Pre-Touch Sensing for Mobile Interaction

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ABSTRACT

Touchscreens continue to advance—including progress towards sensing fingers proximal to the display. We explore this emerging *pre-touch modality* via a self-capacitance touchscreen that can sense multiple fingers above a mobile device, as well as grip around the screen's edges. This capability opens up many possibilities for mobile interaction. For example, using pre-touch in an *anticipatory* role affords an "ad-lib interface" that fades in a different UI—appropriate to the context—as the user approaches one-handed with a thumb, two-handed with an index finger, or even with a pinch or two thumbs. Or we can interpret pre-touch in a *retroactive* manner that leverages the approach trajectory to discern whether the user made contact with a ballistic vs. a finely-targeted motion. Pre-touch also enables *hybrid touch + hover gestures*, such as selecting an icon with the thumb while bringing a second finger into range to invoke a context menu at a convenient location. Collectively these techniques illustrate how pre-touch sensing offers an intriguing new back-channel for mobile interaction.

Author Keywords

Multi-touch; hover; grip; context sensing; mobile interaction

ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation]: Input

INTRODUCTION

Natural human grasping behavior is analog and continuous. Yet the touchscreen of a mobile device typically restricts designers to flatland: a world of discrete state transitions defined by an impoverished, on-screen, two-dimensional view of the human hand.

The problem is that much of what characterizes 'touch' starts *before* contact [16] and originates from *beyond* the confines of the screen. Users first grip their mobile with the left hand or the right [18,22,57]. They then reach for the screen with an index finger, one-handed with a thumb [4,30], or with multiple digits for pinch-to-zoom. As the hand approaches, the posture hints at the user's intent [13,37,44] and the trajectory indicates likely targets [60,61]. This treasury of contextual detail—which in sum we refer to as *pre-touch* (a term introduced by [1,49])—is lost to mobile interaction.

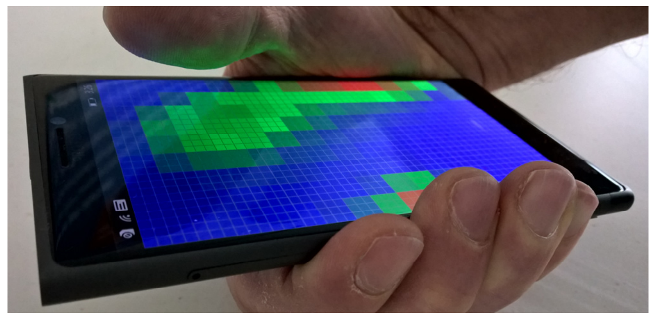

Figure 1. The pre-touch sensing modality detects multiple fingers *above* and *around* (gripping) the edges of the screen.

Pre-touch sensing above and around the screen (Fig. 1) therefore lends new insights to mobile interaction. We focus on contextually rich aspects of touch that take place *before*, or in conjunction with, actual contact—as opposed to *aftertouch*, a term for pressure-sensitive response [14,63] as well as in-air suffixes for gestures [9,33]. The richness of the pre-touch modality, which encompasses both grip sensing and multi-finger proximity, also distinguishes it from *hover* [12,20,33], which connotes a discrete state for tracking a single point (cursor) on legacy input devices [8]; or *in-air gestures* [9,25,50], which focus almost exclusively on overt actions. By contrast, our work on pre-touch emphasizes more casual, adroit, and context-driven interpretations [7,27,45].

Our resulting techniques therefore illustrate three strategies for pre-touch sensing in interaction design:

Anticipatory reactions modify the interface based on the approach of the fingers, in a manner that furthermore may be contingent on grip. For example, we demonstrate a mobile video player with an *ad-lib interface* that fades in when the user's fingers approach the screen, and fades out when the user moves away. These controls are context-sensitive: their presentation depends on the current grip, which direction the hand approaches from, and the number of fingers.

Retroactive interpretations construe touch events based on how the user approached the screen. We show techniques that reinterpret tap or drag events based on whether the user approached the screen in a ballistic motion, or with a finely-adjusted trajectory, allowing on-contact discrimination between flick-to-scroll vs. text selection, for example.

CHI'16, May 07 - 12, 2016, San Jose, CA, USA

ACM 978-1-4503-3362-7/16/05…$15.00
DOI: http://dx.doi.org/10.1145/2858036.2858095

Hybrid touch + hover gestures combine on-screen touch with above-screen aspects, such as selecting an object with the thumb while bringing the index finger into range to call up a *Hybrid Menu*. This reveals contextual options without resort to a time-out, in an easy-to-reach position. Although an overt use of pre-touch, this represents an under-explored class of hybrid gesture—in a way that also uses grip sensing "in the background" of the interaction [7] to support graceful degradation to a one-handed version of the technique.

In sum, then, our work contributes the following:

- The first exploration of pre-touch on a fully mobile device, particularly with regards to background-sensing aspects;
- Mobile interaction techniques that combine rich above-screen proximity with around-screen grip for some (but not all) of the design strategies we identify for pre-touch:
  - anticipatory reactions that adapt a mobile interface based on the context revealed by pre-touch;
  - retroactive interpretations that augment touch events with the trajectory of the approaching finger(s); and
  - hybrid touch + hover gestures.
- A design space organizing these key aspects of pre-touch;
- And preliminary user feedback on our techniques.

Collectively these contributions illustrate the promise of pre-touch as a sensing modality, and point the way to the still largely untapped potential of 'touch' once we free ourselves from the flatland of the standard touchscreen.

RELATED WORK

Our work relates insights from human grasping behavior to a viewpoint informed by sensing techniques, and the lens of background sensing in particular, to re-frame some common issues in mobile interaction as problems of context. Both grip and in-air (hover) sensing are key to realizing this direction.

Natural Human Grasping Behaviors

During prehension, the hand shapes itself—even prior to contact—to grasp tools for a specific purpose [37]. This is reflected by the posture of the hand as well as the kinematics of the reaching movement itself [13,39,44]. For example, probabilistic pointing [19] and expanding widgets [40,61] leverage the two-phase nature of pointing movements: rapid ballistic motion is followed by fine adjustment [41]. We use this insight by reasoning that trajectories with a distinct fine-adjust phase are likely intended for small targets (not large).

At a higher level, in human skilled bimanual action—such as pointing with one hand at a phone held in the other—the nonpreferred hand (grip) precedes and sets the frame of reference for the activity of the preferred hand [21]. Thus mobile interaction (at least in its two-handed manifestation) is a compound task that involves both hands in contact with the device, even if only the contribution of the preferred hand has traditionally been deemed as a 'touch.'

Sensing Techniques

User experiences with technology are increasingly mediated by sensors [3]. In the context of mobile computing, research on hover, as well as grip and motion, is particularly relevant. Yet how we think about these sensors—forsaking the low-hanging fruit of new ways to signal overt gestures in favor of the less obvious, more contextual ways to use emerging modalities—may be a key pivot in our perspective.

Foreground vs. Background Interaction

Buxton introduces a simple model of foreground versus background interaction [7]. The *foreground* includes activity that is at the fore of the user's attention, such as flipping a light switch at the entrance to a room—or tapping a target on a mobile touchscreen. But the *background* characterizes the context of activity taking place 'behind' the foreground—such as sensing the user walk into a room, and turning on the lights in response—or sensing the user's fingers approach the screen, and fading in a context-appropriate interface to suit.

Common Problems in Mobile Interaction as Missing Context

This perspective also helps us to see how many common problems in mobile interaction—such as one-handed interaction [4,30], occlusion of the screen by the fingers, or even the fat finger problem—might be re-framed as problems of context. Sensing which hand is holding the device fosters appropriate one-handed adaptations [18,57]. Occlusion can be avoided if the device can infer what content the hand is blocking [22,55,57]. Fat fingers can be partially remedied by sensing the posture of the touch [28]. And so forth. In this paper we explore just a few techniques motivated by some of these problems, but if pre-touch becomes commonplace it may prove useful in attacking these and many other difficulties in mobile touch interaction.

Grip Sensing Techniques for Mobiles

Grip sensing can enrich mobile interfaces in many ways. For example, grip sensors can determine whether the user is holding a device in the left hand or the right [18,22,57], automatically bring up a viewfinder when the user holds the phone like a camera [32], or suppress automatic screen rotation when the user's grip remains unchanged [10]. Other work has shown that grip, or the change in grip implied by motion sensors [42], can be used to anticipate the general area where the user is about to touch [43]. Grip sensors can also adapt the interface to suit the context [54], such as by bringing up a graphical keyboard at a convenient location [11]. Our work advances this theme in a nuanced way that fades in or fades out multiple, contextually-appropriate variations of a mobile user interface in an ad-lib fashion.

Sensing Hover and In-Air Interactions

A hover state for touch has recently started to appear on some mobiles—albeit typically restricted to single-finger hover—but the modality has long been explored on larger form-factors such as tabletops. The Continuous Interaction Space [38], perhaps the first work to explicitly recognize the continuity between hover and on-screen touch, explores interactions such as providing feedback of possible actions. Our approach to pre-touch builds on this continuity, unifies it with grip sensing, and advances it for mobile interaction.

A proposed model of feed-forward for multi-touch [16] resonates with our insight that grip informs the pre-input phases of touch. Medusa [1] also employs pre-touch feedback by sensing users approaching a tabletop display, with “Just-in-Time Widgets” that appear when users hold an arm above the tabletop. By contrast, our *ad-lib interface* appears when fingers naturally approach a mobile device: indeed, numerous context-appropriate versions of our UI, which are contingent on both grip and hover, fade in or fade out to accommodate various aspects of mobile interaction, thus going well beyond previous work [1,12,16,60].

Air+Touch [9] explores a vocabulary of in-air gestures that occur before, between, or after touches. While this opens up a rich design space of overt (foreground) gestures, our work adopts a complementary viewpoint that primarily considers how the proximity of multiple fingers, and grip, can serve as a background-sensing modality in support of mobile interaction. Our work also considers hybrid gestures with *simultaneous* touch and hover. This possibility has only been hinted at by one previous example, which uses “anchored” interactions with nonpreferred-hand touch to enable in-air gesture with the preferred hand for 3D interaction [29].

While foreground uses of hover tend to dominate the literature, examples of background uses do exist. For example, sensed hand shadows can enrich telepresence by showing communicative gestures in reference to a shared task space [16,52,53]. The imprecision of in-air interaction lends itself to more casual interaction at the periphery of attention [45]. And in addition to Medusa [1], other designs suggest controls that appear on approach [12], and dissolve when the finger moves away [60].

Another intriguing background use is to consider the motion trajectory itself. Zero-Latency Tapping [60] eliminates perceptible latency on a tabletop display by presenting ‘soft feedback’ in anticipation of the user’s predicted landing point. TouchCuts and TouchZoom [61] explore a direct-touch variant of Expanding Widgets [40] that expands icons based on the user’s predicted touch-down location. Our techniques instead focus on mobile interaction, and consider both grip and multi-finger hover as context.

Summary

Our contribution not only conceptually unifies grip and hover sensing under the umbrella of pre-touch, but also offers an interesting application of the background sensing point-of-view to these modalities. Even in cases where we do propose overt gestures—such as our hybrid touch+hover gestures—this consideration led us to bolster them with background attributes—such as accommodating graceful degradation to a one-handed version of the technique.

A DESIGN SPACE OF PRE-TOUCH INTERACTIONS

We devised a design space (Fig. 2) to situate our techniques (shown in bold) in relation to previous hover and grip-based interactions, suggest connections between techniques, and direct attention to relatively under-explored combinations.

On the left side, the rows indicate the property sensed: *hover* or *grip*, plus their use in tandem (*grip+hover*). On the right, we call out the *ground*—that is, the use of *fore-* vs. *background* sensing [7], with the background shown in gray.

The columns encompass our *anticipatory*, *retroactive*, and *hybrid* design strategies. Although these focus primarily on temporal aspects of the interactions, as *design* categories they admittedly lack absolutely rigid demarcations—and additional general strategies could be devised, as well. In this spirit, note that one could potentially add *aftertouch*—either by considering it as another strategy (e.g. for in-air suffixes to touch [9,33]), or by treating *pressure* [14,23,24] as a property sensed (e.g. Apple 3D touch [63])—in future work.

	Anticipatory Reaction	Retroactive Interpretation	Hybrid with Touch (on touchscreen)	
HOVER	Air + Touch [9] Continuous Interaction Space [38] Expanding Widgets [40] Sony [51], Samsung Galaxy 4 [47]	HoverWidgets [20] Gesture continuations (Air + Touch [9], HoverFlow [33])	AnglePose [46]: adds finger pose to touch Anchored above-screen 3D interaction [29]	Foreground
HOVER	Zero-latency tap [60] Hand shadows [52,53] Fade in [12] / out [60] TouchCuts / Zoom [61] ***Calm Web Browser:*** *feather in links; multi-finger gesture guides*	Casual interactions [45] Palm rejection [2] ***Ballistic vs. Fine Tap*** ***Flick vs. Select***	FlexAura [35] (pen with IR proximity-based sensing for hand posture recognition)	Background
GRIP	Occlusion-aware menu [5]	Paperweight metaphor [48]	PinchPad [58] Grip micro-interactions as overt gesture [59]	Fore-
GRIP	Grip activates camera [32], shifts margin for annotations [22] iGrasp keyboard [11] iRotate grasp [10]	Predict touch from back grip [43], Grip change as side-channel [42] Grip+micro-mobility [62] ContextType [17]	Detecting Unintentional Thumb Contact [26]	Back-
GRIP + HOVER			***Hybrid Menu:*** *thumb selects, finger in range calls up menu*	Fore-
GRIP + HOVER	***Ad-Lib Interface:*** *controls fade in depending on the current grip*	***Proposed***: extension of *Ballistic vs. Fine Tap* to take into account grip as well (see Informal Evaluation)	***Hybrid Menu:*** *grip triggers graceful degradation to one-handed menu*	Back-

Figure 2. Design space of pre-touch, with rows for *grip*, *hover*, and *grip+hover* from the perspective of *foreground* vs. *background* interaction—and columns for our three strategies for leveraging pre-touch sensing in interaction design.

While many foreground techniques for both hover and grip have been proposed, here we have intentionally emphasized examples of background sensing, since those are the most relevant to the ideas developed in this paper. The design space also underscores that (to our knowledge) grip + hover have not been used together before. Thus many (but not all) of the following techniques seek to explore this combination.

PRE-TOUCH HARDWARE

The device that we employ is an engineering prototype of a self-contained mobile device based on the Fogale Sensation [15] technology, which uses a self-capacitance touchscreen with a 16x9 matrix of sensors. Hence it is merely an enabling third-party technology: we do not claim it as a contribution. It looks and feels like a normal smartphone, weighing 175 g and measuring 142 x 74 mm, with a maximum thickness of 12.5 mm which tapers to 7.5 mm at the radiused edges.

The 5.2” touchscreen (16:9 aspect) senses 14-bit capacitance for each cell of the matrix, with a 120 Hz sampling rate. The presence of a fingertip can be sensed approximately 35 mm above the screen, but the range depends on total capacitance (e.g. a flat palm can be sensed ~5 cm away). Thus the capacitance values are a proxy—but not a direct measure—of distance. Grip can only be sensed close to the edges (Fig. 3); fingers on the back side of the device cannot be detected.

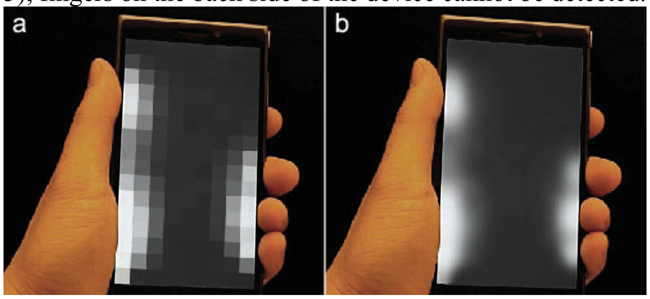

Figure 3. Hardware response to hand grip, with (a) raw 16x9 sensor image and (b) our resulting interpolated image.

IMAGE PROCESSING

We implemented our algorithms in C# and C++ using the OpenCV image processing library. Processing requires ~35ms per frame. For rapid prototyping purposes, we wirelessly transmit the 16x9 matrix of sensor values to a PC, process the image, and send the results back.

Fingertip Extraction

Some of our techniques use the trajectory of an approaching finger, and hence must identify the fingertip in the image. As illustrated in Figure 4, which provides an example of a single thumb approaching the screen, we follow a five-step pipeline to achieve this. We take the raw 16x9 image (Figure 4a) and interpolate it to 180x320 using the Lanzos 4 algorithm (b). A first fixed threshold removes the background noise of the capacitance sensor (c). We then increase contrast and apply a second threshold to isolate the fingertip region (d).

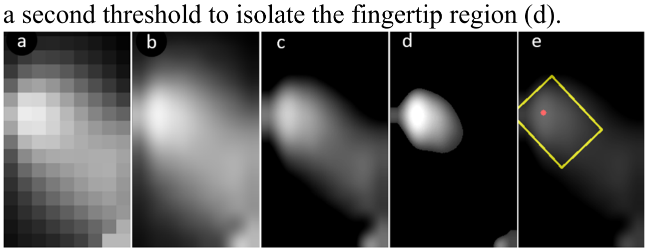

Figure 4. Image processing pipeline for fingertip extraction.

We then find the local maxima by moving a 6.5 x 4.6 mm window by 3.3 mm (horizontally) and 2.3 mm (vertically). If there are multiple local maxima within 1.5 mm, we combine them into a single maxima at the center point. In a second step, we apply a 5 mm radius circular mask around each local maxima; if they meet, we pick the highest maxima as the fingertip. If the local maxima falls at a screen edge, we consider it as part of the grip and do not treat it as a fingertip.

Thumb / Finger Distinction

We next calculate the orientation of the fingertip and use this to identify whether it is a thumb or finger. To determine tilt, we fit rotated bounding boxes (Figure 4e, yellow box) to the fingertip blobs; the aspect ratio indicates whether the finger is upright or oblique. We estimate yaw angle by finding the angle with the least brightness change along the fingertip blob. We then combine these metrics to determine if the blob is most likely a thumb (of the hand holding the device) or a finger from the other hand: if it is oblique and came from the same side that the user is gripping, it is thumb. Otherwise it is a fingertip. This heuristic works well for our purposes.

INTERACTION TECHNIQUES

We explore interaction techniques for each of the anticipatory, retroactive, and hybrid touch+hover design strategies that we identified. As such these are not cut and dried categories, but rather a palette of approaches that can be mixed and matched—or supplemented by new strategies in the future. While we do consider some ways to use grip and hover for overt interaction, we pay particular attention to techniques that employ these 3 strategies in the background.

ANTICIPATORY REACTIONS TO PRE-TOUCH

Anticipatory techniques proactively adapt the interface to the current grip and the approach of the fingers. That is, as one or more fingers enter proximity, the system uses the current grip, the number of fingers, and the approach trajectory to present an appropriate interface—or to otherwise adapt the graphical feedback to suit the shifting context of interaction.

Ad-Lib Interface Controls: A Mobile Video Player

Our video player uses *ad-lib interface controls* (Fig. 5) to present interactive elements in an appropriate manner, at an appropriate location—and only when they are needed. When a finger approaches, the system senses this and responds so that the interface can appear “just in the nick of time.” We pursued a video player because consuming videos on a mobile device exhibits many challenges typical of mobile applications: the more casual interaction context, the need to consume content from a variety of grips (including one-handed), and the desire to have a minimal default interface.

Related Approaches

A few prior examples have hinted at some aspects of this approach. For example, a previous design concept proposes that video controls could fade in with the approach of a finger [12], as does *just-in-time chrome* [56]. Zero-latency tapping suggests a complementary idea, that controls could fade out when the finger lifts, as one of its proposals for future directions [60]. And the Medusa tabletop [1] fades in certain controls at the approach of a hand, or fades in gesture guides when the hand hesitates at the periphery of the display.

Efficiency of Interaction vs. Comfort, Occlusion, Adaptability

Note that comfort and convenience trump efficiency in this interaction scenario; indeed, since our ad-lib controls must respond to an approaching finger, they are unlikely to be as fast as fixed controls that always remain on-screen. Yet dedicated controls consume screen real estate, occlude the content, and cannot readily adapt to changing context (such as one-handed interaction). Therefore our ad-lib controls intentionally sacrifice some measure of efficiency in favor of meeting these other demands of mobile interaction.

Fade In Behavior: Respond Promptly

Of course, the video itself is the center of the experience. So when the user is not interacting, there is no visible interface—just the content. This is the default experience that we optimize for. But when users need to interact, we don't want them to feel like they have to wait around for the controls to appear. The response has to be snappy. As soon as the system detects a hand approaching, it responds in a speculative manner so that it can start presenting an appropriate interface promptly. Popping the controls into existence would feel jarring, so we instead use a 200 ms fade-in animation designed to draw the user's eye to the *core playback controls:* play/pause, rewind, and fast-forward.

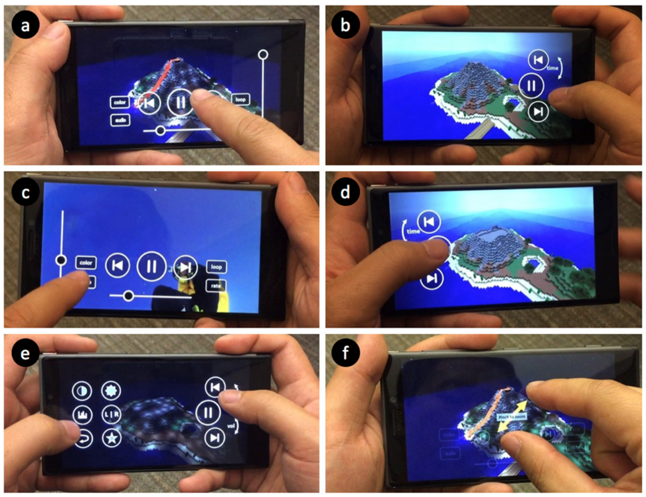

Figure 5. Ad-Lib Interface Controls, with (a) full controls when the user approaches with an index finger, (b) a reduced set of close-at-hand controls for one-handed interaction, (c) volume (vertical slider) flipped to the left when the user approaches from the opposite side; (d) one-handed controls fading in for the left hand; (e) a richer set of options fade in with two-thumb operation; and (f) the controls fade out when two fingers approach for pinch-to-zoom.

Fade Out Behavior: Withdraw Gracefully

When the finger moves out of range, the video player's controls fade, leaving the focus once again on the content. However, for this fade-out transition we want the user's attention to drift back to the video, so our objective is to withdraw gracefully—like a good waiter slipping away when his services are no longer needed. The system therefore reacts deliberately, fading out the UI over a 1.2s animation.

Note that we also experimented with fading based directly on the sensed finger proximity, similar to Medusa [1], but this seemed to make the fade in / fade out feel less predictable and more distracting visually than our fixed-time animations.

Bimanual Grip with Index Finger: Controls at the Center

When the user grips the phone in one hand and approaches the central areas of the screen with the index finger of the opposite hand, we fade in the default full set of controls. The fade-in animation, in this case, emphasizes the core playback controls (they fade in over just 100 ms and expand as they do so, drawing the eye). The core playback controls are then surrounded by other ancillary controls, including a vertical slider for volume control. Having a full set of controls come up in this case makes sense, because an index finger poised above the screen is nimble enough to reach a variety of locations. Furthermore, the two-handed usage posture indicates the user is engaged with the system—and likely has more cognitive and motor resources available—as opposed to one-handed interaction scenarios.

One-Handed Interaction with the Thumb

We started our design with the idea that the ad-lib interface fades in the UI when a finger approaches, and fades out the UI when the finger moves away.

But our key insight was the following: since the interface fades in and fades out anyway, it might as well *fade in a context-appropriate variation each time*, which suits the current grip, when the system senses the hand approaching.

Thus, when the user grips the device in a single hand and reaches over the screen with their thumb, the ad-lib interface fades in a UI specifically designed for one-handed use. Since it is hard to reach the center of the screen with the thumb, we fade in the controls closer to the edge, with a fan-shaped layout that suits the natural movement of the thumb, and we render a version for either the right hand (Fig. 5b) or the left (Fig. 5d), respectively. Furthermore, because one-handed interaction is less dexterous and more suited to casual activity, we fully render only a *subset* of the default interface—the core playback controls.

We also provide *dialing* controls for the thumb (Fig. 6) that allow the user to scrub through the timeline, or adjust the volume. This illustrates how we take a graphical control (linear sliders) and translate them to a gestural interpretation for the one-handed variant of the interface.

Figure 6. Dialing. The timeline and volume controls morph into dials when they fade in for one-handed interaction.

Note that our design makes no attempt to predict precisely where the thumb will land. The controls always animate to the same, fixed location that is a comfortable distance from the edge of the screen. We chose to do this for three reasons. First, the difficulty of accurately predicting the landing position from the early portion of a movement trajectory is well known. Second, we didn't feel that further fine-tuning the placement was necessary for typical small-screen mobile scenarios; presenting the controls centered, near the edge, is good enough on a small screen. Third, this makes the final position of the controls completely predictable once the user is familiar with them. An experienced user can therefore aim for a particular screen location out of habit, without fully attending to the graphical feedback.

As one final design flourish, when the one-handed controls animate onto the screen, they follow a path that mimics the finger approach. This helps to reinforce the connection between the one-handed version of the controls and the coming and going of the thumb from the screen.

Two-Thumb Interaction: Advanced Controls for 2nd Thumb

When the user reaches onto the screen with a second thumb, the ad-lib interface supplements the one-handed controls with an additional set of advanced options (Fig. 5e). These only slide in for the second thumb. The first thumb always invokes the one-handed version of the UI described above.

Pinch-to-Zoom Variation

Of course, two-thumb interaction is just one way of using two fingers on a touchscreen; if we sense the fingers approaching in a pinch-to-zoom zoom posture, we fade out the interface and present a gestural guide (Fig. 5f) instead. While pinch-to-zoom is familiar to most users these days, this approach could be used to reveal additional multi-touch gestures—an example of which we present in the next section, on our "calm" web browser.

Approach Direction

We use the approach direction in several ways. For example, as mentioned above, the one-handed variant of the ad-lib interface slides into the screen in a path that mimics the approach of the thumb. The approach trajectory also refines the presentation of the vertical volume slider for the bimanual grip with the index finger (with the controls at the center of the screen). If the index finger approaches from the right, the volume slider appears to the right of the main controls (Fig. 5a). But if it approaches from the left, indicative of left-handed use, the volume slider flips to the opposite side to make it easier to reach (Fig. 5c).

Summary of the Ad-Lib Interface

All of these nuances illustrate the many ways that the ad-lib interface combines various aspects of grip, the number of fingers, and the approach trajectory to optimize how the UI presents itself. Multiple variations of the interface come and go depending on the context, and carefully crafted animations make the interface responsive (on approach) yet unobtrusive (on fade-out) as appropriate. These accommod-ations are directed at comfort and convenience in mobile interaction, particularly taking into account one handed interaction for example, rather than efficiency per se, thereby resulting in a novel user experience that uses the background sensing capabilities afforded by pre-touch to tailor the interaction to various contexts of mobile interaction.

Calm Web Browser: Revelation of UI Affordances

Web pages employ various visual conventions to provide affordances for actionable content. Links are underlined, hashtags are highlighted, and playback controls are overlaid on interactive media such as videos or podcasts. But showing all of these affordances can add a lot of clutter to the content itself, whereas pages that omit such bells and whistles in deference to a cleaner design can leave the user uncertain of which content is interactive.

On desktop web browsers, mouse-over often lights up items—as can hover for touch as well [16,47,51])—but if the input is treated as a single point, the user must resort to tedious serial interrogation to figure out what can be tapped.

We implemented a mock-up of a web browser to explore use of the pre-touch modality to provide a more 'calm' web browsing experience—one that is free of such clutter in the reading part of the experience, allowing the user to enjoy a clean web page while holding (and reading from) the device.

Figure 7. Our *calm web browser* reveals interactive affordances in a nuanced way that feathers off with the finger contours.

When the user's finger(s) approach the screen, the hyperlinks and playback controls reveal themselves—and in a rich way that feathers off with the contours of the finger, thumb, or even the whole hand waving above the screen.

This feathering (gradual trailing-off) of the interactive affordances allows the user to quickly see *many* actionable items, rather than visiting them one-by-one. Furthermore, this emphasizes the items nearby, while more distant items are hinted at in a subtle manner (Fig. 7). This leads to *gradual* revelation of the affordances, in accordance with proximity to the hand, rather than having individual elements visually "pop" in and out in a way that would be distracting; for example, note how the video playback control (at the upper right of Fig. 7) blends in a subtle way onto the page, rather than popping in as a discrete object.

We implement this effect by alpha-blending an overlay image, containing the various visual affordances, with the thresholded and interpolated raw finger image (Figure 4c). The overlay appears immediately when a finger comes into proximity, and transitions from fully transparent to fully visible as the hand moves closer to the screen.

Freitag et al. [16] demonstrate hand shadows, but we give this a fresh twist by using the hover profile to selectively reveal interactive affordances, in a way that is truly multi-touch and corresponds to the sensed posture of the fingers.

Self-Revelation of Multi-Touch via Gesture Guides

Our web browser mock-up supports a two-finger tabbing gesture to slide back and forth between browsing tabs. To afford self-revelation of this gesture, the system fades in a gesture overlay when it senses two fingers side-by-side in the appropriate posture for 100 ms (Fig. 8a). At the same time the hyperlinks (and other visual affordances) fade out. Note that Medusa [1] also reveals a fixed gesture guide when the arm hovers at the tabletop periphery, whereas ours appears in-context and is contingent on the posture of the fingers.

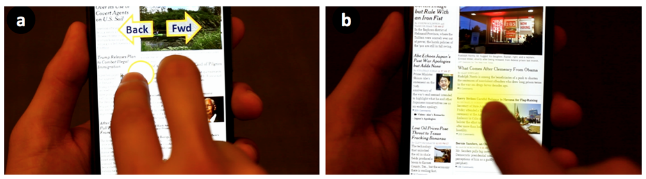

Figure 8. The multi-finger gesture guide (a) and highlights for collaboration using the sensed finger contour (b).

Finger Contour Highlighting for Collaborative Reference

We also support a collaboration mode where the sensed hand contour can be used to highlight portions of the page (Fig. 8b). The ability to easily refer to areas of a workspace (for example using hand shadows) has previously been shown to be vital to collaboration [52,53]; our highlighting feature demonstrates how pre-touch could be used to realize this for mobile devices. The yellow highlight is more expressive than a simple spotlight: it conforms to the contours of the fingers.

RETROACTIVE USES OF PRE-TOUCH

Pre-touch can also act as a back-channel that augments touch events, by retroactively inspecting the approach trajectory at the time of the touch-down event to glean more information about the pointing movement. As such, this way of using pre-touch resides in the background: it supports the foreground action (the intentional act of touching) in a way that is invisible to the user. Said another way, unlike the anticipatory techniques described in the preceding section, retroactive techniques produce no effect if the user doesn't complete the movement and make contact with the screen.

Our insight is that the approach trajectory provides additional information that may help to better reveal the user's intent. The example aiming movements shown in Fig. 9, which were recorded for a right-handed pilot user tapping on targets with his index finger while holding the phone in the nonpreferred hand, provide an illustration of this. When tapping on a small target, the user makes fine adjustments prior to tapping down. But for a large target, the finger simply lands on the screen with a ballistic motion.

Although as of this writing the effectiveness of such retroactive interpretations lacks formal empirical support, our observation is in accordance with the two-phase model of pointing [40,41,61]. And like probabilistic pointing [19], it suggests that the fine-adjustment phase may be limited or absent when acquiring large targets. In the following sections, a pair of techniques illustrate how we might leverage this distinction to enrich mobile interaction.

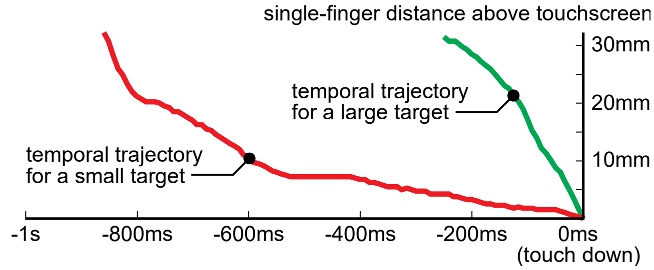

Figure 9. Example pre-touch trajectories from one pilot user for a small target (5x5 mm) versus a large target (40x40 mm). The small target requires fine adjustment, whereas the finger can "dive" to the large target with a purely ballistic motion.

Ballistic vs. Fine Tap: a Twitter Application Mockup

We implemented a mock-up of a mobile Twitter application to illustrate this idea in practice. Like many mobile apps, this use case provides a long list of large targets (the tweets themselves) that are mixed in with much smaller controls (the reply, retweet, and favorite icons).

Two problems present themselves. First, when the user taps on a large target (a tweet, to see its full contents), this imprecise, ballistic action may just happen to land on one of the small icons, triggering an accidental and unwanted action (Fig. 10a). Second, when the user attempts to tap on the very small icons, if the user misses even by a few pixels (which is easy to do with a fat finger, as shown in Fig. 10b) this instead expands the tweet, which was not the intended operation. In a sense the problem arises because the small targets nest within the visual gestalt of the large one, the tweet itself.

To distinguish these cases, we inspect the in-air approach trajectory upon the finger-down event. If we observe that the finger motion was purely ballistic, we dispatch the tap event to the large target (Fig. 10a). If the motion appears to include fine adjustments, we instead dispatch it to a small target if one lies within 7.7 mm of the finger-down event (Fig. 10b).

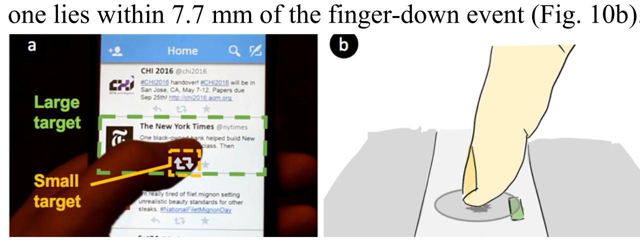

Figure 10. Twitter mockup. (a) Each tweet (large target) contains reply, retweet, and favorite icons (small targets). (b) Precise pointing redirects to a nearby small target.

At present, we identify the fine-adjust phase by looking for a touch trajectory with an altitude under 10 mm above the screen, and within 15 mm of the touch-down location, for the 250 ms before the finger makes contact. This is a global setting that was chosen heuristically for the bimanual grip, with the index finger used to acquire the target. As our forthcoming informal evaluation reveals, this heuristic probably could be improved by optimizing it for one-handed grips as well as on a per-user basis; different users appear to have varying confidence (or tolerance for errors) when they acquire small targets. Nonetheless, even in its present form this technique provides an intriguing example of applying a retroactive interpretation to pre-touch.

Flick vs. Select Discrimination

We explored a second example that uses this same insight to distinguish between flick (scrolling) and select (for a passage of text) at the moment the finger comes into contact with the screen. This dispenses with the need to separate these transactions by a tedious tap-and-hold interaction, which is standard practice in touchscreen interfaces. We interpret an approach trajectory with a ballistic swiping motion as a flick. But selecting a passage of text requires a fine acquisition phase to target the correct word boundary. We therefore can immediately trigger text selection for such movements.

HYBRID TOUCH + HOVER INTERACTIONS

Finally, pre-touch lends itself to hybrid touch + hover gestures, which combine on-screen touch with simultaneous in-air gesture. This brings to light a little-explored class of gesture—but previous work has used nonpreferred-hand touch to “nail down” [29] tabletop modes while the preferred hand makes in-air movements to manipulate 3D parameters.

These hybrid gestures clearly reside in the foreground, yet the example below illustrates how bringing in the background sensing perspective affords graceful degradation to a one-handed version of the technique.

Hybrid Menu Combining Touch and Hover (and Grip)

We implemented a mock-up of a mobile file explorer, with a grid of icons (files) that support commands such as *Copy*, *Delete*, *Rename*, and *Share*. Of course, these commands are meaningless unless a file is selected first. Hence this is a compound task: users must first *select* the file, and only then can they *pick* the command that acts on that object.

Traditionally, on mobile devices the user performs the *select* subtask with a tap-and-hold gesture on the desired object. Tap-and-hold with a typical 1000 ms time-out is a widely used but slow way to switch modes [34], yet the standard vocabulary of mobile interaction offers few alternatives.

We therefore implemented a hybrid touch+hover gesture (Fig. 11) that integrates selection of the desired object with the activation of the menu—articulated as a single compound task. The user first selects the desired file by holding a thumb on it, while simultaneously bringing a second finger into range. This *immediately* summons the object’s menu. Furthermore, since the system knows where the user’s finger is, it can invoke the menu at a convenient location, directly under the finger. The opacity of the menu is proportional to the finger’s altitude above the display. The user then completes the transaction by touching down on the desired command. Alternatively, the user can cancel the action simply by lifting the finger.

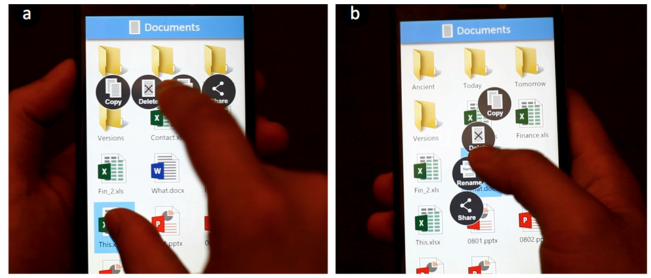

Figure 11. Hybrid touch+hover. (a) Selecting an icon with the thumb while moving a second finger into range calls up a convenient context menu. (b) With a one-handed grip, the menu gracefully degrades to a thumb-activated variant.

Hence, the technique offers three potential benefits: (1) it shortcuts the time-out that would otherwise be required by tap-and-hold; (2) it calls up the menu at a convenient, user-specified location directly under the finger; and (3) it phrases together selection and action (calling up the menu) into a single compound task [6].

While the technique is predominately designed to select the icon with the thumb, and then pick the command with the index finger, to accommodate icons near the top of the screen the user can alternatively touch down with the index finger first (to select) and then pick from the menu with the thumb. Our implementation supports either way of articulating the gesture.

Also, to clarify why hover is necessary (as opposed to “Pin-and-Cross” [36] style interactions on a second touch), our Hybrid Menu uses foreknowledge of the second, approaching finger to reveal the menu options before the user has to commit to anything—and to do so in the right place, and without the finger fully occluding the screen location.

One-Handed Variation for Picking Commands with a Thumb

The menu activation gesture described above only makes sense when using a mobile with both hands.

But because pre-touch affords sensing grip, the system knows when the user is interacting one-handed. Thus, in this situation, the technique gracefully degrades to enable menu activation with a single thumb.

In this case, we have not devised any clever means to short-circuit the timeout, so the user must tap-and-hold on the desired icon with the thumb. This then activates the menu. The system knows the thumb was used in this case, so it presents the menu with a fan-shaped layout that arcs in a direction appropriate to the side (right or left) that the thumb approaches from. The user then picks the desired command.

Possibilities for Mobile Gaming

We implemented a simple prototype of a soccer game to illustrate the potential of hybrid touch+hover for gaming (Fig. 12). The game uses the fingers to mime kicking a soccer ball: one finger stays planted, while the other finger strikes the ball. The 3D trajectory of the kick depends on the direction of movement and how high (or low) to the ground the user kicks. The finger can also be lifted *above* the ball to "step" on it, or to move over it in order to back-foot the ball, for example. The phone vibrates when the finger hits the ball. Other possible uses include controlling an avatar, or sensing walking-in-place interactions for virtual navigation [31].

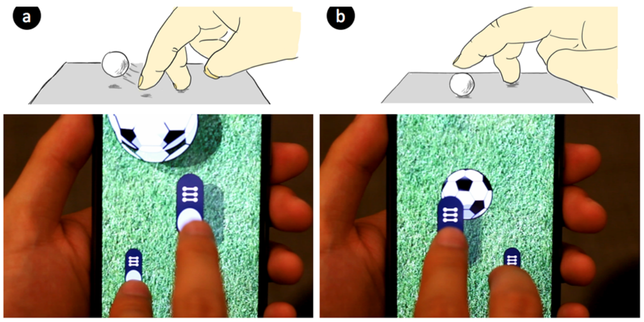

Figure 12. Soccer game. (a) Striking the ball along a 3D trajectory. (b) Moving *over* the ball does not strike it.

INFORMAL EVALUATION

To gain some initial insight into our interaction techniques, we had test users try them out and offer some preliminary feedback. Participants tried all applications described above except for the soccer game.

Participants

We recruited 7 participants (3 female, 4 male) aged between 23-31 (average 27) years. All used a touchscreen mobile phone every day, and had owned one for more than 2 years.

Procedure

Participants used the phone while seated, resting their arms on a table, and were allowed to use the phone as they found comfortable (e.g. one-handed with a thumb vs. two handed, using an index finger to point, or interleaving the two as desired). However, we did also ask users to try the interfaces using the various grips supported. We also interviewed users regarding each technique. The study took about an hour; participants were compensated with a $10 cafeteria coupon.

For the video player (with ad-lib interface controls), web browser (with calm revelation of hyperlinks), and file explorer (with the hybrid touch+hover menus), we briefly explained and demonstrated each interaction technique. Participants then tried the techniques on their own. But for the Ballistic vs. Fine Tap and Flick vs. Select discrimination, since the intervention is supposed to be completely invisible, we simply asked users to tap on various targets (for the Twitter mock-up) or scroll and select passages of text (for flick vs. select) without any prior explanation of the techniques. After users tried them for a while, only then did we disclose how they worked. Users then had a final opportunity to experiment with them further.

Results

All participants were able to learn the techniques within a few attempts—even the touch+hover hybrid gesture to call up a menu, which at present clearly requires an initial demonstration for users to discover the technique. Overall, participants responded positively to the techniques.

Ad-lib Interface (Video Player). Users appreciated that the controls got out of the way (didn't block the video) while viewing content; as one user commented, "I like the transparent controls, and they're predictive." Users particularly liked the facile transition to one-handed interaction, which "feels very natural to my hand" and allows using "a single hand in a comfortable position." Users also really liked the transformation of the volume and timeline controls to a dialing gesture. A couple of users expressed a desire for the controls to respond (appear or transition) more quickly to their grips. One user with large hands felt that the one-handed controls were too close to the edge. In regards to two-thumb interaction, another user felt that the core playback controls should always appear for the *right* thumb, with the advanced controls always on the *left* thumb, rather than bringing up the playback controls for whichever thumb approaches first. When trying pinch-to-zoom, one user suggested another dialing control for one-handed zooming.

Calm Web Browser. Users liked the clean design for reading and found it "really helpful to see hyperlinks in an efficient way" so that "I know exactly what I need when browsing the web page." Users also appreciated clear information on the content type (video, images, links). Several users commented that the graphic design of our revealed hyperlinks could be subtler and "more transparent with less emphasized borders." Thus, the reading experience satisfies our 'calm' design goal, but the hyperlink overlays are perhaps more distracting than we intended—although it would be straightforward to tone that down slightly. Users appreciated the guide for the tab switch gesture, but also felt that it should eventually be suppressed because it is only be useful for first-time users.

Ballistic vs. Fine Tap and Flick vs. Select. Users tried these techniques both bimanually (holding the device in the nonpreferred hand while using the index finger of the preferred hand to point) as well as one-handed. Reactions were divided. For some users, the interactions seemed to be well-tuned to how they naturally pointed at small targets, making it "an elegant solution to handling low-resolution thumbs" and a technique that "helps me avoid tapping on the wrong things." Other users "would need some time to adjust to it" or felt "it didn't work well with my fingers." This hints that these interventions can succeed with appropriate design, but per-user and/or per-grip settings (rather than the global time and motion thresholds that we currently employ) may be necessary to accommodate users' varied styles of pointing at small targets. Clearly, empirical studies will be necessary to sort out these issues and unpack the technique's potential.

Hybrid touch+hover gesture for menus. Users liked that this "pinch context menu" helps to "shorten the selection time," allowing them to "go to the buttons faster and more naturally." Users also really liked that the technique automatically senses grip to accommodate one-handed interaction: "adapting to the hand position is great." However, we also observed that our gesture recognition for this action has some quirks that caused false-positive appearances of the menu for some users. Users could easily escape the menu by withdrawing their hand, but this added effort was annoying when it occurred.

Overall reactions. No technique stood out as a universal favorite, yet almost all of the techniques had strong supporters. The ad-lib interface (and particularly the one-handed version thereof), calm web browser, ballistic vs. fine tap, and automatic presentation of one-handed context menus in the file explorer were all explicitly mentioned as favorites. However, the Ballistic vs. Fine Tap (and Flick vs. Select) exhibited a clearly bimodal response, as some users found the techniques completely natural while others found them ill-suited to their typical way of selecting small targets. And while users were able to learn the "pinch context menu" that we explored fairly quickly, the need to learn a new, unfamiliar gesture for this caused a majority of participants to rank this technique slightly lower than the others.

CONCLUSION AND FUTURE WORK

The sensor that we employed for our explorations has what might be viewed as a quirk: the touchscreen senses both grip and hover. But as our explorations have demonstrated, this apparent "quirk" actually presages a deeper insight. To use a phone during everyday mobile activity, the first thing one must do is pick it up, and hold it, with a particular grip on the device—which of course involves contact of the hand and fingers. Grip therefore precedes interaction with the screen itself through 'touch.' Likewise, traditional touch events fire at the moment one makes contact with the digitizer, yet the genesis of the grasping or aiming movement comes much earlier, and originates away from the screen itself.

Therefore, this sensor and its quirk—the seemingly incidental unification of grip and hover afforded by self-capacitance—compelled us to conceive of 'touch' in a way that embraces these natural human behaviors and that furthermore fully leverages them to add more contextual richness to mobile touch interaction. We signified this shift in perspective by envisioning this emerging modality as *pre-touch*, a term that properly frames this channel as an umbrella for both grip and hover, and that fosters its conception *as a sensing modality* that augments and enhances normal touch inputs from the background of the interaction.

The thread connecting our contributions has been the observation that multi-touch hover and grip, as afforded by self-capacitive touchscreens, raises many possibilities—and particularly in a mobile setting, with an emphasis on contextual sensing in the background. We conceptually unify grip and hover under pre-touch, a perspective which significantly extends the most closely related works (e.g. [1,9,16,60]) that leverage the pre-input stages articulated by Freitag et al. [16]. Some techniques we chose to explore were motivated by common problems in mobile interaction, where re-framing these as problems of missing context led to novel techniques. Additionally, several techniques combine grip+hover, most notably the Ad-Lib Interface (which goes beyond previous work by morphing the entire mobile UI between different, context-appropriate presentations that take into account both grip and hover).

But this is also apparent in the grip-contingent aspects of our Hybrid (touch+hover) menu, and in the way our findings suggest a natural extension of the Retroactive interpretation of Ballistic vs. Fine Tap to take into account grip as well. Nonetheless the Calm Web Browser, Soccer Game, and our present implementation of Ballistic vs. Fine Tap (and its Flick vs. Select variation) use only hover, but in new and interesting ways, to extend the themes of our research.

An interesting future direction would be to employ pre-touch hardware to explore unencumbered aiming movements on mobile devices in detail. Our exploration of Ballistic vs. Finely Targeted taps hints at some insights that might be revealed by such a study, but a much deeper analysis that looks at a variety of mobile contexts (and one-handed interaction in particular) is called for. As user comments revealed, our distinction between ballistic and finely-targeted taps likely requires a grip-contingent model (among other possible refinements) to meet wider success.

Exploring pre-touch on other form-factors could also yield new techniques. For example, one direction would be pre-touch sensing for tablets, where the larger screen brings about a greater diversity of grips, which therefore might demand different approaches to some of the design decisions than we made for our handheld form-factor. In particular, better prediction of the touch-down location from the grip and approach trajectory might be necessary to effectively support anticipatory techniques on a larger screen.

Clearly, the unification of grip and hover as *pre-touch* raises many possibilities for direct-touch interaction. While we have concerned ourselves particularly with the opportunities this emerging sensing modality opens up for a few common problems that users encounter when using mobile devices, pre-touch appears to offer much promise in addressing additional issues in mobile interaction as well. Future explorations of pre-touch can explore, study, and analyze these and many other possibilities—both expected and wholly unanticipated—that surely await discovery if one only looks not only under, but also *around and above* the right stones.

RIGHTS FOR FIGURES

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