Designing Rich Touch Interaction through Proximity and 2.5D Force Sensing Touchpad

Seongkook Heo, Jaehyun Han, and Geehyuk Lee
Department of Computer Science, KAIST
Daejeon, 305-701, Republic of Korea
seongkook@kaist.ac.kr, jay.jaehyun@gmail.com, geehyuk@gmail.com

ABSTRACT
The touchpad is the de facto standard input device for controlling the GUI on portable computers. Most touchpads detect only finger contact and ignore other physical actions, such as applying force or hovering over the device. In this paper, we introduce a novel touchpad capable of tracking finger hover and measuring normal and shear forces. We also present two design strategies for the hover- and force-enhanced touchpad: multi-level user interaction and mimicry of physical manipulation. We illustrate the two design strategies using two applications that we developed based on the design strategies.

Author Keywords
Force sensing, hover tracking, proximity sensing, touchpad

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation: User Interfaces – Input Devices and Strategies

INTRODUCTION
The touchpad is now widely used on many mobile and portable devices from TV remote controllers to laptop computers. Touchpads usually detect the 2D locations of fingers touching the pad. Some touchpads [2, 12] use multi-touch movements for additional features, such as scrolling or switching between workspaces.

In the real world, we utilize many physical properties associated with a finger touch. For instance, we can naturally control normal and shear force to hold and manipulate an object. In contrast, as only the movements of contact fingers are used, the input vocabulary of a touchpad is limited. If a touchpad can respond to more physical properties of a touch used in a real world interaction, it may have a richer input vocabulary.

Intensive research has been done to enrich touch input by using additional physical aspects of touch. Proximity sensing has been studied on table computers. Rekimoto [14] implemented a proximity sensing multi-touch table system and demonstrated the possible scenarios. Z-touch [16] installed multi-layered line laser modules and camera to detect hand location over the tabletop surface and finger postures. Medusa by Annett et al. [1] uses 138 infrared (IR) proximity sensors on the bezel of the touch table to detect users information such as presence, proximity, or which arm they are using. Hilliges et al. [10] implemented a camera-based proximity sensing multi-touch table and introduced in-the-air gestures. Marquardt et al. [13] designed an interaction technique for combining in-the-air and touch gestures. Cypress Semiconductor developed TrueTouch [5], a capacitive touch screen with proximity-sensing capability. Choi et al. [3] developed a proximity-sensing touchpad using IR LEDs to show the potential of remote touch concept. Choi et al. [4] also designed area gestures on a ThickPad, which is a touchpad capable of sensing proximity image, sized similar to a typical touchpad on a laptop computer. Force has also studied to enrich touch interaction. Rosenberg and Perlin [15] presented UnMousePad, which is a low-cost touchpad that can measure normal force of multiple touches and pens. Shear force, which is force applied perpendicular to the surface normal, is currently being studied intensively because of its high degree of freedom. Heo and Lee [9] showed that normal and shear forces can be used to enrich touch gestures and Harrison and Hudson [7] introduced possible scenarios using shear force. Recently, Heo and Lee [8] proposed a method to infer
the shear force of multiple fingers by utilizing the micro touch movement.

However, no study so far involved hover, touch, normal force, and shear force altogether. In this paper, we present a novel touchpad capable of tracking all these features, and introduce design strategies and applications.

**PROXIMITY- AND FORCE-SENSING TOUCHPAD**

**Hardware Configuration**

Figure 1 shows the touchpad prototype, which can track a hovering finger and measure normal and shear forces applied to a surface. The prototype is 142×88×21 mm, which is the typical size of large smartphones (approx. 6.2). The prototype device consists of three parts: a proximity-and-touch-imaging part, force-sensing part, and sensor data acquisition-and-transmission part. The touchpad prototype optically tracks finger position, hover, and touch using a set of IR LEDs and phototransistors, and it measures normal and shear forces with force-sensing resistors (FSRs). A 3mm thick flat acrylic plate is placed over four force sensors to measure normal and shear forces. We placed a silicon layer with 3mm thickness on the acrylic plate to enhance the sensitivity of finger touch detection as we will explain in the next section.

**Sensing Method**

**Proximity Sensing**

The device tracks fingers above the surface with a similar approach to that used in ThickPad [4]. As shown in the figure 1, 15×8 IR LEDs and 16×9 phototransistors are attached to the circuit board. The LEDs are individually controlled, and the phototransistors (S1) on the bottom are wired in parallel, working as a single large photo sensor. The working principle is shown in figure 2. When an LED is turned on, the phototransistor array S1 measures the intensity of IR light reflected by a finger above the surface. The intensity becomes larger when the finger approaches the surface, thereby indicating the approximate distance between the finger and the surface.

**Touch Detection**

Unlike the ThickPad [4], which can detect the touch of only one finger, our prototype is capable of sensing touches from multiple fingers using an internal scattering method [6]. For touch detection, 22 phototransistors (S2) were installed at the edges of the acrylic plate, as shown in figure 1. These phototransistors (S2) were also wired in parallel. When a finger touches the surface, IR light emitted from the LEDs is scattered at the point of contact and reflected inside the elastic acrylic plate to the S2 phototransistors. The phototransistor array S2 measures the intensity of the reflected IR light.

We obtain two sets of sensor values from the phototransistor arrays S1 and S2. Even if we capture two images, each LED is turned on/off once per image frame, because the position of an image pixel is dependent only on the LED states and no interference exist between S1 and S2. To reduce the effect of the ambient light, our prototype reads sensor values twice, when one LED is turned on and when all LEDs are turned off. Then, the prototype subtracts values obtained when LEDs are off from those when LEDs are on; the difference represents the intensity of light reflected from the fingers. For all the signal process steps, the frame rate of the current prototype is about 50fps for two 8×15mm images.

**Image Processing**

Several image processing steps are applied on raw images to find finger tips (See figure 4). The first step is the ambient light compensation. Even if we reduce the effect of the ambient light in the signal processing, the prototype structure itself, such as the acrylic plate and the elastic layer, reflect the light. This reflection appears constantly, thus we can compensate for this reflection by simply subtracting the baseline image, which was captured without any fingers, from the raw images. Then, we normalize each pixel value to compensate for the differences among each LEDs and phototransistors. We perform gamma correction and cubic interpolation to the normalized images to get clearer and smoother images. We then calculate the finger center by calculating the center of mass of the pixels in each finger blob and stabilize the finger position using speed-dependent low-pass filter [11].

**Force Sensing**

We implemented force detection with 2.5 degrees of freedom by using 12 FSRs. Four FSRs were attached to the circuit board and under the acrylic plate, and two FSRs were attached to each of the four side walls along the edges of the acrylic plate (Figure 1). Sensor values change according to the orientation of the touchpad.
because of the weight of the acrylic plate. In order to reduce the effect of gravity, the system calibrates force sensors by recording the sensor values at the moment of initial finger contact and by subtracting those values from sensor values measured while the finger is touching the pad. When calibrated sensor values are collected, the system calculates the shear vector. The 2.5D force vector \((x, y, z)\) can be calculated as follows:

\[
(F_R - F_L, F_T - F_B, -F_V)
\]

where \(F_T, F_B, F_L, \) and \(F_R\) are the forces obtained from the top, bottom, left, and right side walls, respectively, and \(F_V\) is the sum of the force values under the acrylic plate.

**APPLICATION SCENARIOS**

The proposed touchpad prototype enables hover- and force-enhanced touch interaction. We show possible application scenarios using interaction mappings designed with two design strategies: multi-level user interaction and mimicry of physical manipulation.

**Multi-level User Interaction: Video Browsing**

When browsing a video, both quick skimming and precise navigation are important. In order to enable multi-level user interaction, we divided the operations of the touchpad into three categories: hover, touch, and force operations. These types of touchpad operations can be used for different types of interactions depending on their properties, such as the level of stability and the type of control (position or force).

The hover operation is the most temporary and unstable positional operation among three types of operations, because the user could hold their finger in the air without intending any action. We mapped the horizontal axis of the touchpad to the video timeline and showed a preview of the scene corresponding to the touch position (Figure 5). Hover preview is used only to skim the video content and to perform the video playback, because it is not a stable operation. The touch operation is more stable than the hover operation; therefore, we mapped the touch movement to actually change scenes in a playing window. Similar to the hover operation, the horizontal position of a touch is directly mapped to the video timeline.

Rate-control input devices, like a jog shuttle, are widely used for browsing and editing video. However, a position-control touchpad is not ideal as a rate-control input. We use shear force, in place of a rate-control joystick, to support precise video browsing. Users can change the direction and the speed of the video playback by changing the direction and the strength of the shear force applied to the surface. Because the shear force input is isometric and continuous, users do not need to move their finger repeatedly to browse through a long stretch of the video. When users are applying shear force for rate control, an arrow-shaped indicator is displayed on the timeline to show the direction and the speed, as shown in figure 5b.

**Mimic physical interaction: 3D Manipulation**

When making something out of clay, we press the clay with our fingers to change the shape; for example, we can push the clay from the side or pinch it with fingers. While performing these processes, we naturally move our fingers to different locations, turn our fingers to change the contact area size, or change the direction and strength of the force we apply.

Because the proposed touchpad can measure physical features, we designed an interaction that uses these natural movements. A finger is represented by a circular-shaped projected cursor whose radius changes based on the size of the contact area, as shown in Figure 6. Users can lower the surface by pressing the touchpad or distort the surface by applying shear force at an angle. While applying force, the size of the contact area changes how the surface is modified; users can make sharp or stubby impressions by using the fingertip or the finger pad, respectively (Figure 6). The prototype device is limited to 2.5 degrees of freedom; therefore, interactions in the
reverse direction cannot be supported. As a solution, we provide a modifier key to invert the direction of the finger movement.

CONCLUSION AND FUTURE WORK
In this paper, we introduced a new touchpad that tracks hovering fingers and measures normal and shear forces. We also presented applications for the technology and described the relevant features. We adopted two design strategies to develop user interactions using the physical properties of the touchpad. The first design example showed the possibility of using physical properties to multiply the types of interactions. The second design example demonstrated that natural touching actions on the touchpad can be used to mimic real world interactions.

The current prototype has a limitation that it can measure only the total normal force applied to the surface although the touchpad can track multiple fingers. We are currently revising the hardware so that it can estimate forces by up to two fingers individually. With the individual normal force estimation, individual shear forces for multiple touches will be able to be estimated without requiring force sensors around the surface as in the current hardware [8].

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