Around-Body Interaction: Sensing & Interaction Techniques for Proprioception-Enhanced Input with Mobile Devices

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ABSTRACT
The space around the body provides a large interaction volume that can allow for big interactions on small mobile devices. However, interaction techniques making use of this opportunity are underexplored, primarily focusing on distributing information in the space around the body. We demonstrate three types of around-body interaction including *canvas*, *modal* and *context-aware* interactions in six demonstration applications. We also present a sensing solution using standard smartphone hardware: a phone's front camera, accelerometer and inertia measurement units. Our solution allows a person to interact with a mobile device by holding and positioning it between a normal field of view and its vicinity around the body. By leveraging a user's proprioceptive sense, around-body Interaction opens a new input channel that enhances conventional interaction on a mobile device without requiring additional hardware.

ACM Classification: H.5.2 [User Interfaces]: Input devices and strategies, Interaction styles.

Keywords: Proprioception; around-body; mobile devices.

INTRODUCTION AND RELATED WORK
Modern mobile devices rely on touch as the primary input modality. However, as devices become smaller, touch interaction gets more difficult, because our fingers do not shrink with our devices. Meanwhile, mobile usage often occurs when a user's attention is divided among multiple tasks, making touch-based interaction increasingly difficult.

By expanding the input space beyond the device's screen, we can situate interaction in the space within arm's reach around the body. This increases the space for interaction, thus mitigating the small screen problem while allowing for expressive input with more degrees of freedom. Further, arm movements naturally leverage *proprioception* [9] – our awareness of the relative position of neighboring body parts – to further reduce the attention required for interacting with a mobile device.

However, the lack of an established, low-cost solution for around-body sensing prevents developers from fully leveraging the space around a user's body to ease the use of miniaturized devices, or to enhance the expressiveness of interactions. Although some prior research has explored the use of proprioception to enable interaction around a user's body [5,8,9,13], the space of such interaction is underexplored, primarily focusing on distributing information in a user's around-body space.

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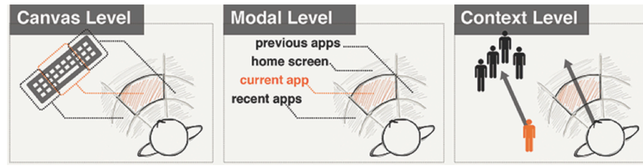

Fig 1. Around-body interaction expands the interaction space (left), mediates the switching between applications/modes (center), and increases context-awareness of the device (right).

The goal of this paper is to provide technical and design solutions that can increase the variety of interactions available between a mobile device and the space around a person's body. To achieve this, we developed a set of around-body, proprioception-enhanced techniques that allow a person to interact with a mobile device in the space around her body for a variety of application scenarios.

To explore these techniques, we built a sensing mechanism to track a smartphone's 3D location relative to a person using its front camera, accelerometer and inertia measurement units. This sensing capability allowed us to rapidly prototype a diverse set of around-body interactions.

In particular, we contribute three categories of interactions demonstrated in six exemplar applications. At the *canvas* level, the around-body space expands the interaction area beyond the screen's boundaries. This allows for placing a UI element, or operating an interactive component in a space that is much larger than the screen (Fig. 1, left). At the *modal* level, around-body movement supports switching between different applications, or different modes within a given application (Fig. 1, center). At the *context* level, the device's spatial relationship to the user may indicate level of privacy. For instance, the farther the device is from the body, the more visible it may be to other people nearby (Fig. 1, right). All these interactions are achieved by leveraging a user's proprioception to hold and position a mobile device around her body, while the device's sensors inform its spatial relationship to the user.

Although we believe it to be underutilized, the use of proprioception is not entirely new to mobile devices. For example, *Body Mnemonics* associates digital information with different body parts [1]. *Virtual Shelves* makes mobile phones more accessible to visually impaired people by associating programmable shortcuts with locations around the user [8,9]. Proprioception-enabled interactions are also used in virtual reality systems, for example zooming by bimanually setting a rectangular frame [10].

Related to our use of devices' *motion and spatial* awareness for creating interactions, past work also explored using a device's motion sensors to support device-centric motion-based interaction, such as device tilting and gestural input (*e.g.,* [2,11,12]) or to infer and adapt to device-oriented context, e.g., switching between portrait/landscape, or activating the phone when picked up [7]. Others focus on the spatial aspect of devices, such as a device that displays information according to the part of the environment it is situated in [6]. Cao and Balakrishnan turned a handheld projector into a spatially aware device which can be used to project on and interact with multiple information spaces embedded in physical environments [4].

Our sensing and interaction techniques explore and open a space of proprioception-enhanced mobile interaction not covered by previous work. Next we describe sensing solutions that allow devices to be spatially aware around a user's body entirely based on commodity hardware. Following that we present six example applications that demonstrate the variety of interactions supported by our sensing solutions, and that illustrate three categories of around-body interaction.

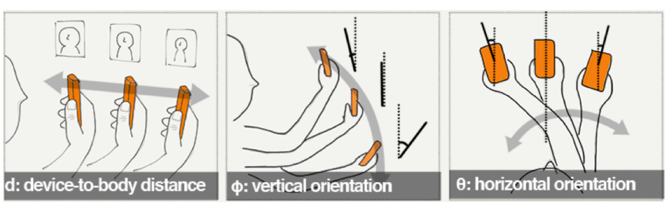

Fig 2. Sensing a device's 3D location: device-to-body distance d; vertical orientation φ; and horizontal orientation θ.

SENSING A DEVICE'S AROUND-BODY LOCATION

We built a sensing mechanism to estimate a smartphone's 3D location (d, θ and φ, as shown in Fig. 2) relative to the person holding and using it. Our system uses four of the phone's built-in sensors: accelerometer, gyroscope, magnetometer and the front camera.

Using front camera to track device-to-body distance ***d***. Using face detection, we estimate the head size (H) of the user from the front camera image. The range of the device-to-body distance corresponds to a minimum (H_{min}) and maximum (H_{max}) head size. For a given head size H, we estimate $d = (H_{max} - H) / (H_{max} - H_{min})$. This normalized value indicates how far away the device is held relative to the face. To calibrate to each particular user's head size and arm length, our system starts with an initial H_{min} and H_{max} (*e.g.,* $H_{min} = \frac{1}{4}W$, $H_{max} = \frac{3}{4}W$, where W is width of the front camera image). Over time, we update H_{min} and H_{max} to match the actual range of the device. This allows our system to adapt to any user and to respond to changes in range of movement for different types of interactions.

Using compass to track horizontal orientation $\boldsymbol{\theta}$. As the device moves horizontally around the body, the compass's value ($\theta_{device\text{-}world}$) changes (Fig. 2 left). When a person brings the device close (normalized $d < 0.25$, face visible), we record the compass' reading as the body's orientation relative to the world ($\theta_{body\text{-}world}$), and subsequently use it to calculate device's orientation relative to the body as $\theta_{device\text{-}body} = \theta_{device\text{-}world} - \theta_{body\text{-}world}$. The value $\theta_{body\text{-}world}$ is only updated when the device is relatively stationary, which can be detected by comparing the sum of the gyroscope reading against a small threshold ε.

Using accelerometer to track vertical orientation $\boldsymbol{\varphi}$. As the device moves vertically around the body, the user naturally tilts the device to make it visible (Fig. 2 center). This behavior allows us to infer the device's vertical orientation (φ) using the accelerometer. The vertical orientation, φ, can be calculated from the degree the device is tilted relative to the accelerometer's x axis. We dynamically update the range of the vertical orientation, similar to how we calculate d.

PROPRIOCEPTIVE, AROUND-BODY INTERACTION

Our sensing techniques leverage a person's proprioceptive sense to provide a large interaction canvas for a mobile phone. Yet it is still unclear how this capability can enhance the expressiveness of interaction beyond simply distributing the interactions equally around the body.

Past work has suggested *dimensions* such as proximal spaces to situate mobile interactions on/around a person's body [5]. In VR, spatial *metrics* were developed to mediate interpersonal communication [3]. In contrast, our goal is to create sensing and interaction techniques that explore categories of interactions to fully make use of the around-body space. Below we demonstrate these three categories: canvas, modes, and context.

Expanding the Canvas for Interaction

At the *canvas* level, the around-body space expands the interaction canvas beyond the screen's boundaries.

Fig 3. Around-body interaction maps a physical keyboard around the body

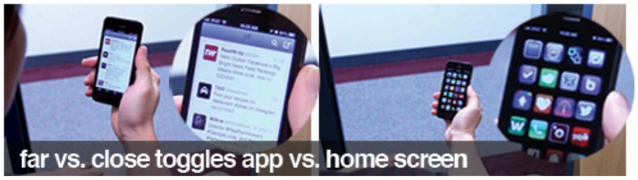

Fig 4. Around-body interaction toggles apps and home screen.

Typing around the body. Our spatial and kinesthetic memory allows us to fluently and quickly access keys on a physical keyboard. Likewise, Around-Body Interaction can leverage a user's proprioceptive sense to access a virtual keyboard mapped out beyond the small phone screen. As shown in Fig. 3, our keyboard design centers alphabet keys – the primary keys used in day-to-day typing – in the user's field of view (Fig. 3, center). Intermittently accessed keys – such as symbols and numbers – are placed on the left and right sides of the body (Fig. 3, left & right). Using proprioceptive arm movement to switch between key sets maintains a constant grip for single-handed typing.

Around-body treasure hunt. As another example (shown in our video figure), Around-Body Interaction provides a large gaming area and a range of interaction beyond 'finger poking' the screen. In our 'treasure hunt' game Player 1 places the treasure somewhere near his body and Player 2 moves the device to search for that relative location. The space around the body can be mapped to a variety of game scenes thus adding to the gaming experience for the player.

Mediating Application and Mode Switching

At the *modal* level, the device's around-body movement can mediate the switching between different applications, or different modes within a given application.

Switching between applications. Displaying multiple applications is infeasible on a small screen. Around-body interaction enables toggling between an application and the home screen by holding the phone closer in the field of view vs. farther away (Fig. 4). A person can retrieve previous apps by shifting the device to the right (Fig. 5abc), and return to more recent apps by shifting it to the left (Fig. 5cde). In addition, holding the device to the right or left starts a quasi-mode where one can swipe the screen to go forward/backward in application history.

Switching between modes within an application. With only one thumb available, typical map navigation such as pinch-to-zoom becomes cumbersome. By associating different functions with different around-body locations, we can improve this situation. In the normal field of view, a person can use a thumb to scroll-and-pan the map (Fig 6, left); holding the device further out switches to scroll-and-zoom (Fig. 6, center); shifting to the right shows menus for changing map views (Fig. 6, right). Thus the device's around-body location augments the limited expressivity of the thumb and enables more variety of interactions in a one-handed scenario.

Increasing the System's Context-Awareness

At the context level, the device's spatial relationship to the user can increase the system's *context-awareness*.

Mediating public vs. private phone behavior. During social interactions (*e.g.*, a face-to-face meeting), around-body interaction infers context from the phone's proximity to the body, and mediates its behavior accordingly. Notifications are pushed to the user when the phone is held close, where typically only the user can see the display (Fig 7, right). Holding the phone in a 'public zone' – where it is also visible to the others – will hide notifications. This enables socially appropriate phone behavior without requiring the user to explicitly switch modes.

Inferring states of application usage. When using an application, the device's around-body location can imply different states and provide a way to proactively select UI views that match such states. Our video figure shows a person raising the device up and holding it horizontally as he prepares to take a photo. This is sensed using the device's around-body location (up above the field of view), causing the camera to open. After taking the photos, as the device is lowered relative to the eye level, the change in around-body location switches the view to an image browser.

PERFORMANCE TEST, LIMITATIONS AND TRADEOFFS

We conducted a preliminary performance test of the sensors we used. Our goal is not to run a task-based usability evaluation of the interaction, but to collect sensor data and use machine learning analysis to test the saliency of the this data in estimating the device's around-body locations.

Fig 5. Around-body interaction enables multitasking between previous and more recent apps.

Fig 6. Around-body interaction mediates mode switching in a map app.

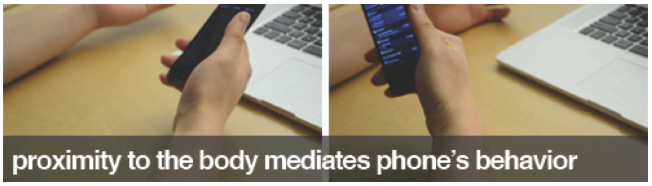

Fig 7. Around-body interaction increases context-awareness.

One experimenter held and placed a smart phone at a number of locations pre-calibrated and evenly distributed around a fixed central point (representing the user's body position). We used these locations as ground truth and logged sensor and camera data at each location. We tested all the three axes (d, θ and φ) and varied the sensing resolution (the number of distinct locations) on each axis (3, 5, and 7 for θ and φ; 2, 3, and 4 for d). We repeated the measurement 25 times at each location (975 data points total) by moving the device between that location and the central point.

For each sensing resolution on each axis, we used ten-fold cross validation with a 1R classifier to estimate the accuracy of the best sensor for that dimension (camera-d, accelerometer-θ and magnetometer-φ, respectively). As shown in Table 1, the sensors achieved 100% accuracy in identifying 3×3×3=27 around-body locations (3 on each axis). However, performance dropped on θ and φ axes as sensing resolution increased.

d	# of locations	2	3	4
	Accuracy	100.00%	100.00%	99.04%
	Kappa	1.00	1.00	0.99
θ	# of locations	3	5	7
	Accuracy	100.00%	84.80%	74.73%
	Kappa	1.00	0.81	0.71
φ	# of locations	3	5	7
	Accuracy	100.00%	95.20%	85.71%
	Kappa	1.00	0.94	0.83

Table 1. Performance test of around-body sensing.

Although the accuracy decreases as the number of locations increases, this result still promises a good match for users' needs. Li et al. [8] found people are best at discerning seven or fewer directions around their body. This suggests a simple yet useful division of the around-body space into a normal field of view and six peripheral interactive zones.

Several possible explanations for these errors exist. We assume a user will tilt the device to be visible while holding and positioning it around the body. However in reality such tilting does not always perfectly align with the device's *true* around-body location, thus causing errors.

Beyond this performance test, there are other limitations to address. For example, to reliably track the device's horizontal orientation, our current solution demands a frequent update of the body's orientation, which requires frequently bringing the device into focus while interacting with it. Further, our calculation of device-to-body distance relies on face detection, whose accuracy subjects to the physical environment. To address all these sensor related uncertainties, the interface can provide active feedback as well as allowing for manual overriding false sensing results.

User error is another important consideration. For example, gesturing with a device in hand during conversations could cause false positives. To solve this we can develop ways to detect suspicious device movement. We can also employ explicit activation mechanisms to start an interaction.

CONCLUSION

We presented a series of around-body, proprioception-enhanced interaction techniques that open a new input channel on a commercial smartphone. Our sensing mechanism requires no custom hardware, and performs at high accuracy for the normal field of view and a few periphery zones. We demonstrate three categories of interactions: 1) increasing the interaction space for interactors or an entire interface, 2) mediating application and mode switching, and 3) increasing the device's context-awareness. Collectively, they offer new ways of leveraging the around-body space to enhance mobile interaction. Our future work includes further testing and improving the sensing techniques, and developing around-body interaction at the toolkit level.

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