching to the interactive surface is critical to estimate the appropriate timing for haptic feedback on the surface. Furthermore, the approaching velocity of the user's hand or object determines the initial amplitude of surface vibration, which expresses the material property of the surface [11, 28]. In addition to haptic feedback, the capability of sensing the approaching velocity can enhance interactions with the touch screen. For example, in the previous example of a musical instrument, piano players can express the sound intensity by simply tapping slowly or fast.

In this paper, we present a novel sensing architecture, HACHIStack (Haptic and Auditory Computer-Human-Interaction Stack), which can acquire the approaching velocity of the user's touch or object before she is contacting with the screen. HACHIStack includes two optical sensing layers stacked vertically on top of a touch-sensitive screen, and computes the approaching velocity accurately by measuring the time at which the user's hand or object travels through the layers. Moreover, HACHIStack can also predict the contact time based on the approaching velocity.

The contributions of this work are: 1) the implementation of approaching velocity sensing with optical sensors for interactive surfaces; 2) our quantitative examination of the HACHIStack's sensing capabilities; and 3) demonstrations

of applications with HACHIStack. The paper first describes a literature review of above-surface sensing, approaching velocity sensing, and touch sensing with photo sensors related to interactive surfaces. Next, we describe our HACHIStack sensor architecture and evaluations of our prototype. We then explain three applications, and discuss the limitations of the present work and future research directions.

RELATED WORK

Above-Surface Sensing and Interaction
Interaction above surfaces has explored to enhance user experience on interactive tabletops. Many of these systems use external multiple cameras and devices with fiducials [5, 9, 32, 41] or capacity sensing [38]. For example, Benko et al. developed a system that combines multiple see-through head mounted 3D displays with a 2D display projected on a touch-sensitive surface [5]. When the user performs a grabbing gesture on a 2D virtual object projected on the surface, its 3D model appears, and the user can directly manipulate it.

Transparent sheets or screens are often integrated into interactive surface systems to create additional information or interaction space with above-surface sensing. Matsushita and Rekimoto's HoloWall consists of an infrared camera, a projector and an array of infrared light-emitting diodes (LEDs) behind the rear-projection sheet [33]. The infrared camera can capture movements of user's hands for on- and above-surface interaction. Wilson developed TouchLight, in which two cameras behind a semi-transparent screen recognize user's interaction with the projected objects [48]. SecondLight built by Izadi et al. employs a switchable diffuser screen to an interactive surface with combining multiple projectors and cameras [24]. By rapidly toggling the state of the screen, their system cannot only project information onto the screen, but also different images onto the transparent sheet held above the screen. The cameras can detect user's interaction on both the screen and transparent sheet.

Depth sensing cameras, such as Microsoft Kinect, is another common method to detect interaction above the surface. Wilson and his colleagues have explored various interaction spaces and applications by combining depth sensing cameras with displays or projectors [4, 6, 7, 18, 20, 49, 50]. One advantage of using depth sensing cameras is that it does not require devices with fiducials or complex processing to recognize user's interaction. Another is that the systems can scale up beyond tabletops. For example, LightSpace offers a room-size environment which allows the users to interact with multiple displays by physical gestures (e.g., picking up a virtual object projected on the table to user's hand by swiping and selecting a different menu by moving the hand vertically [50]).

Above-surface interaction also has been explored in devices which have different form-factors from tabletops and wall displays. For example, a digitizer can detect the location of the pen held by the user when it is proximal to the screen. With this, Grossman et al. developed Hover Widgets, which utilizes a hovering gesture to activate context menus (which they call interface widgets) [13]. Subramanian et al. further extended this design space by integrating the notion of layers [42]. LucidTouch allows the user to control the applications by touching on and hovering over the back of a mobile device [46]. SideSight [8] and HoverFlow [26] use infrared proximity sensors to detect the user's gesture around the device. Harrison and Hudson developed Abracadabra, an input technique with a magnet that detects the user's finger movements around the device [19].

The work discussed in this section illustrates various techniques for above-surface sensing, and highlights the benefits of interaction enabled by them. Our work complements these projects by demonstrating a novel way to recognize the approaching velocity of the user's hand or object to the surface.

Camera-Based Approaching Velocity Sensing
Velocity can be computed by measuring the time of passing at two points given that the distance between them is known. There are a number of methods to estimate the velocity of an object approaching to a screen. For example, capacitive sensing technologies, such as SmartSkin [38], can sense proximal objects by electromagnetic induction. However, it does not offer accurate measurement because it does not directly sense the velocity. Similarly, methods relying on indirect measurement, such as the impact of the contact sensed by accelerometers or pressure sensors, generally yield inaccurate sensing. Some of these methods cannot estimate the approaching velocity until the contact with the surface is made. This may cause a non-negligible delay on haptic or auditory feedback provided for user interaction.

In the context of tabletops, one common technique to measure the approaching velocity is camera-based, such as diffused illumination (e.g., Frustrated Total Internal Reflection (FTIR) [17]). The principle is to generate a fairly constant field of infrared light on the screen and detect the reflected light from the object with a camera. This approach is able to acquire a rough vertical position of the object by the amount of reflected light while it does not provide accurate measurement in general.

In addition to the limitation of accurate measurement, acquiring depth data either requires multiple cameras and precise calibration or produces inaccurate estimation. Furthermore, the sampling rate of a camera is generally of the order of milliseconds, which is not suitable for applications that require high-speed sensing.

Touch and Velocity Sensing with Photo Sensors
Another method to detect the approaching velocity is photo sensor based. Sensing technologies with photo sensors have an advantage in the sampling speed. Thus, such technologies can minimize the delay for haptic or auditory
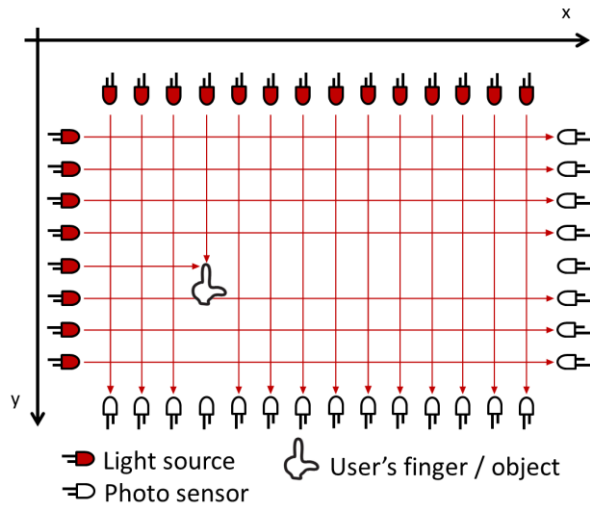
Figure 1. An illustration of the photo sensor based technique with light occlusion, called sensor occlusion.

feedback on user interaction. As mentioned earlier, even a delay of 5 ms could impact on the perceived stiffness [36] of the haptic feedback. For virtual musical instruments, the allowable delay is considered to be 70-80 ms (calculated from [31]). The sampling rate to satisfy such small delays would be difficult with camera-based approaches because of their limited frame rate.

The fundamental principle of a photo touch sensor is to emit a light source from an LED, laser, or projector and detect the light occluded or reflected by an object using photo sensors. There are a few of possible configurations of the light sources and photo sensors to detect the light occlusion. Sensing the light occlusion from the underneath of the surface is one of the common configurations [10, 21, 22, 23, 40], but non-trivial algorithms and tuning may be necessary to distinguish two states of contact and hovering (we refer this to "the proximity touch error problem"). Unlike these projects, HACHIStack uses the layer configuration like shown in Figure 1 to avoid this problem.

Photo sensor based techniques can be categorized into two types. The first arranges the light sources and photo sensors in two dimensions and detects occluded and reflected light. For example, Hodges et al. developed ThinSight [22], in which pairs of LEDs and photo sensors are placed behind the screen in a grid, enabling the position detection of the object which is on or near the screen. A similar concept is applied in Microsoft Surface 2 [40] and BiDi screen [21]. Echtler et al. built an LED array multi-touch display that can use LEDs themselves as the sensing units [10]. While the prototype can only operate at ~10 Hz, one of its major advantages is the use of modulated infrared light to reject ambient light. However, like the diffused illumination

method using computer vision, this technique cannot compute the approaching velocity accurately.

The other type of techniques, called sensor occlusion, arranges the light source and photo sensors linearly on the x- and y-axes of the screen, and detects light occlusion. Figure 1 illustrates this principle of the light occlusion detection technique. When a finger or an object is in the space, it occludes the light and some of the photo sensors are not activated. With this, the system can estimate where the finger or object is located. This technique is employed in many commercial photo touch sensors. ZeroTouch augments this technique to achieve multi-touch sensing [34]. Medusa built by Annett et al. includes a number of proximity sensors around the surface, and determines the user's body and arm locations [2]. Z-touch built by Takeoka et al. also integrates the notion of layers, which allows the user to perform gestures related z-axis (e.g., the tilt of the finger) [44].

HACHISTACK
In this section, we describe the concept of HACHIStack, which is capable of accurately measuring the approaching velocity and solving the proximity touch error problem for tapping interaction.

The main objective of this work is to develop a system which can detect the approaching velocity accurately at a high sampling rate. We thus determined to use the light occlusion detection technique, in which the light sources and photo sensors are arranged linearly on the x- and y-axis of the screen (illustrated in Top View of Figure 2). In this manner, HACHIStack can simultaneously detect both the touch position and touch velocity. To acquire the approaching velocity, we separate the linear array layers of
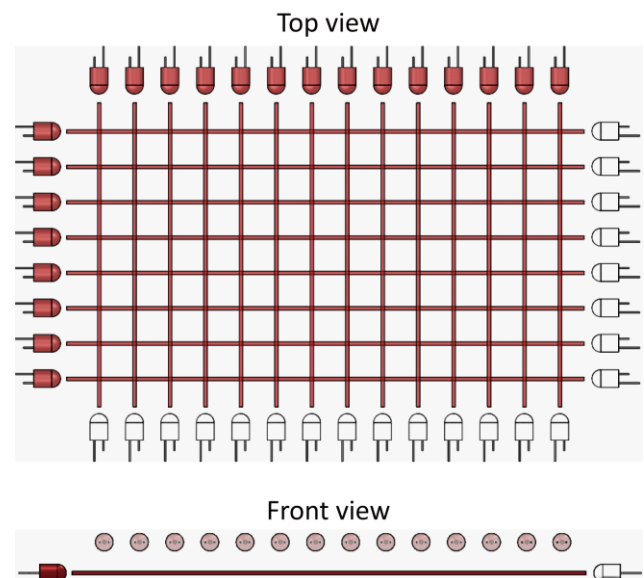

Figure 2. The photo sensor configuration of the HACHIStack. HACHIStack uses two optical sensing layers stacked vertically on the screen.
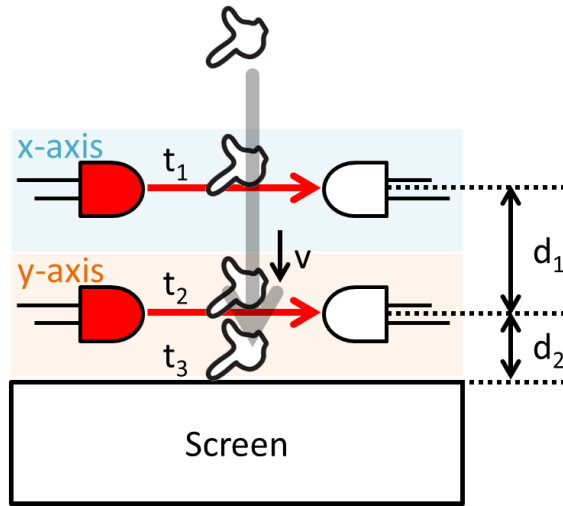
Figure 3. An illustration of the method for acquiring the approaching velocity and predicting the contact time of the tapping interaction. For the sake of simplicity, the x- and y-axes are shown parallel to each other.
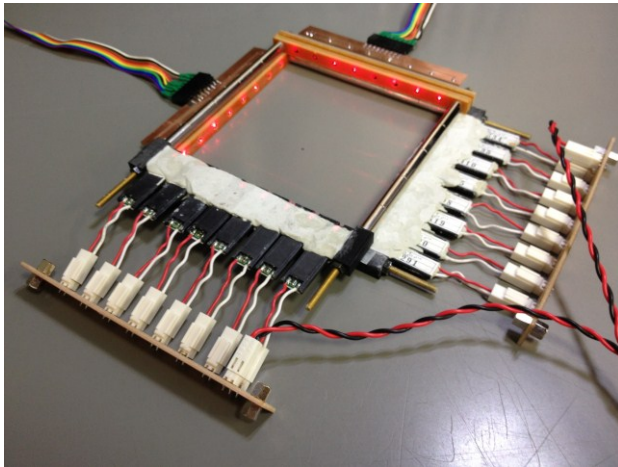

Figure 4. Our HACHIStack prototype.

the two axes and stack them vertically. Thus, as shown at the bottom of Figure 2, there is a gap between the x-axis (top) and y-axis (bottom) array.

As illustrated in Figure 3 (where, for the sake of simplicity, the x- and y-axes are shown parallel to each other), the approaching velocity v can be calculated by measuring the time difference in light occlusion, i.e., $t_2 - t_1$, and the known distance d_1 between the x- and y-axes. Furthermore, the time t_3 at which the object contacts with the surface can be predicted by the known distance d_2 between the y-axis and the surface of the screen and the acquired approaching velocity v. This prediction can be achieved accurately with HACHIStack unless the velocity of the object greatly changes after it crosses the second sensing layer.

Prototype

We created a prototype of HACHIStack, consisting of two layers of laser and photo sensor modules as shown in Figure 4. Each module consisted of eight laser modules (Wanta Electronic Co., Ltd, LM-102-B, 10 mm in width) and eight phototransistors (New Japan Radio Co., Ltd., NJL7502L, 3 mm in diameter) placed facing each other. These two layers are stacked vertically with each layer to sense the position along a single axis only. The current prototype has the work space of 94 × 94 mm with 12 mm spatial resolution for the two axes. The distances d_1 and d_2 are set to 7.0 mm and 3.5 mm, respectively.

Sampling Rate

As illustrated in Figure 5, each laser emits light toward the facing phototransistor. The states of all phototransistors are transmitted to the microcontroller (NXP Semiconductors, mbed NCP LPC 1768) through parallel-in shift resisters (Toshiba, 74HC165) in a Serial Peripheral Interface (SPI) bus. The microcontroller then computes the touched position and approaching velocity. With an SPI clock frequency of 24 MHz, it only takes 31 μs to read 16 phototransistors and compute the position and approaching velocity. This is a much smaller latency than conventional camera-based techniques. The time needed for processing is linear to the number of sensors, which is constrained by the SPI protocol. But, the speed of the SPI protocol can be up to about 1 GHz, which means that a future prototype can accommodate approximately 600 sensors with a sufficiently small latency.
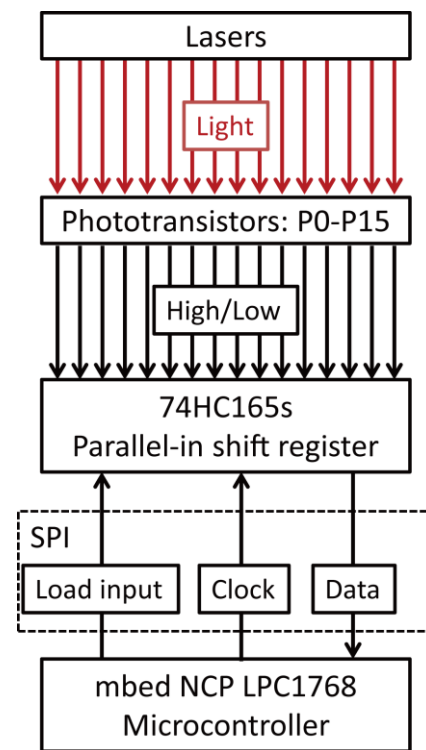

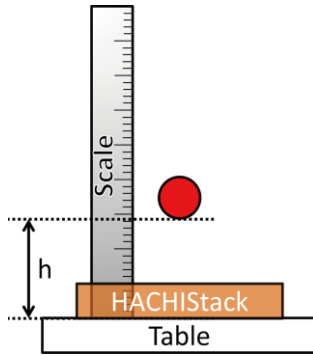**Figure 5. The HACHIStack system architecture.**

Figure 6. The experimental setup for measuring the velocity of a free falling ball.
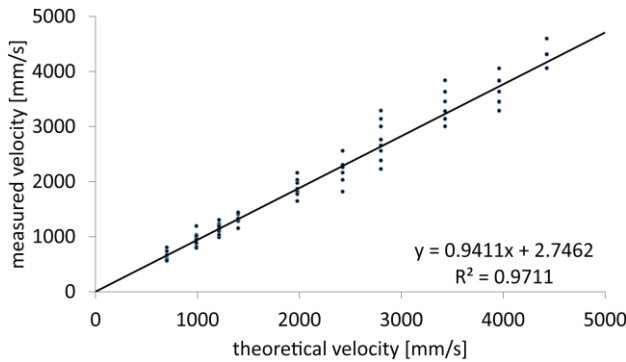

Figure 7. The result of measuring the velocity of a free falling ball. (The x- and y-axes denote the theoretical and measured velocity, respectively.)

SYSTE EVALUATION

Velocity Measurement

To examine how accurately HACHIStack can measure the approaching velocity, we conducted an experiment with a free falling ball.

Setup

As illustrated in Figure 6, we placed the HACHIStack device on a flat table and fixed a scale vertically to the table. We manually dropped a rubber ball, with diameter 28 mm and weight 12 g, from a height h of {25, 50, 75, 100, 200, 300, 400, 600, 800, 1000} mm. We calculated the theoretical velocity $v_{theoretical}$ of the ball at the surface of the table, assuming simple free fall ignoring air resistance, using the following equation:

$$v_{theoretical} = \sqrt{2gh} \quad ,$$

where g is the gravitational acceleration (9.80665 m/s^2). We measured the velocity ten times for each height at a 10 kHz sampling rate.

Results

Figure 7 shows the plot of all 100 velocity data with the theoretical and measured velocity. We performed a linear regression on the data, showing a high goodness-of-fit (R^2 = .9711; $p < .001$). This result confirms that HACHIStack is capable of estimating the approaching velocity accurately.

We also observed that the estimation error tends to be larger for faster velocity, up to around 3000 mm/s. One reason can be the manual release of the ball, which might have given the ball additional potential energy. However, the estimation error tends to be small because HACHIStack offers a high temporal resolution. As an extreme example, HACHIStack cannot measure the velocity of the object passing two layers faster than the sampling rate (i.e., $t_2 - t_1$ is measured as 0).

Contact Time Prediction

We conducted another experiment to investigate how accurately HACHIStack can predict the time of contact with the surface of the screen.

Setup

As illustrated in Figure 8, we placed HACHIStack on an aluminum sheet connected to the I/O port of the microcontroller and grounded via a pull-down resistor. The aluminum sheet was fixed to a flat table. We used a stick with the head covered with a conductive coating material connected to the power supply of the microcontroller. Conduction between the stick head and the aluminum sheet allowed for accurate measurement of the actual contact time.

Three participants (1 male and 2 female; age between 24 and 26) participated in the experiment. They were asked to manually tap the aluminum sheet with the stick 100 times, with varying velocities. We recorded the approaching
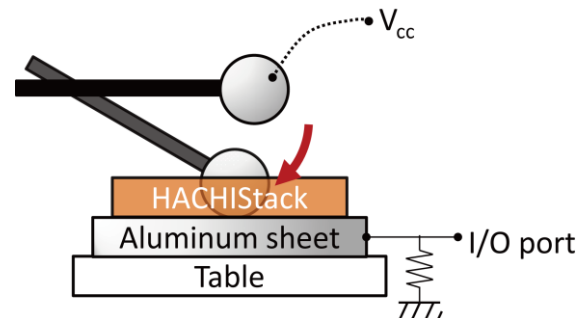

Figure 8. The experimental setup for comparing the predicted and actual contact time.
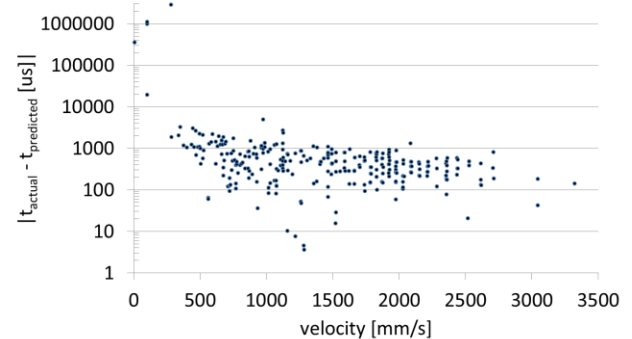

Figure 9. The plot of differences between the predicted and actual contact time along the approaching velocity.

velocity, and the difference between the actual contact time t_{actual} and the predicted contact time $t_{predicted}$ at a 10 kHz sampling rate.

Results

Figure 9 shows the plot of all 300 trials with the approaching velocity and the difference between the actual contact time and the predicted contact time ($|t_{actual} - t_{predicted}|$). As seen in the plot, the prediction shows large errors of the order of a second when the approaching velocity was below 200 mm/s. The reason for these errors seems to be that the approaching velocity greatly changed after it was acquired by HACHIStack. In other words, when the participants tried to tap slowly, they tended to stop the stick exactly on the sheet as if they silently placed the stick head, resulting in large deceleration. On the other hand, when the approaching velocity was greater than 200 mm/s, HACHIStack could predict the contact time accurately. More specifically, 65.7% of the trials were within 1 SD (Standard Deviation without trials below 200 mm/s; 564.8 μs), and 88.3% were within 2 SD (1129.6 μs). These results indicate that except the case of slow approaching velocity (slower than 200 mm/s), HACHIStack can reliably predict the timing of the contact. This is sufficient to satisfy the strict requirement of haptic interaction [36].

DISCUSSIONS

While multi-layered photo touch sensors have been used to detect the hovering position of the object [34, 44], their use is limited to acquire the three dimensional posture of the object with a sampling rate of at most the order of a millisecond. Our system extends the prior work by enabling accurate acquisition of the approaching velocity and a sampling rate of the order of a microsecond. In addition, for tapping interaction, HACHIStack can accurately predict when the contact will be made on the surface of the screen. As the hovering state of the hand or object is sensed by the layers of photo sensors, not the surface, the proximity touch error problem would not be raised in HACHIStack.

In terms of velocity acquisition, the photo sensor technique used in HACHIStack has three advantages over existing techniques such as proximity (e.g., capacitive, diffused illumination based photo), acceleration, and pressure sensors. First, the HACHIStack can directly and accurately compute the approaching velocity. Second, the photo sensor technique can compute the velocity before the contact is made whereas many of other techniques can only do so after the contact. This enables provision of feedback at the moment of contact, which is especially important for haptic presentation that has strict temporal requirements as mentioned in [36]. Third, our technique does not require contact with the objects. This also contributes to haptic presentation, especially to our haptic augmented reality system [16] described in the next section since it does not generate any haptic stimulus for the measurement. Besides, a contactless sensor can also be used for mid-air interaction.

LIMITATIONS AND POSSIBLE IMPROVEMENTS

The current HACHIStack prototype and present study have several limitations besides general issues associated with photo touch sensing techniques (e.g., disturbance by ambient light and dust).

The current system cannot detect multi-touch. A possible solution for this is to stack the optical multi-touch detection sensor [34] vertically. This would solve the spatial resolution issue; however, the temporal resolution issue could emerge. Another possible improvement for spatial resolution is to stack the HACHIStack module above a capacitive touch sensor that can measure the position of the hovering hand or object without contact. In this case, HACHIStack would only compute the approaching velocity and predict contact time while the capacitive touch sensor would measure the position.

The present study only covers a single tap, and some improvements are necessary to correctly detect a series of taps (e.g., playing the piano). For the sake of simplicity, we assume that the user would raise all her fingers above the topmost layer before making the next tap. This would not be unrealistic if the layers are thin enough, but it would require faster sampling and processing for contact time prediction. More specifically, time $t_{advance}$, denoting how long in advance HACHIStack can predict the contact, can be expressed by the following formula:

$$t_{advance} = d_2 / v - t_{latency},$$

where $t_{latency}$ is the latency caused by the computation of velocity and contact time prediction. If $t_{advance}$ is negative, the prediction cannot be computed. Based on this formula, if the user taps the screen with velocity 1000 mm/s and d_2 and $t_{latency}$ are 3.5 mm and 100 μs, respectively (i.e., the current HACHIStack's specification), HACHIStack can predict the contact 3400μs before the actual contact occurs.

As the results of the second experiment show, poor precision of contact time prediction for low speed tapping (slower than 200 mm/s) is another current limitation. The precision in such a case was in the order of a second, which is worse than that of general touch sensing technologies. The poor precision appears to be as a result of large acceleration/deceleration. A possible improvement is to stack more layers to increase the vertical spatial resolution.

APPLICATIONS

In this section, we describe three applications of the HACHIStack, augmented chromatic percussions, haptic augmentation with material simulation, and a virtual piano instrument. For these, we created a larger HACHIStack prototype with the workspace of 294 × 190 mm and 24 × 16 laser modules and phototransistors as shown in Figure 10.

The first two applications with haptic feedback aim to demonstrate the unique capabilities of HACHIStack. Approaching velocity acquisition is used to determine the initial amplitude of haptic. Contact time prediction enables
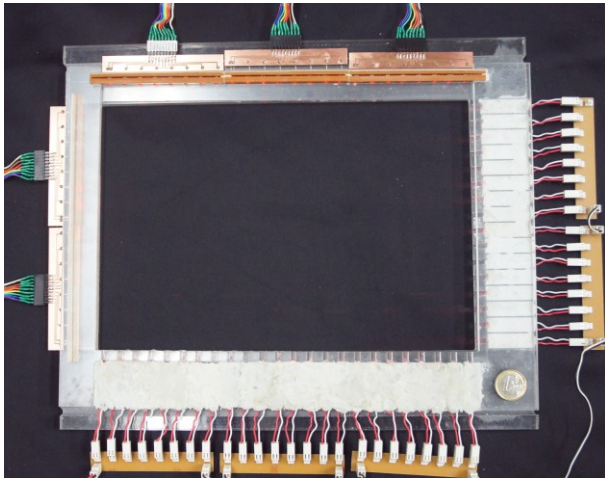
Figure 10. A large HACHIStack prototype with the workspace of 294 × 190 mm and 24 × 16 laser modules and phototransistors.

no-delay haptic feedback on the contact, thereby fulfilling the strict temporal requirement [36]. Besides, since our measurement technique does not require physical contact, it does not interfere with a mechanism to provide haptic sensation. The accompanying video also shows the live demonstrations of these applications.

Augmented Chromatic Percussions (Xylophone and Glockenspiel)
Figure 11 shows the setup for the augmented chromatic percussions (xylophone and glockenspiel). It consists of HACHIStack mounted on a 17-inch LCD screen covered with elastic sheet. The screen displays a virtual xylophone and glockenspiel. The user interacts with this using a stick which embeds a vibration actuator to provide the haptic feedback of the bar the user is hitting [14, 15, 16].

As demonstrated, HACHIStack is able to acquire the approaching velocity and predict the contact time. These capabilities contribute to no-delay auditory and haptic feedback when the user is hitting a bar. The vibration actuator in the stick renders haptic feedback of a wood or metal bar at the moment that the stick head contacts on the surface (technical details of haptic feedback rendering are discussed in the next section). The strength of the feedback is determined by the approaching velocity. The combination of them results in realistic sensation of hitting a bar of the virtual xylophone and glockenspiel. Along with auditory feedback generated through MIDI, this application creates multimodal interaction that otherwise would be difficult. We also would like to emphasize that contact time prediction is important for synchronizing different modalities.

Haptic Augmentation with Material Simulation
In this section, we describe our haptic augmentation used in the keys of the virtual xylophone and glockenspiel. As mentioned in the introduction, people can discern different

materials through haptic cues, such as the kinesthetic sensation (i.e., the reactive force from the surface of the object) and vibrotactile sensation (i.e., cutaneous mechanical deformation and vibration).

Wellman and Howe demonstrated a method of emulating realistic haptic feedback with a vibrator mounted on an active force feedback device [45]. Okamura et al. extended this method by providing kinesthetic and vibration stimuli simultaneously using only an active force feedback device [37]. These methods are based on the following decaying sinusoidal waveform to simulate the vibration resulting from tapping:

$$Q(t) = A(v)exp(-Bt) \, sin(2\pi ft),$$

where acceleration of vibration Q is determined by the amplitude A as a function of the impact velocity v, decay rate of sinusoid B, and sinusoid frequency f, where A, B, and f depend on the material to be simulated.

While the systems used in [37, 45] require expensive haptic displays, we use cost-effective equipment: the stick with a vibration actuator (TactileLabs, Haptuator), and pad with an elastic sheet [16]. When the user taps the pad, the innate
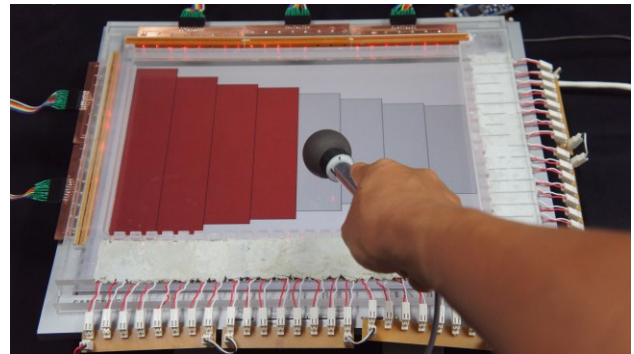

Figure 11. Augmented chromatic percussions (xylophone and glockenspiel). The LCD displays one octave of a xylophone and a glockenspiel. The application offers simulated haptic feedback on the key.

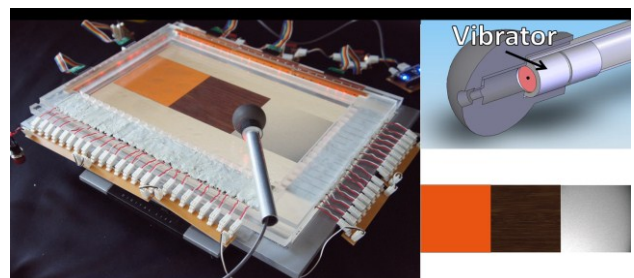**Figure 12. Demonstration of haptic augmentation with material simulation. The system consists of HACHIStack mounted on an LCD covered with the elastic sheet and a stick with a vibration actuator. The actuator (the top right of the figure) generates decaying sinusoidal vibration and the LCD displays the three materials (rubber, wood and aluminum; the bottom right of the figure).**

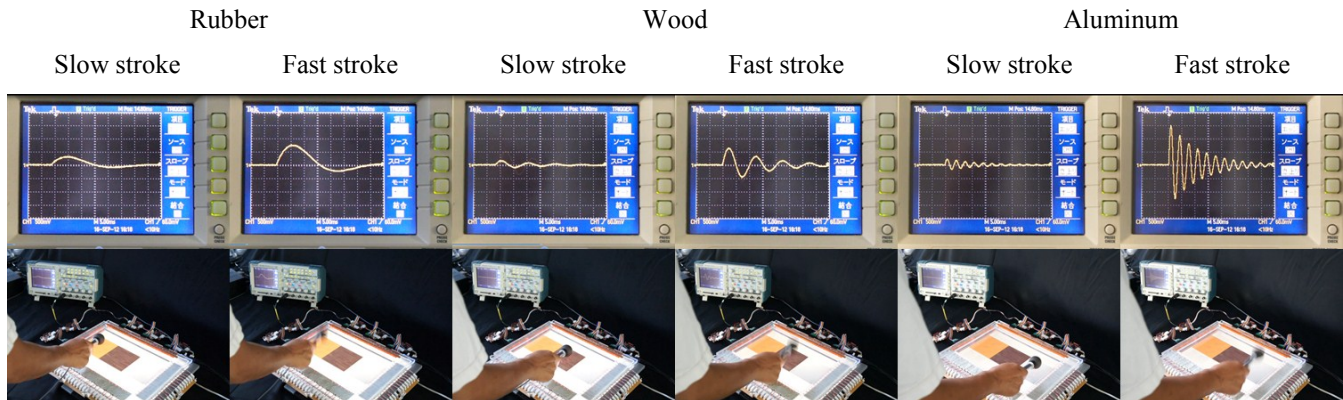| Rubber		Wood		Aluminum	
Slow stroke	Fast stroke	Slow stroke	Fast stroke	Slow stroke	Fast stroke

Figure 13. Decaying sinusoidal vibration for the three materials (rubber, wood and aluminum) and two different stroke intensities (slow and fast strokes).

vibration resulting from the tapping is absorbed by the elastic surface. Simultaneously, the vibration actuator provides the simulated vibration, which represents the material that the user has hit.

To detect contact between the stick and the pad, our system uses electric conduction, similar to what was used in our second experiment. With HACHIStack, the system can detect the approaching velocity of the stick, and estimate the appropriate timing for haptic feedback similar to the previous application.

Figure 12 shows the setup for the demonstration of haptic augmentation with different simulated materials (rubber, wood and aluminum). It consists of the HACHIStack component mounted on an LCD covered with the elastic sheet. When the user makes a stroke on one the three panels displayed in the screen, she receives different haptic feedback from the stick. The application also changes haptic sensation depending on how strongly the user hits a simulated material. Figure 13 shows Q for the three materials and two different stroke intensities. Note that the waveform depending on which panel and how the user is hitting.

We demonstrated this application at EuroHaptics 2012, and it was positively received. Most of the audience could distinguish the three materials accurately through haptic feedback. Although future work should consider how accurately people can distinguish different materials through haptic feedback, more than three materials can be simulated in our system. When the timing for haptic feedback was intentionally preceded or delayed in a few milliseconds, some of the audience commented that they felt attracting or repelling force from the stick. This implies that our system has a potential to offer various types of force feedback by precisely controlling the timing for haptic feedback.

Realistic Virtual Piano
While the previous two applications include the stick device, the HACHIStack's sensing capability can detect touch with

bare hands. Our third application is a virtual piano instrument. It consists of HACHIStack mounted on the LCD displaying the virtual keyboard of a piano as shown in Figure 14. The application is connected to a MIDI interface to transmit the pitch and velocity of MIDI data. Unlike existing touch screen keyboard instruments, players can express different sound amplitudes by simply changing the approaching velocity on the key. In addition, the capability to predict contact time reduces the delay of sound production. In this manner, HACHIStack can contribute to developing a virtual musical instrument which offers realistic user experience.

CONCLUSION AND FUTURE WORK
In this paper we present a novel photo touch sensor architecture, HACHIStack, which can measure the approaching velocity of an object above the surface of the screen. HACHIStack uses two layers of photo sensors to measure the approaching velocity. HACHIStack can also predict the time of contact. The benefits of HACHIStack can be characterized as follows: high-speed sampling, approaching velocity acquisition, and contact time prediction. Our evaluations confirm that HACHIStack can detect the approaching velocity and predict the contact time
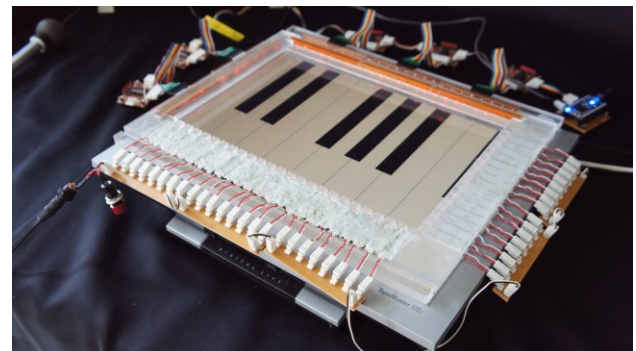

Figure 14. Our piano application. Unlike other piano applications, players can express the sound intensity by simply changing the approaching velocity.

accurately. We also present three applications which highlight the capabilities of HACHIStack.

We plan to conduct a user study examining the user experience of HACHIStack. In particular, we are interested in how changes in the timing for haptic feedback would influence on the sensation (e.g., sensitivity to the tapping action and vibration presentation asynchrony) including the study on the mechanism of attracting or repelling force sensation reported by the audience when the haptic feedback was preceded or delayed in a few milliseconds. This allows us to know multisensory integration and design requirements for multimodal interactive systems involving tapping interaction like those in [1, 35, 36, 51].

ACKNOWLEDGMENTS

REFERENCES

1. Adelstein, B.D., Begault, D.R., Anderson M.R. and Wenzel, E.M. Sensitivity to haptic-auditory asynchrony. In *Proc. ICMI 2003*, ACM Press (2003), 73-76.

2. Annett, M., Grossman, T., Wigdor, D. and Fitzmaurice, G. Medusa: a proximity-aware multi-touch tabletop. In *Proc. UIST 2011,* ACM Press (2011), 337-346.

3. Bau, O., Poupyrev, I., Israr, A. and Harrison, C. Teslatouch: electrovibration for touch surfaces. In *Proc. UIST 2010*, ACM Press (2010), 283-292.

4. Benko, H. Beyond flat surface computing: challenges of depth-aware and curved interfaces. In *Proc. MM 2009,* ACM Press (2009), 935-944.

5. Benko, H., Ishak, E. W. and Feiner, S. Cross-dimensional gestural interaction techniques for hybrid immersive environments. In *Proc. IEEE Conference on Virtual Reality,* IEEE (2005), 209-216.

6. Benko, H., Jota, R. and Wilson, A. D. MirageTable: freehand interaction on a projected augmented reality table top. In *Proc. CHI 2012,* ACM Press (2012), 199-208.

7. Benko, H. and Wilson, A. DepthTouch: using depth-sensing camera to enable freehand interactions on and above the interactive surface. *Microsoft Research Technical Report MSR-TR-2009-23,* Microsoft (2009).

8. Butler, A., Izadi, S. and Hodges, S. SideSight: multi-"touch" interaction around small devices. In *Proc. UIST 2008,* ACM Press (2008), 201-204.

9. Cutler, L. D., Fröhlich, B. and Hanrahan, P. Two-handed direct Manipulation on the responsive workbench. In *Proc. I3D 1997,* ACM Press (1997), 107-114.

10. Echtler, F., Pototsching, T. and Klinker, G. An LED-based multitouch sensor for LCD screens. In *Proc. TEI 2010*, ACM Press (2010), 227-230.

11. Fiene, J.P. and Kuchenbecker, K.J. Shaping event-based haptic transients via an improved understanding of real contact dynamics. In *Proc. IEEE World Haptics Conference 2007*, IEEE (2007), 170-175.

12. Fukumoto, M. and Sugimura, T. Active Click: tactile feedback for touch panels. *Ext. Abstracts CHI 2001*, ACM Press (2001), 121-122.

13. Grossman, T., Hinckley, K., Baudisch, P., Agrawala, M. and Balakrishnan. Hover Widgets: using the tracking state to extend the capabilities of pen-operated devices. In *Proc. CHI 2006,* ACM Press (2006), 861-870.

14. Hachisu, T., Cirio, G., Marchal, M., Lécuyer, A. and Kajimoto, H. Virtual chromatic percussions simulated by pseudo-haptic and vibrotactile feedback. In *Proc. ACE 2011*, ACM Press (2011), 20.

15. Hachisu, T., Sato, M., Fukushima, S. and Kajimoto, H. HaCHIStick: simulating haptic sensation on tablet PC for musical instruments application. In *Proc. UIST 2011*, ACM Press (2011), 73-74.

16. Hachisu, T., Sato, M., Fukushima, S. and Kajimoto, H. Augmentation of material property by modulating vibration resulting from tapping. *EuroHaptics 2012 Part 1*, Springer (2012), 173-180.

17. Han, J.Y. Low-cost multi-touch sensing through frustrated total internal reflection. In *Proc. UIST 2005,* ACM Press (2005), 115-118.

18. Harrison, C. Benko, H. and Wilson, A. D. OmniTouch: wearable multitouch interaction everywhere. In *Proc. UIST 2011*, ACM Press (2011), 441-450.

19. Harrison, C. and Hudson, S. E. Abracadabra: wireless, high-precision, and unpowered finger input for very small mobile devices. In *Proc. UIST 2009,* ACM Press (2009), 121-124.

20. Hilliges, O., Izadi, S., Wilson, A. D., Hodges, S., Garcia-Mendoza, A. and Butz, A. Interactions in the air: adding further depth to interactive tabletops. In *Proc. UIST 2009,* ACM Press (2009), 139-148.

21. Hirsch, M., Lanman, D., Holtzman, H. and Raskar, R. BiDi screen: a thin, depth,-sensing LCD for 3D interaction using light fields. In *Proc. SIGGRAPH Asia 2009,* ACM Press (2009), 1-9.

22. Hodges, S., Izadi, S., Butler, A., Rrustemi, A. and Buxton, B. ThinSight: versatile multi-touch sensing for thin form-factor display. In *Proc. UIST 2007*, ACM Press (2007), 259-268.

23. Hofer, R., Nadff, D. and Kunz, A. FLATIR: FTIR multi-touch detection on a discrete distributed sensor array. In *Proc. TEI 2009*, ACM Press (2009), 317-322.

24. Izadi, S., Hodges, S., Taylor, S., Rosenfeld, D., Villar, N., Butler, A. and Westhues, J. Going beyond the display: a surface technology with an electronically

switchable diffuser. In *Proc. UIST 2008,* ACM Press (2008), 269-278.

25. Janasen, Y., Karrer, T. and Borchers, J. MudPad: tactile feedback and haptic texture overlay for touch surfaces. In *Proc. ITS 2010,* ACM Press (2010), 11-14.

26. Kratz, S. and Rohs, M. HoverFlow: expanding the design space of around-device interaction. In *Proc. MobileHCI 2009,* ACM Press (2009), Article No. 4.

27. Kyung, K.U. and Lee, J.Y. Ubi-Pen: a haptic interface with texture and vibrotactile display. *IEEE Computer Graphics and Applications 29*, 1 (2009), 56–64.

28. LaMotte, R.H. Softness discrimination with a tool. *J. Neurophysiology 83* (2000), 1777-1786.

29. Lee, J.C., Dietz, P.H., Leigh, D., Yerazunis, W.S. and Hudson, S.E. Haptic Pen: a tactile feedback stylus for touch screens. In *Proc. of UIST 2004*, ACM Press (2004), 291–294.

30. Lylykangas, J., Surakka, V., Salminen K., Raisamo, J., Laitinen, P., Roning, K. and Raisamo, R. Designing tactile feedback for piezo buttons. In *Proc. CHI 2011*, ACM Press (2011), 3281-3284.

31. Mäki-Patola, T. and Hamalainen, P. Latency tolerance for gesture controlled continuous sound instrument without tactile feedback. In *Proc. ICMC 2004* (2004).

32. Malik, S. and Laszlo, J. Visual touchpad: a two-handed gestural input device. In *Proc. ICMI 2004,* ACM Press (2004), 289-296.

33. Matsushita, N. and Rekimoto, J. HoloWall: designing a finger, hand, body, and object sensitive wall. In *Proc. UIST 1997,* ACM Press (1997), 209-210.

34. Moeller, J. and Kerne, A. ZeroTouch: an optical multi-touch and free-air interaction architecture. In *Proc. CHI 2012*, ACM Press (2012), 2165-2174.

35. Ng, A., Lepinski, J., Wigdor, D., Sanders, S. and Dietz, P. Designing for Low-Latency Direct-Touch Input. In *Proc. UIST 2012*, ACM Press (2012), 453-464.

36. Ohnishi, H. and Mochizuki, K. Effect of delay of feedback force on perception of elastic force: a psychophysical approach. *IEICE Transactions on Communications E90-B(1)* (2007), 12–20.

37. Okamura, A.M., Cutkosky, M. and Dennerlein, J. Reality based models for vibration feedback in virtual environments. *IEEE/ASME Transactions on Mechatronics 6* (2001), 245–252.

38. Rekimoto, J. SmartSkin: an infrastructure for freehand manipulation on interactive surfaces. In *Proc. CHI 2002,* ACM Press (2002), 113-120.

39. Saga, S. and Deguchi, K. Lateral-force-based 2.5-dimensional tactile display for touch screen. In *Proc. Haptics Symposium 2012*, IEEE (2012), 15-22.

40. Samsung. SUR40 for Microsoft Surface 2.0. http://www.samsunglfd.com/product/feature.do?modelCd=SUR40.

41. Starner, T., Leibe, B., Minnen, D., Westeyn, T., Hurst, A. and Weeks, J. The perceptive workbench: computer-vision-based gesture tracking, object tracking, and 3D reconstruction for augmented desks. *Machine Vision and Applications 14,* Springer (2003), 59-71.

42. Subramanian, S., Aliakseyeu, D. and Lucero, A. Multi-layer interaction for digital tables. In *Proc. UIST 2006,* ACM Press (2006), 296-272.

43. Tactus Technology, Inc. Taking touch screen interfaces into a new dimension. *A Tactus Technology White Paper* (2012).

44. Takeoka, Y, Miyaki, T. and Rekimoto, J. Z-Touch: an infrastructure for 3D gesture interaction in the proximity of tabletop surface. In *Proc. ITS 2010*, ACM Press (2010), 91-94.

45. Wellman, P. and Howe, R.D. Towards realistic display in virtual environments. *In Proc. ASME Dynamic Systems and Control Division 57*, ASME (1995), 713-718.

46. Wigdor, D., Forlines, C., Baudisch, P., Barnwell, J. and Shen, C. LucidTouch: a see-through mobile device. In *Proc. UIST 2007,* ACM Press (2007), 269-278.

47. Wintergerst, G., Jagodzinski, R., Fabian, H., Müller, A. and Joost, G. Reflective haptics: enhancing stylus-based interactions on touch screens. *EuroHaptics 2010 Part 1,* Springer (2010), 360-366.

48. Wilson, A. TouchLight: an imaging touch screen and display for gesture-based interaction. In *Proc. ICMI 2004,* ACM Press (2004), 69-76.

49. Wilson, A. D. Using a depth camera as a touch sensor. In *Proc. ITS 2010,* ACM Press (2010), 69-72.

50. Wilson, A. and Benko, H. Combining multiple depth cameras and projectors for interactions on, above and between surfaces. In *Proc. UIST 2010*, ACM Press (2010), 273-282.

51. Zampini, M., Brown, T., Shore, D.I., Maravita, A., Röder, B. and Spence, C. Audiotactile temporal order judgments. *Acta Psychologica 118* (2005), 277-291.