Sensing Tablet Grasp + Micro-mobility for Active Reading

Dongwook Yoon[1,2], Ken Hinckley[1], Hrvoje Benko[1], François Guimbretière[1,2], Pourang Irani[1,3], Michel Pahud[1], Marcel Gavriliu[1]

[1]Microsoft Research, Redmond, WA, United States, {kenh, benko, mpahud}@microsoft.com
[2]Cornell University, Ithaca, NY, United States, dy252@cornell.edu, francois@cs.cornell.edu
[3]University of Manitoba, Winnipeg, MB, Canada, irani@cs.umanitoba.ca

ABSTRACT

The orientation and repositioning of physical artefacts (such as paper documents) to afford shared viewing of content, or to steer the attention of others to specific details, is known as *micro-mobility*. But the role of *grasp* in micro-mobility has rarely been considered, much less sensed by devices.

We therefore employ capacitive grip sensing and inertial motion to explore the design space of combined grasp + micro-mobility by considering three classes of technique in the context of active reading. *Single user, single device* techniques support grip-influenced behaviors such as bookmarking a page with a finger, but combine this with physical embodiment to allow flipping back to a previous location. *Multiple user, single device* techniques, such as passing a tablet to another user or working side-by-side on a single device, add fresh nuances of expression to co-located collaboration. And *single user, multiple device* techniques afford facile cross-referencing of content across devices. Founded on observations of grasp and micro-mobility, these techniques open up new possibilities for both individual and collaborative interaction with electronic documents.

Author Keywords

Grasp sensing; tablets; grip; micro-mobility; active reading.

ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation]: Input

INTRODUCTION

Active reading—the deep engagement with multiple documents and work surfaces during challenging intellectual tasks—characterizes much of knowledge work [18,29,34]. With the rise of electronic reading comes a desire to better support such activity on tablets and e-readers, for example through stylus input for mark-up [1,29], or more embodied interaction [5,10]. However, the user experience of such devices is still far from optimal for tasks such as nonlinear navigation, working with multiple reading and writing surfaces, or supporting nuanced co-located collaboration. Sensor modalities that inform context and enrich interaction offer a possible solution to these problems by sensing how tablets are grasped, fingered, oriented, passed around, or held aside, thus opening up a new vocabulary of prehensile behaviors with digital content on tablets (Figure 1).

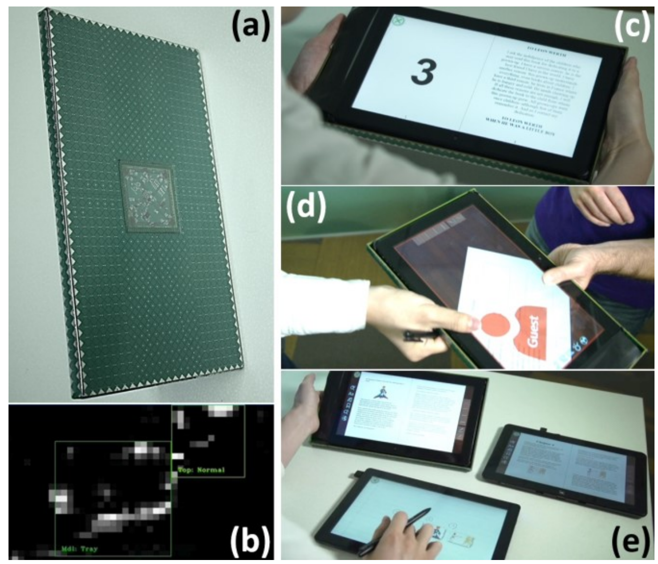

Figure 1. (a) Tablet case with (b) grip and motion sensing affords combined grasp + micro-mobility for (c) immersive reading, (d) collaboration, and (e) multi-tablet interaction.

In particular, our research unites two traditionally isolated perspectives: *grasp sensing* [19,36,38,41], and the *micro-mobility of physical artefacts* [13,23,25]. Micro-mobility concerns how people employ subtle manipulations—such as a doctor orienting a medical record towards a patient to invite comment—to afford the shifting demands of an activity.

We expand on this traditional view of micro-mobility in two ways. First, rather than solely a manifestation of orientation, we argue that the *dynamics of grasp*—how and where a person grips an artefact—also influences the semantics of micro-mobility. And likewise, micro-mobility affords essential cues to interpret grasp. Second, we observe how micro-mobility-like behaviors manifest *at the level of the individual*—not just in joint activities—to optimize device orientation for the task at hand, or to direct one's own attention across multiple mobile artefacts.

Our techniques underscore this perspective. For example, we recognize characteristic ways of holding the device during immersive reading; we design gestures founded on natural behaviors to support collaboration; and we employ fine-grained grip sensing to afford facile cross-referencing of

UIST '15, November 08 - 11, 2015, Charlotte, NC, USA

ACM 978-1-4503-3779-3/15/11…$15.00
DOI: http://dx.doi.org/10.1145/2807442.2807510

information across multiple tablets. As a whole, then, our work contributes the following:

- The fundamental insight that grasp and micro-mobility are interrelated human behaviors that provide complementary information (via capacitive grip sensing and inertial motion) to lend meaning to dynamic grasp interactions.
- Behavioral observations that document grasp + micro-mobility behaviors for individual and collaborative tasks.
- Grip-sensing algorithms that segment multiple hands and recognize grasp types (built upon existing hardware [16]).
- Interaction techniques that employ grip and micro-mobility to support active reading for 1) individual work on a single tablet, 2) dyadic collaboration over a single tablet, and 3) cross-referencing between multiple devices.
- Preliminary user reactions to our techniques.

Collectively, these contributions emphasize our perspective that grasp + micro-mobility are closely coupled human behaviors. And our techniques show ways one can leverage these modalities during both individual and collaborative activities associated with active reading.

RELATED WORK

Our research combines themes from human grasping behavior, grip sensing, and the micro-mobility of physical artefacts. Our emphasis on active reading—nonlinear navigation, cross-referencing content, working together over a document—lends a fresh task-centric view to these topics.

Human Grasping Behaviors and Grip Sensing

Human grasp [24] can reveal intentions [31] and as such represents a potentially rich source of insight into user activity [2,19,41]. The sub-conscious level at which people shape their hands to manipulate objects [2] or pass objects to one another [28] makes grasp difficult to interpret unambiguously [41]. Nonetheless, insights into how users grip objects such as tablets [40], pens [16,36], or mobiles [7] can inform designs and suggest relevant aspects of context to sense. Several systems use 3D orientation as a machine learning feature to improve grip recognition [16,36]. Our research further advances these ideas by showing how grasp and device micro-mobility offer mutually reinforcing perspectives.

Small devices have motivated research into bezel [19,20] and back-of-device interaction [30,43]. Grasp sensing can detect handedness [10,42], avoid unintended screen rotations [7], or call up a graphical keyboard [8]. Other work explores grip-dependent functions [19,38,41] as well as combined front / back touch gestures [43] and bimanual tablet interactions [40]. Our work goes beyond these efforts by using fine-grained grip sensing on the entire back surface and sides of a tablet in combination with inertial motion sensing.

Several efforts have explored hybrids of touch and motion sensing, but none consider the interplay between micro-mobility and grasp sensing. For example, touchscreen contact combined with motion enables multimodal gestures [12,16,17,33], and motion resulting from handling devices reveals telling details of context [12,30].

Sensors also afford more embodied ways of interacting with devices. For example, angling a device can evoke flipping through rolodex contacts [10], turning over pages [5], or sliding content across devices [25]. Our work probes the continuum between directly embodied interactions that interpret device grips and motions as overt gestures, all the way to subdued background-sensing techniques [4] that adapt to a specific activity such as immersive reading.

Our system builds on existing hardware [16], but here we focus on the theme of grasp + micro-mobility. While [16] does briefly touch on the idea of handing a tablet to another user, here we explore this class of multi-user, single device techniques much more deeply. Our work also differs significantly from the micro-mobility interactions explored by [25], which lacked grip sensing and relied on depth cameras to support multi-user, multi-tablet interactions. In the present paper we contribute techniques that demonstrate how grasp enhances micro-mobility.

The Micro-mobility of Physical Artefacts

Traditionally, micro-mobility is (1) *a manifestation of device orientation* that is (2) *specific to co-located collaboration with shared physical artefacts*. Yet to manipulate an object for micro-mobility [23,25], clearly grip (and not just orientation) must come into play. Territoriality [21] and passing prehension while handing objects to another person [28] have been studied, but *how and where users grasp artefacts* remains a neglected aspect of micro-mobility. Furthermore, regarding point (2), although "people smoothly and easily shift their artefacts from personal to public and the many shades in-between" [13], the manifestation of micro-mobility at the personal end of this spectrum—to accommodate shifting task demands at the level of the individual—has not been articulated. In this view, how a person grasps and orients objects to manipulate the attention of others may follow from habits first developed to allocate *one's own attention* to multiple physical artefacts.

A microanalysis of active reading [18] notes that people keep gripping artefacts (such as a document, or a laptop) that they intend to return to shortly. This observation bolsters point (1) because it shows how grip, and not just orientation, plays a role in directing attention. It further bolsters point (2) because this behavior occurs in the context of individual work (as opposed to the traditional association of micro-mobility with collaboration). Likewise, Chen's *Conduit technique* [6] enables users to touch a control on a 'source tablet' while employing a pen to transfer content to a 'target tablet.' And Conductor [14] prominently illustrates the user holding the specific tablets he is interacting with—but the paper does not remark on this, nor does grip sensing come into play. We build on these examples by sensing which tablet a user holds, and where the user grips it, to support multi-device interactions.

Active Reading Behaviors in Knowledge Work

Studies show that knowledge workers interleave episodes of deep, immersive reading [18] across multiple reading and writing surfaces [34], while annotating, cross-referencing, and collecting encountered information [27]. Similar patterns hold for both paper and electronic documents [29,34], but the ease with which paper supports such activities has motivated the design of many nonlinear navigation techniques [6,15,37], including techniques that closely mimic paper-like interactions [5,20,44].

Occasionally, microanalyses delve into specific manual actions, such as turning pages [26], multi-tasking [18], or lifting documents for closer inspection [39], but detailed observations at the level of hand grips and micro-mobility remain uncommon. We therefore further inform and motivate our work with the following observational study of tablet grips and movements in diverse active reading tasks.

FORMATIVE STUDY OF GRIP + MICRO-MOBILITY

We conducted a formative study with the goal of observing solo and dyadic instances of grasp + micro-mobility during document work. Our research ventures into areas lacking clear design guidance (grasp + micro-mobility, passing prehension [28], and the micro-territoriality of shared grips). To address this gap, our study sought primarily to generate design insights through qualitative observations that could inform, inspire, and serve as points of departure for our techniques.

We gathered these observations using non-interactive acrylic props, rather than fully interactive electronic tablets. This was a carefully considered choice that best serves our principal goal: to observe natural human behaviors related to grasp + micro-mobility. Non-interactive props have different affordances than touchscreens. Users can grasp and manipulate them in fully natural ways, without fear of 'accidentally' touching something. Hence a broader spectrum of natural behaviors can potentially be observed.

This choice also extends and complements previous studies that show how touchscreens can bias users' grip on the tablet or the posture of their hands – such as to prevent drops, or to avoid Midas Touch [1,16,40]. The props enable us to largely remove these biases and instead focus our findings and insights around the underlying grasp + micro-mobility behaviors themselves, naturally-occurring behaviors that serve as the bedrock for our designs. Of course, the resulting designs still must take into account the interactive properties of touchscreens; as such it would be interesting to repeat the study that follows for fully interactive tablets in future work. For our present purposes, however, we assert that conducting the study with non-interactive props was the best choice.

Tasks

We explored competitive, presentation, and cooperative tasks. By design these elicited different roles between users, hence varying relative body orientations [25,35] that might influence grasp and micro-mobility. In the ***competitive task***, users memorized a list, passed it to their partner, and then named the objects; this naturally led users to work face-to-face [35]. In the ***presentation task***, one user read text or an infographic for 1 minute—a solo activity—and then explained key details to their peer using the content as a visual aid—a dyadic activity. The peer then repeated this task with different content. This activity afforded observation of individual reading behaviors as well as collaborative micro-mobility in relative body orientations that shaded between side-by-side and corner-to-corner [25,35]. The ***cooperative task*** asked participants to discuss an infographic on a single prop while viewing it together. This let us observe how users shared the device in a side-by-side setting.

Apparatus

The non-interactive acrylic props were 9mm thick, in *tablet* and *e-reader* sizes of 176 × 250 mm vs. 135 × 200 mm, weighing 464g vs. 284g, respectively. Since the larger prop was only 5g lighter than the iPad Air, it represents a good proxy for state-of-the-art tablets. Paper sheets, which the user could mark-up as desired, were affixed to the acrylic to serve as the 'on-screen' content. Users employed the props with content formatted in both portrait and landscape orientations, and while standing as well as while seated at a table. All of the tasks allowed users to optionally employ a pen to point or mark up the infographics, and hence our tasks sometimes also elicited grasp behaviors with a pen in hand [16,32].

Participants and Design

16 people (2 female, all right-handed) participated in 8 pairs. The study lasted one hour, composed of 4 sessions, each with competitive, presentation, and cooperative tasks lasting about 1½–2 minutes each. The conditions and tasks were fully counterbalanced to control for the order of presentation.

Grips and Behaviors Observed

All sessions were videotaped and analyzed by the lead investigator via 2-step encoding—open coding followed by flat coding—with an emphasis on how people grasped, passed, angled, or gestured at the acrylic props. A second author independently sampled the study sessions and noted consistent behaviors as well, and furthermore several of the behaviors had been initially suggested in a separate pilot study conducted by a third author. Our qualitative analysis of the present study thus yielded the following noteworthy behaviors (B1-B9):

B1. Thumb grips for temporary one-handed use. All 16 participants held the props with the nonpreferred hand while the preferred hand gestured. We observed the following principal grips:

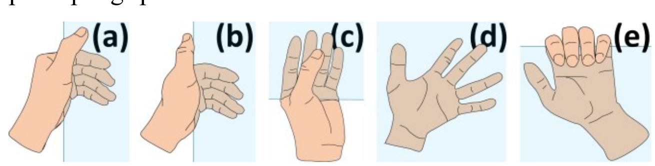

Figure 2. Grips: *a)* Thumb Left, *b)* Thumb Left–Edge variant, *c)* Thumb Bottom, *d)* Tray, *e)* Fingers Top (wrap-around).

As in the *Thumb Left* and *Thumb Bottom* grips noted by BiPad [40], participants held the props deep in the thumb cleft, with fingers extended for support, preferentially along the left or bottom edges (Figure 2a,c). However, the lightness of our props also allowed us to observe a new variation: the *Thumb Left–Edge* grip (Figure 2b). Users employed this grip to avoid occluding content, especially during bimanual use (see also B3, B5 below). We saw only a few instances of wrap-around grips (Figure 2e), which emphasizes that people rarely needed such grips for our lightweight devices.

B2. Tray grip for longer-term support & writing. About half of the participants exhibited Tray grips (Figure 2d) when they expected to maintain possession for a longer period of time, or if they needed a stronger opposition force, such as when annotating or gesturing at content (Figure 3c). However, users were not consistent about when they used the Tray vs. Thumb grips; preference seemed to depend on fatigue / comfort as well as the preceding grip on the device.

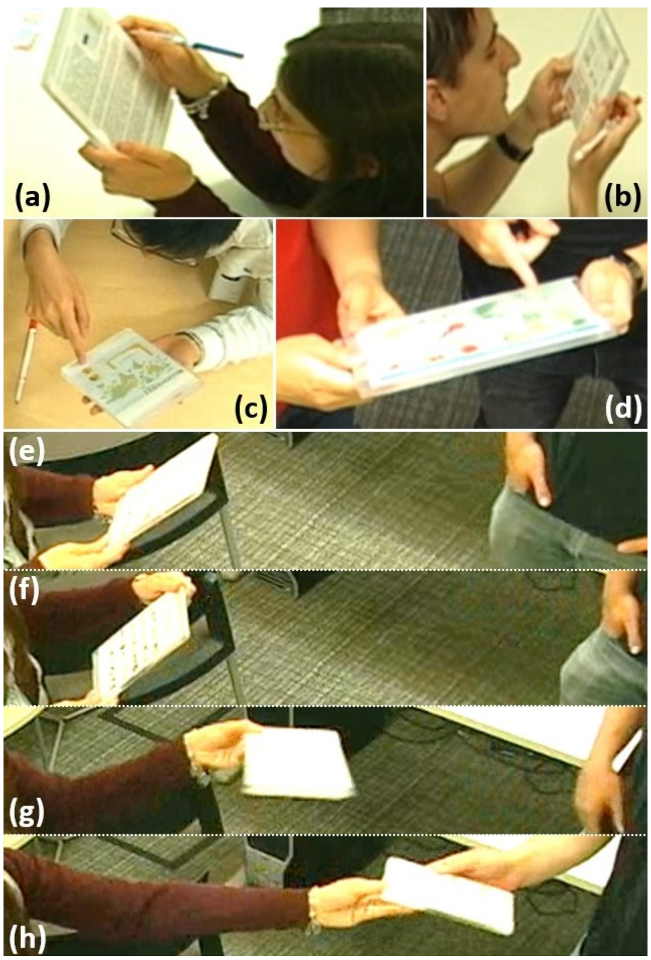

Figure 3. Grip + micro-mobility behaviors observed.

B3. Bimanual grips for a stable grasp. Bimanual grips enhanced stability and minimized fatigue; although perhaps only essential for extended use in landscape format, we observed bimanual grips in all settings (e.g. Figure 3a,b). All but one participant exhibited bimanual grips when the preferred hand was not immediately needed to gesture or write. We also observed many instances of users holding the props with the pen tucked near the edge (also seen in Figure 3a,b). Bimanual support also encouraged greater use of the Edge variant (Figure 2b) of the Thumb Left grip.

B4. Flexibility and diversity of grips. Behaviors B1-B3 are not static but part of a shifting allocation of grips. As such the assignment of grip to task is a somewhat flexible construct. For example, at times all participants transferred grips from hand to hand in response to the task context or a movement initiated by their partner (in addition to likely considerations of fatigue and comfort [40]). Furthermore, the details of how the user's thumb, fingers, and palm contacted the tablet exhibited much diversity, suggesting that any particular grip does not unambiguously indicate the user's intent in the absence of additional cues from micro-mobility.

B5. Bimanual symmetric grip for immersive reading. About three-quarters of the users consistently elevated the props with both hands while reading, often at bilaterally symmetric locations (Figure 3a,b). They also angled the prop at an optimum angle for reading [29] and pulled it closer, to fill their field of view and mask out peripheral distractions. This reinforces and brings together scattered findings [18,29,39]. It also shows how micro-mobility, in the form of an *orient-to-self* behavior, reinforces the interpretation of a particular grip—in this case, a symmetric bimanual grip with the thumbs held along the left and right edges of the device.

B6. Grip indicates locus of attention. While sitting, several participants placed their left hand near the line they were reading (Figure 3b), echoing prior observations of the hands anchoring attention [18,39]. The thumb tended to track the reading position as the user progressed down the page. We also noted that most users made fine-grained optimizations of the tablet's tilt to adjust the reading angle to suit the current reading position on the page. At present we do not employ this in our proposed techniques, but it does suggest another *orient-to-self* manifestation of micro-mobility.

B7. Directing the attention of others. Of course, as reported by Luff [23], during collaborative activity we observed all participants adjust tablet slant or lateral translation to steer attention (Figure 3c,d). This confirms our study elicited micro-mobility as traditionally conceived—yet we were struck by how users performed similar changes in tablet orientation during their individual work also (Figure 3a,b).

B8. Lateral swing for face-to-face handoff. During our competitive task, passing a tablet while standing in the face-to-face relative body orientation entailed a "lateral swing" – a Frisbee-toss motion, as in Figure 3e-h. All but one participant employed this lateral swing to accommodate the recipient's viewpoint. The thumb at the top keeps a firm grip while also allowing the giver to pass and rotate the prop with a single deft flip of the wrist. Here again, we see the interplay of a particular grip (preferentially at the top) with micro-mobility (reorienting the tablet to face the partner).

B9. Micro-territoriality. When performing our side-by-side cooperative task while standing, the giver often extended the tablet towards the recipient with two hands: one hand on the far edge, and one hand near the middle but still on the "giver's half" of the tablet. The recipient responded by supporting the opposite side of the tablet with one or both hands (Figure 3d). In this way, *three or four hands* gripped the tablet simultaneously, and the collaborators jointly adjusted the device's orientation. This accommodation cedes part of the tablet's territory to the partner; yet users clearly respected each other's grasping territory, rarely touching their peer's portion of the tablet. While territoriality on large tabletops has been noted [21], this *micro-territoriality* within a single mobile artefact (observed for 10/16 participants) appears to be a novel result of our study.

Closing Remarks on the Formative Study

One theme, evident for B5-B9, is the many examples of the interplay between grasp and micro-mobility. As such—just as is the case with micro-mobility itself—the way people employ grasp, orientation, and movement of physical artefacts is specialized to the task, the context of use, and specific situational aspects—such as whether the users are working face-to-face or side-by-side [25,35].

The diversity of grips observed (B4) might seem discouraging if one fixates on recognizing only naturally-occurring behaviors. However, we instead take these observations as points of departure—as provocations for possible gestures, contexts, and *designed* interactions founded on common patterns in how people employ grasp + micro-mobility. With this perspective and goal in mind, we set off to explore interaction techniques as follows.

GRIP + MICRO-MOBILITY SENSING AND RECOGNITION

We built a system to sense tablet grasp + micro-mobility. We use the hardware from [16], which consists of inertial sensors plus a capacitive array on the back and edges of the tablet. We improved the firmware to bring the grip sampling rate to 50Hz. The capacitive sensor array (44×26) covers the back and sides of a 337×197×16 mm case which weighs 1.4 kg, including the enclosed 11.6" Samsung ATIV tablet.

Grip Recognition Software

We devised algorithms to classify the grip type of multiple hands grasping the tablet. The recognition software consists of two modules that are independent of one another: a grip recognizer and a motion-gesture recognizer. The motion-gesture recognizer is built on top of the grip recognizer, at the application level, by using the inertial motion data in addition to the sensed grips.

Our grip recognizer processes the raw capacitance map into multiple hand datasets (Figure 4). These consist of hand-regions labeled with respective grip types through a 4-step *denoise-segment-classify-stabilize* process. This approach contributes a practical and fairly robust way to recognize the grip types noted in Figure 2 (and B1-B3) even when multiple users' hands (per B9) grasp a single device.

Denoise. This step suppresses temporal noise in the raw capacitance signal. We first perform per-cell min-max calibration of capacitance intensity for normalization. Then, we squelch minor capacitance noise by thresholding (20% intensity cutoff), and smooth temporal signal fluctuations via low-pass filtering (f_c = *19.89Hz*) with bilinear interpolation.

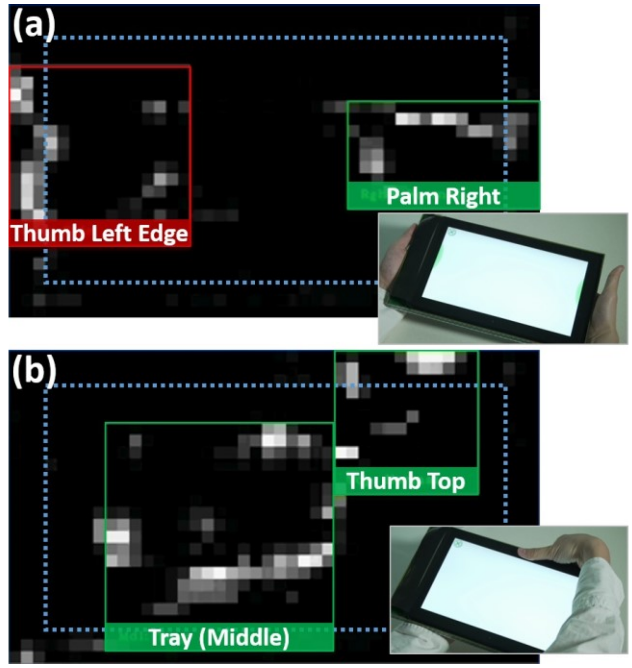

Figure 4. Tablet grip sensor data and recognition results. Capacitive touches on the side-edges were mapped outside the dotted blue area, with 3 pixel thickness in the sensor map.

Segment. From the denoised capacitance map, our segmentation module (using OpenCV) extracts isolated images of each hand via geometric criteria, such as edge connectedness or contact size, of the observed grip types (per BiPad [40], B1-B3, and Figure 2; with Thumb and Finger grips on the edge, and Tray grip in the middle). By segmenting grasp images, we can handle the shape of each grasp as a mutually independent entity; otherwise training and classifying the entire capacitance map results in an intractable explosion of grasp types and hand positions.

The recognizer first segments images of grips on the edges by regarding an edge blob as the seed of a hand's contact region. A labeling algorithm iteratively dilates the window of each hand region, which stems from the seed, to expand the hand's blob-set until no more adjecent blobs can be found in the window's adjacency set, or the integrated intensity sum of the window exceeds a predefined threshold (9 full intensity grids). Our algorithm then separately segments non-edge grasp images if any remaining blobs exceed a minimum intensity threshold sum for a hand. The grip regions of different hands rarely intersect, since holding the tablet with two overlapping hands is unnatural and was not observed in our study even when a pair of users held the same tablet (B9).

Classify. From the set of grasp images, we then classify the low-level individual hand grips using features including hand position, size, and intensity pattern of the contact area window. Edge grasp images can be classified as Thumb, Thumb Left, or Finger grips, while the non-edge contacting grasp image becomes a Tray grip (B3—Figure 2d) without running the classifier. A one-versus-all multiclass Support Vector Machine (SVM) classifier takes the grip bounding box (x, y, width, and height) and the normalized grip image (16 x 16) as the feature vector. Dynamic motions and the inertial sensors were not employed at this low level of processing, because here we are just identifying individual hand grips as building-blocks for subsequent interactions.

Stabilize. Finally, we recognize stable grips using a voting scheme with a state transition model where each state represents a grasp type. We queue the grasp types detected from a dataframe. The model moves from the current grip type to a new one, and triggers a corresponding grasp event, only when one grip type dominates the queue. Our prototype employs a queue size of 10 and voting threshold of 7.

Training Data

We collected training data with 4 participants (2 female, all right-handed). We led users to exhibit each grip type for various positions, with 50 × 6 (positions and types) × 4 users =1200 samples total. All grip recognition was performed from this training data.

GRIP + MICRO-MOBILITY INTERACTION TECHNIQUES

Building on behaviors B1-B9 above, we set out to explore interactions that leverage the interplay between grip and micro-mobility in active reading. Active reading represents a cognitively demanding task with ingrained habits stemming from physical pen and paper. It therefore seems ripe for fluid interaction techniques that keep users in the flow of deep concentration while also affording more embodied ways to interact with electronic books and documents. By the same token, our intent was not to follow a strictly literal interpretation of B1-B9: interfaces can be evocative of familiar interactions without being strictly beholden to the limitations of documents and physical artefacts. Our application also supports ink annotation with a stylus because mark-up is central to active reading [29,34].

We deliberately set out to explore techniques covering the three major categories of behaviors that we observed, as illustrated in the design space of Figure 5 – in addition to a fourth possible area of *muti-user, multi-device* techniques that we leave to future work. The design space highlights how our work fully combines grip and micro-mobility sensing, while most related techniques either focus on grip or micro-mobility, but not both. However, as noted in the table, a few previous works do hint at combined grip and orientation sensing.

Single user, single device interactions start from the core tasks of immersive reading and single-document navigation [26]. *Multiple user, single device* interactions explore grip-dependent micro-mobility behaviors for co-located collaboration between a pair of users working on a tablet. And *single user, multiple device* interactions explore how grasp + micro-mobility enriches activities spanning multiple surfaces [6,14]. The intriguing class of *multiple user, multiple device* techniques with grip + micro-mobility remains a potentially fertile area to explore in future work.

	SINGLE USER		MULTIPLE USER	
	Grip	**Micro-mobility**	**Grip**	**Micro-mobility**
SINGLE DEVICE	Grip sensing [19,38,41] FlexAura [22] iGrasp [8] BiPad [40]	Dual-display e-book [5]		Territoriality on tabletops [21]
	Systems which exhibit some elements of combined grip & orientation sensing: iRotate Grasp [7], Embodied UI's [10]		Passing prehension [28]	
	Single User, Single Device techniques: ***Sensing Immersive Reading*** ***Thumb Bookmark with 'Tip-to-Flip'***		*Multiple User, Single Device techniques:* ***Face-to-Face Handoff*** ***Side-by-Side Micro-Territoriality***	
MULTIPLE DEVICE	Multi-slate reading (conduit) [6]	Terrenghi observations [39]		GroupTogether [25] PDA's & Shared Public Displays [13]
	Single User, Multi-Device Techniques: ***Fine-Grained Reference*** ***Hold to Refer Back*** *Tablet+Stylus Sensing* [16,36]		*Multiple User, Multi-Device grasp + micro-mobility techniques:* *(Left for exploration in future work)*	

Figure 5. Design space of grip and micro-mobility techniques. Techniques highlighted in green are explored in this paper.

SINGLE-USER, SINGLE-DEVICE INTERACTIONS

The first category of grasp interactions for active reading supports individual reading and navigation tasks.

Sensing Immersive Reading for Deep Engagement

Following from our observation B5, we sense immersive reading when the user exhibits a bimanual symmetric grip on the left and right sides of the tablet. This grip conveys a heightened level of engagement in a reading activity.

When we sense immersive reading, the application fades away peripheral distractions (such as the menus at the borders of the screen, as well as any overlaid ink mark-up). The application simultaneously performs a slow zoom by a factor of 1.15 such that the content expands into the margins and the space freed up by fading away the menus. This focuses closely on the book content itself (Figure 1c) and produces a visual effect which is the equivalent of pulling a book about 5cm closer (from a typical reading distance of 40cm). This technique thereby supports deeper engagement with the content in a refined and non-demanding manner.

The user can exit immersive reading in a straightforward manner simply by relinquishing his grip on the tablet. However, the user may remove one hand to perform other tasks (e.g. pick up a pen) without exiting the slightly zoomed-in view. Thus, immersive reading is a "mode," but one implemented in a very lightweight manner that largely retreats to the background of user attention [4].

We experimented with sensing B5 literally, i.e. with a bimanual symmetric grip *while* angling the tablet. However, given the bulk of our prototype, and since our slow-zoom animation produces a similar visual effect as lifting the tablet, we found the technique more satisfactory when we based sensing immersive reading solely on the grip rather than requiring users to also lift the tablet. This shows one example where a design may be inspired by a natural behavior (B5), yet interprets the user's intent in a non-literal fashion to take advantage of the digital affordances of electronic documents. It would be interesting to see if users would prefer this with a much more lightweight version of our prototype, but at present our grip sensors add too much bulk and weight to the tablet to investigate this.

Thumb Bookmark with 'Tip to Flip'

In physical books, users naturally interleave a thumb or finger between pages to easily flip back to content of interest. Note that this involves both placing a finger as well as physically orienting the document so that the document flips back to the desired page [26]. Our system supports this lightweight bookmarking behavior by sensing when the user rests a thumb along the edge of the tablet (Figure 6a). This draws on the prevalence of the thumb in reading grips (B5) and in the role of grip in tracking the locus of attention (B6).

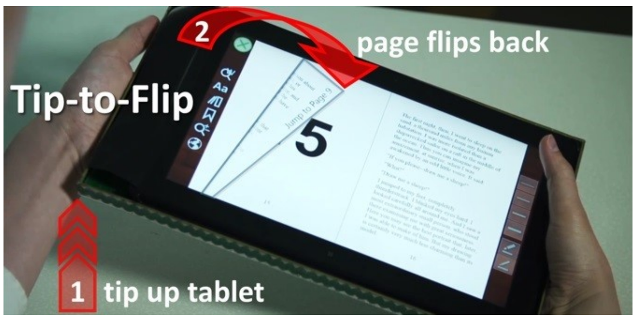

Figure 6. Holding the edge creates a *Thumb Bookmark*. The user can then 'Tip to Flip' back to the page held by the thumb.

Resting a thumb on the edge of the tablet accordingly reveals a small dog-ear that shows the current page is held by a thumb bookmark. This is intentionally subtle so that any incidental activation of these lightweight bookmarks does not distract the user, yet the feedback is clear when the user intentionally rests a thumb to bookmark a page.

We use the *'Tip to Flip'* interaction to ensure that flipping back to a bookmark is always an intentional gesture. To return to a thumb bookmark, the user must make an overt gesture of tipping up the bookmarked edge of the tablet by at least 10 degrees. This "peeks back" to reveal more of the bookmarked page (Figure 6) in a physically embodied manner, but does not actually perform page navigation. To confirm the action, the user taps his thumb against the edge of the tablet while it is tilted. The page then flips back to the page indicated by the thumb bookmark. The user can alternatively cancel the flip-back by withdrawing his grip.

MULTI-USER, SINGLE-DEVICE INTERACTIONS

Our second class of interactions support collaboration with a shared device [21,23,25] in both face-to-face and side-by-side settings, as observed in B7, B8, and B9. Our e-reading application color codes ink mark-up as information elements that are bound to each user, with blue annotations for one user (the owner) and red for the other (the guest). Our techniques fade in and fade out these annotations to indicate dynamically changing ownership and access for each user, as appropriate to the specific technique.

We explored two different techniques, a Face-to-Face Handoff based on the lateral swing observed in B8, as well as a Side-by-Side technique based on the micro-territoriality observed in B9 during cooperative work. However, we decided to support these behaviors as designed gestures that users would intentionally trigger, rather than attempting to respond to any plausible activity that looked like it might be device sharing. This leaves users in control of these interactions in a way that respects the spirit of micro-mobility, which users employ to share *or not share* according to the specific context, task, or mood demanded by the occasion of an encounter. Employing a specific, designed gesture also acknowledges the practical constraints imposed by the flexibility and diversity of grips we observed (B4).

Face-to-Face Handoff

Our Face-to-Face Handoff technique (Figure 1d) provides a lightweight way for a user to give a collaborator *temporary* guest access to the content on his or her screen. Furthermore, we also employ this as a lightweight way to distinguish whether the owner or the guest has made annotations without requiring authentication (log on, swiping a badge, etc.). Note also that this form of sharing content differs markedly from sending the content itself to another device. The owner maintains control of the digital content and it is only accessible to a collaborator while he is in physical possession of the tablet itself. This semantic of sharing is more akin to physical sharing, yet it represents a shade of meaning that has been largely absent from electronic documents.

Based on the hand-off behavior we observed in B8, we look for a hand grip at the top of the device followed by a lateral swing of the device. We sensed this as a quick yawing motion that covered more than 80 degrees of rotation. Pursuant to our stated goal to support designed, intentional gestures for this class of interaction, we only recognize handoff when the lateral swing occurs with the hand grip at the top. This is consistent with the grasp + micro-mobility behaviors we observed, yet also keeps the user in full control of the interaction and the degree of sharing (or not sharing).

When we recognize the Face-to-Face handoff gesture, our e-reading application shows clear feedback of the Guest profile "swinging" onto the screen in an animation that mimics the lateral swing motion itself. Note that the current holder is not sensed *per se*, but rather assumed based on the order of appearance of the grips. The application then shows the device holder's mark-up with higher opacity, while the other user's annotations fade away. Furthermore, contrary to Hinckley et al.'s hand-off gesture [16], our interaction more closely follows natural hand-off movements by taking the lateral swing motion into account. It also thereby prevents false-positives that could be triggered by the user's other unintentional grip changes or device movements.

Side-by-Side: Micro-Territoriality during Joint Use

Since our Face-to-Face Handoff technique accommodates collaborative tasks of a more competitive nature [35], we sought to explore different behaviors for more cooperative interactions typical of side-by-side interaction. In particular we thought it would be interesting to sense the micro-territoriality of grips on a shared artefact as observed in B9.

Figure 7. Micro-Territoriality during Side-by-Side use.

Our system detects the Side-by-Side interaction by sensing multiple (more than two) hands simultaneously gripping the tablet while it is close to being held level (Figure 7). When our e-reading application recognizes such a side-by-side interaction, we again show distinct animated feedback that shows the screen sliding sideways towards the collaborator before coming back into place. This indicates side-by-side use with the users on equal footing as collaborators. We furthermore show each user's ink mark-up in different colors, but with the same opacity level, so that they can mutually view and discuss one others' ideas.

We maintain this state until the user who initiated side-by-side sharing releases his grip on the bottom. This embodied way of holding the mode clearly indicates who initiates—and in a sense, 'owns'—the exchange, while also offering a lightweight way to back out of the shared status if the user changes his mind, or happens to trigger a false positive. However, while this design choice minimizes the users' collective physical effort, and leaves their other hands free to interact or gesture as desired, it also means that the user who initiated the interaction cannot fully relinquish his grip (e.g. to pick up a pen). We discuss this further in our evaluation.

SINGLE-USER, MULTI-DEVICE INTERACTIONS

While we did not explicitly probe multi-tablet behaviors in our formative study (B1-B9), reading and writing on multiple working surfaces is a pervasive theme in active reading tasks [34], and several systems have already explored multiple-device approaches to support such activity [6,14]. Furthermore, some of our observations, such as the tendency for grip to indicate the locus of attention (B6), resonate with behaviors noted elsewhere, such as users' prevalence to hold and orient an artefact to themselves (B5, B7) if they intend to devote their attention to it soon [18,39].

We therefore explored two techniques for multiple-device interactions. At present, we only have one grip sensing case, so we prototyped these techniques by employing the second device's tilt to infer its state (resting flat on a surface, or held in midair). We also employed the pen and touchscreen inputs to keep track of the most recently used device.

Fine-Grained Reference to Parts of a Document by Grip

Participants in our formative study often put their thumb or other fingers on the outer edge of the device, close to the location where they were reading (B6). This pattern of behavior is particularly informative for capturing user intentions in multi-device interaction, since it provides a clue about not only which device a user is referring to, but also what part of the screen is likely the focus of their attention.

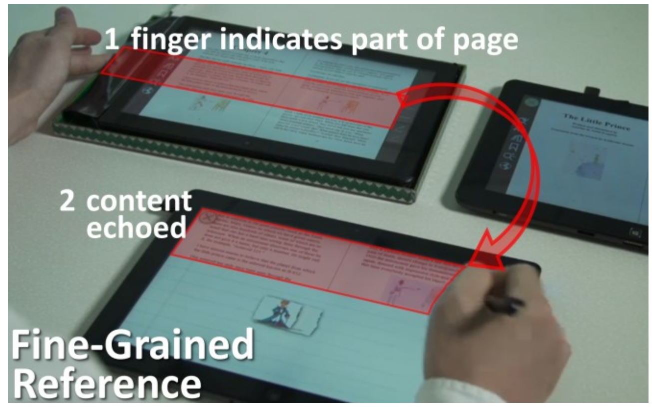

Figure 8. Fine-grained reference to part of a document.

With this in mind we employed the location of isolated touches along the screen edge to enable fine-grained reference to a portion of the screen. As shown in Figure 8, this echoes the corresponding horizontal strip of the screen to the user's most recently used remote tablet. The user can then clip out part of the echoed content by performing a marquee (rectangular) selection with the pen. This simple touch-and-clip interaction is quick to perform, and leverages the natural behavior of keeping the hand grip close to the passage being read. This makes it easy for the user to gather encountered content in a lightweight manner that is minimally disruptive to the reading task itself [27]. At present, we only support this when the tablet is flat, because using multiple tablets in this manner only makes sense on a supporting surface.

Hold to Refer Back Technique

When a user picks up an artefact and orients it to himself (B5, B7), this indicates increased focus of attention on the object [18,39]. Inspired by these observations we devised a "hold to refer back" technique for revisiting pages.

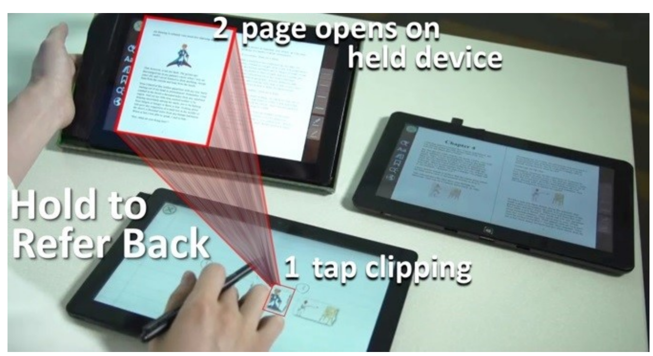

Figure 9. Hold to Refer Back Technique.

The clippings captured by the Fine-Grained Reference technique automatically include hyperlinks to the content. When the user subsequently taps on the clipping, our e-reading application triggers an animated page flip back to the source content on the other device – i.e. the device that the user is currently holding (Figure 9). In this way the user can easily cross-reference content from other documents and arrange a set of working documents on multiple tablets to facilitate viewing scattered pieces of desired information.

Although we currently employ orientation sensing to support additional tablets without our grip-sensing hardware, the capacitive sensor offers a more robust and physically intuitive solution for detecting which device a user grasps. In the future this may enable techniques that leverage richer grasp-sensing capabilities on both tablets to be more fully explored.

PRELIMINARY EVALUATION

The goal for our evaluation was to assess preliminary user reactions to our proposed grasp + micro-mobility techniques. Hence our approach was an informal one, intended to solicit qualitative feedback of users' experience with the techniques in action. Since this type of evaluation lacks ground truth data, we did not tabulate false positive rates, but our recognition techniques worked well enough for users to experience the techniques as we intended.

We recruited 16 users (4 female, all right-handed, 25-48 years old, mean 28.5) in 8 pairs for 90 minute sessions. None of these users participated in the formative study. The experimenter briefly demonstrated each technique, and the participants then practiced until they felt comfortable to proceed. Each user performed the single-user interactions alone, and the multi-user interactions in collaborative pairs.

Overall, we found that we could reliably sense hand position and grip size. However, a few participants initially held the tablet case too lightly, which caused it to sense unstable grip data (we believe this was caused by air gaps forming under a protective layer over our capacitance sensor). We addressed this issue by simply asking these users to grip the tablet a bit more firmly, which successfully resolved the problem. Finally, although a pen was employed in our formative study, our prototype tablet was too bulky to afford tucking a pen while also holding the device [16,32]. We therefore did not have users hold the pen while trying out our techniques.

Immersive Reading. Users readily picked up on this technique, with several commenting on its real-life familiarity (per B5). Some users disliked the immersive reading technique's requirement to constantly hold the tablet's outer edge, which leads us to contemplate more relaxed ways of maintaining the immersive reading mode once initiated. Beyond the overt behavioral level, some users also remarked on how the technique afforded their engagement with the content, such as one user who commented "This [action] means a focusing for me." This suggests that the semantics encoded in the physical action of B5 were well supported by the digital counterpart that we designed. Even though a literal interpretation of B5 would require lifting and angling the tablet, our technique clearly captured the user's intention effectively. It also shows how sensing grip might obviate the need for micro-mobility manipulations in certain cases.

Thumb Bookmark. People enjoyed the direct intuition of holding a finger in place to anchor a page, tipping up the screen to reveal the held page, or withdrawing the hand to let go of a bookmark. However, one minor issue we noted was that letting go of a bookmark currently requires completely letting go; this transfers the entire weight of the tablet solely onto the remaining hand, which users did not like. We plan to explore a more subdued notion of withdrawing the thumb, but this of course must be balanced against the possibility of letting go by accident which would also be undesirable.

Face-to-Face Handoff. Participants appreciated that our system responded when they "tried to do [the handoff] naturally, and it worked almost every time." Users also felt that switching the tablet to a guest profile, with the corresponding annotations emphasized, made good sense. While most users employed Face-to-Face Handoff as we envisioned it, a few pairs of users co-opted the sensing to be triggered *by the recipient*, such that the giver would rotate the device halfway through the lateral swing *without grasping the top*, and the recipient would then grasp the top of the device and complete the rotation, triggering hand-off. This illustrates that our designed gesture for handoff actually supports one of our intended goals effectively, namely to leave the users in control of the micro-mobility of the device.

However, our detection mechanism did miss some passing events. For example, one pair of users attempted to pass the tablet back and forth while standing side-by-side. Since this form of handoff is not naturally accompanied by a lateral swing, it was not detected as such by our system. This suggests a design choice, of detecting a greater variety of such handoffs and using them for augmented interactions, or of intentionally deciding *not to recognize them* so that they remain available for natural micro-mobility motions. While the correct choice remains unclear, our work has served its purpose to the extent that it surfaces such considerations.

Side-by-Side Micro-Territoriality. People understood that 3 hands on the tablet indicates a joint grip. And they could use the supported interaction technique easily. But users sometimes found our current implementation too inflexible to trigger, because they sometimes tried to share the tablet using a different pattern of shared grips, such as one case where each user attempted to support the tablet with a single hand: "It limited my behavior too much. There can be many ways to share the device." This again reinforces the need to support flexibility in grasp behaviors (B4). However, we must also recognize that attempting to recognize all possible ways of sharing a device may not be feasible or even desirable, if we are to leave open-ended micro-mobility manipulations available to users who are collaborating.

Fine-Grained Reference and Hold to Refer Back. Users easily understood the concept of touching and holding a tablet to designate a source device. Participants found the cross-referencing feature useful, especially if they personally owned multiple tablets. However, a couple of users reported confusion that they had to perform the clipping action on the destination tablet, rather than on the source tablet: "I would accidentally clip the wrong tablet, because I focused on the first tablet—because I was using my finger there." This suggests we could improve the technique by allowing users to clip content on either tablet (rather than solely from the echoed content on the destination device).

CONCLUSION AND FUTURE WORK

Our work establishes the interplay of grasp + micro-mobility in physically-embodied human activity during individual work, dyadic collaboration, and multiple-device interactions. Sensing both grip and micro-mobility then supports a broad design space of interactions or contextually-dependent techniques, including a number of promising designs that we explored in the context of active reading. Yet, since relatively little is known about this space, we encountered a number of challenges in sensing the diversity of grips and device motions that users might exhibit "in the wild," particularly for the multiple-user interactions we explored. We believe our formative study, hardware-software platform, and interaction techniques represent meaningful contributions towards establishing the design space of grasp + micro-mobility, and understanding it more deeply.

Our interaction designs sampled various behaviors as points of departure to suggest possible categories of contexts and gestures that can be sensed and recognized by grasp + micro-mobility techniques. Yet this represents only a preliminary taxonomy, and many classes of related techniques or behaviors likely remain hidden below the surface, waiting to be unearthed. For example, the class of "Multi-User, Multi-Device Interactions" (where users collaborate over multiple tablets) noted in the tableau of Figure 5 seems plausible as a fertile area for additional techniques.

False positives can be a challenge with the type of sensing techniques contemplated by this paper. We had the advantage of our formative study observations (B1-B9) to guide the selection of our carefully-considered gestures. To further minimize the impact of any false positives, we provided distinctive feedback, easy fallbacks, and careful choice of appropriate semantics in the design of our system. To take our Side-by-Side interaction as an example, the state transition to shared status was visually indicated with a slide-in, slide-out animation of the entire screen. Also the sharer could easily revoke an unwanted activation by simply partially releasing his grasp.

Such animations help users to understand the gesture, but obviously remain an incomplete solution for self-revelation, which is a common problem for many types of gestures. While some techniques, such as Immersive Reading, were close enough to their natural counterparts to require no such hand-wringing, others clearly require some explanation for users to discover them. While existing techniques for self-revelation of gestures [3,9,11] may prove fruitful in this regard, it also seems likely that new techniques particularly tailored to grasp and motion gestures operating in tandem may be helpful, and hence offer a rich topic for future work.

Finally, while we have focused here on tablets, we fully expect that grasp + micro-mobility could apply to diverse form-factors such as smartphones, tangibles, or other "smart objects"—as well as for heterogeneous combinations of different device types as well. As such, a society of mobile appliances with rich grasp and micro-mobility sensing capabilities could help lead us to far more natural, more expressive, and more creative ways of engaging in the individual, collaborative, and cross-device knowledge work of the future.

RIGHTS FOR FIGURES

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