Disambiguating Touch with a Smart-Ring

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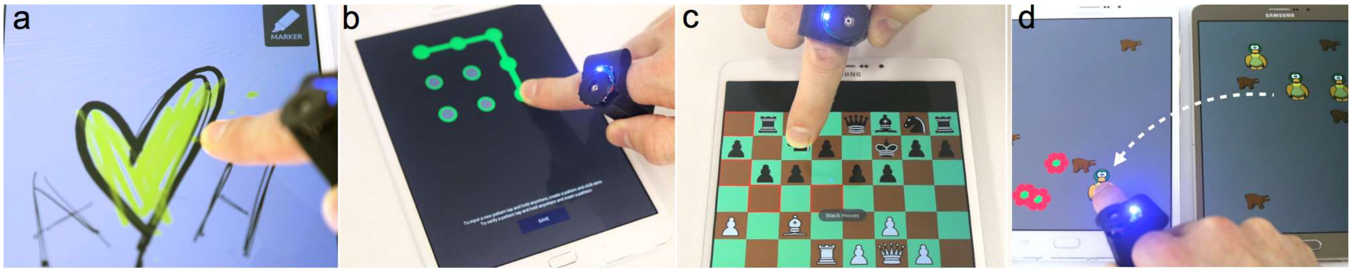

Figure 1. By disambiguating touch, it is possible to associate different meanings to touch events. Using a wearable smart-ring, users can select tools or operational modes without using graphical menus (a). Graphical passwords can be strengthened using touch as the vehicle for two-factor authentication (b). Touches can also be used for recognizing users (c) and pairing devices (d).

ABSTRACT
Capacitive touchscreens have changed the way in which people interact with computational devices. In fact, direct touch input on screens is immediately understandable and appealing to both novice and advanced users and, more importantly, it leverages people's natural ability to use multiple fingers for input gestures. However, currently off-the-shelves touchscreens are unable to disambiguate among different fingers or to determine whether different touch-points belong to the same user, reducing the expressiveness of finger touches to that of multiple pointers. In this paper, we propose to augment human touch using a smart-ring. When the finger wearing the ring is in contact with the touchscreen, a unique ID is transmitted through vibration patterns from the ring to the touched device. It therefore becomes possible to distinguish touch between different users, or to associate different meanings to different touches for the same user. In this paper, we explore this design space and present a set of applications to demonstrate the feasibility of this technique.

CCS Concepts
• **Human computer interaction (HCI) →Interaction devices**

Keywords
Wearable; smart-ring; touch disambiguation; augmentation.

AH '17, March 16-18, 2017, Mountain View, CA, USA

1. INTRODUCTION
Mobile devices and smartphones with capacitive touchscreens are used by millions. One of the reasons behind this widespread adoption is perhaps that they afford simple yet powerful ways of interacting with digital content through direct touch input. Touch input is easy to understand for novice users, and, by leveraging people's natural ability to use multiple fingers for input gestures, it allows advanced users to achieve fine levels of control. However, currently off-the-shelves touchscreens are unable to disambiguate touch input. In fact, touchscreens cannot determine whether the touches belong to different users or have different meanings, and they simply interpret touches as points with specific spatial coordinates and area. This inability to disambiguate touch greatly hinders the potential expressiveness of the input space on touchscreens.

Researchers partially addressed this issue by proposing methods to disambiguate users (rather than *touches*) interacting with either portable touchscreens or large-scale tabletop systems. *Capacitive fingerprinting*, for example, enables recognition of different users using the Swept Frequency Capacitive Sensing described in [20]. A similar technique was further developed by Holz and Knaust [8] in order to achieve continuous and implicit user authentication based on touch input in portable devices. The authors of this work mostly focused on user-disambiguation, and did not explore the design space of touch-disambiguation to achieve higher input expressiveness. Bootstrapper [17], Fiberio [7] and IR ring [18], on the other side, are examples of user recognition systems for tabletops. eBootstrap recognizes users by their shoes, while Fiberio biometrically distinguishes between users by using their fingerprints while they interact with the touchscreen. Differently, IR ring encodes unique infrared patterns in a wearable ring that can be sensed using the tabletop camera. Though these techniques can help recognize users, they require specific hardware settings [5, 8] and software modifications not available in off-the-shelf devices [10]. Moreover, these techniques can only differentiate users and they cannot disambiguate touches from the same user.

In this paper, we propose a technique for augmenting the human touch using a wearable smart-ring named *VibRing*. VibRing allows users to make an input selection on the ring and to transmit it to a device with a touchscreen using a unique vibration pattern. The device uses a built-in accelerometer to collect and analyze the vibration patterns and reconstruct the selection performed by the user on the ring. Using this technique, we can therefore distinguish between different users and also disambiguate among different operational modes or tools, augment the security of graphical passwords and support multiple device pairings. In this paper, we present in detail the prototype of the VibRing smart-ring, and the interaction design space with a set of applications that demonstrate the potential of this approach. We conclude the paper by indicating limitations and future applications.

2. RELATED WORK

The literature about smart-rings and finger augmentation devices is vast and we invite the reader to refer to Shilkrot et al.'s survey paper for a complete review of ring-based input techniques [22]. Overall, the small size of smart-rings and their proximity to the fingertips afford rich but subtle user feedback and always-available input capabilities. Examples of applications include notifications for social media and cellphone calls [12], subtle multi-modal notifications [19], finger tracking [2, 9, 14], input [1, 15, 25], and user implicit authentication [18]. Particularly relevant to our work are PickRing [24], IR Ring [18] and the ring developed by Fukumoto [3]. PickRing supports implicit pairing between a ring and a mobile device held with the same hand by comparing their motion data. Pairing is established when the motion signatures collected using the Internal Measurement Unit (IMU) sensors match. This technique does not allow touch disambiguation but ensures that two devices are held by the same user. IR ring [18] is another wearable ring that supports disambiguating users around a shared tabletop surface through modulated IR patterns. Finally, the work of Fukumoto [3] introduces a system that modulates an audio signal using vibrations that are transmitted through the finger to the user's head, similarly to a bone-conducting speaker.

3. DISAMBIGUATING TOUCHES

When a finger touches the capacitive screen of a tablet or smartphone device, only the touch location and the size are registered. To solve this limitation, we present *VibRing*, a wearable smart-ring capable of augmenting the touch information with an invisible identifier that is transmitted from the ring, through the finger, to the touched device (Figure 2). We achieve this by modulating a structured vibration pattern (e.g., vibration at constant frequencies), which is then absorbed by the finger bones and tissues and carried to the touched device (Figure 3). The vibration pattern is then detected and acquired by the device accelerometer – a common sensor in currently available smart devices. The vibration signal is filtered, demodulated and reinterpreted as a unique disambiguating ID.

Similar techniques with capacitive screens and wearable devices were proposed in the past for sensing users' biometric properties as a means for disambiguation [8, 18, 20]. However, differently from our work, these techniques do not allow users to actively modify or specify the identification signals transmitted: practically, they can only be used to disambiguate among users' identities, rather than their input actions. More recently, structured vibrations were also employed as a transmission protocol among devices (e.g., a vibrating device and a smartwatch) [10]. The advantage of this method is that, not only does it allow disambiguation of users' identities and their input actions, but also the user receives immediate haptic feedback about the system transmission.

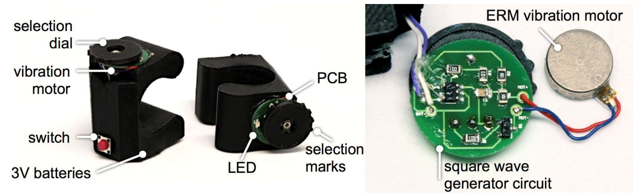

Figure 2. The VibRing prototype (left), and the printed circuit board with the square-wave generator (right).

However, previous work mostly focused on the transmission encoding and did not consider the usage of a wearable device (specifically, a smart-ring) for input selection. Finally, it is worth mentioning Expressy [23], an input technique for augmenting available touchscreen devices with continuous data collected from a wrist-worn IMU. This technique, similarly to our approach, augments touch input through a wearable device, but it requires pairing by Bluetooth with a mobile device.

3.1 Hardware and software prototype

VibRing (Figure 2) is a smart-ring prototype consisting of a driving circuit board, an input selection dial, a vibrating actuator, batteries and a power switch. The ring is shaped as an incomplete circle (a "C") to easily accommodate the finger sizes of different users, and it was 3D printed using flexible PolyLactic Acid (PLA) filament. Two coin-shaped 3V batteries power a custom-made square-wave generator built with a low power single op-amp (LM321), whose modulating frequency can be controlled through a 10k potentiometer attached on the top of the ring and used as a selection dial. When the pushbutton switch is pressed and held, vibrations are delivered using a 10mm shaftless eccentric rotation mass (ERM) vibration motor (Precision Microdrives 310-101), and transmitted by contact to the finger. This motor has an average lag time (time between off state and a vibration amplitude of 0.08G) of 42ms, meaning that the maximum theoretical frequency that the ring can reliably reproduce is 23Hz. In practice, we found that 20Hz is a more realistic figure.

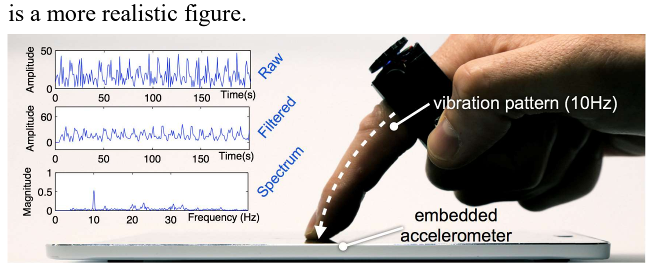

Figure 3. A schematic representation of the VibRing working principle and the software algorithm used to disambiguate selections encoded as vibration patterns (unique IDs).

Practically, a user can input a selection on the ring by spinning the rotary potentiometer and pressing and holding the power switch. Physical bumps on the dial clearly demark different inputs (i.e., frequencies), in the range between 4-20Hz. Empirically, we selected 5Hz, 6Hz, 7Hz, 11Hz and 15Hz so that the five corresponding marks on the selection dial could be equally spaced (22.5° apart). When a user touches the screen, the vibrations travel through the finger and reach the device accelerometer where they are sampled at 100Hz. The *xyz* components of the acceleration are then converted in the absolute rate of change of the raw signal (1).

$$raw_i = \left| \sqrt{x_i^2 + y_i^2 + z_i^2} - \sqrt{x_{i-1}^2 + y_{i-1}^2 + z_{i-1}^2} \right| \quad (1)$$

This raw data is then filtered with an anti-alias low-pass filter (40 Hz cutoff frequency), normalized and Hann-windowed in a zero-padded 512 samples array. Using a Discrete Fourier Transform (DFT) we convert the signal to the frequency domain, from which we identify the dominant frequency components representing the user's input selection. The overall decoding process is highlighted in Figure 3 and from touch to recognition takes 800ms.

4. APPLICATIONS

Disambiguating users' touch input on a mobile device offers the opportunity for several types of applications. Specifically, we were able to identify four possible design domains that leverage the disambiguating capabilities of VibRing: 1) tool selection; 2) augmented passwords; 3) multi-user recognition; and 4) device pairing. With *tool selection*, a single touch input can be mapped to different operational modes or tools without requiring users to navigate menus to perform a selection. With *augmented passwords,* graphical authentication patterns can be made more resistant against malicious observations using the ring vibration encoding to achieve a two-factor authentication. Finally, the ring can also be used for both determining the identity of multiple users interacting with the same device (*multi-user recognition*), or for *pairing multiple devices* belonging to different users. In the following subsections we present four examples of applications developed for an Android tablet (Galaxy Tab S2) that concretely instantiates each of these four interaction spaces.

4.1 Tool selection

Commonly, mobile applications support different modes of operation, multiple views and input functionalities that can be accessed using graphical menus (flat lists, drop-down, pop-up, contextual and expanding menus [21]) or physical shortcuts (e.g., physical buttons, touch gestures, force input [6]). It is well known in literature that selections become more complex with the increase of possible choices and with smaller on-screen target sizes [11]. Mobile devices and tablets usually have smaller screens than personal computers, which usually results in degraded usability or compromises about the number of possible selections that users can perform using the screen GUI. We propose to use VibRing as an alternative or complementary selection mechanism, capable of freeing screen space and helping users to perform more rapid contextual selections without relying on graphical menus.

To explore this scenario, we developed a drawing application that allows users to select five different tools (pen, pencil, marker, brush and eraser) without using menus. Instead, the input selection is performed directly on the ring. The user can therefore quickly change drawing tools without losing focus on the canvas by simply performing a selection on the ring dial and then placing the finger on the canvas. This interaction fully supports the user's primary task (drawing) minimizing distractions. We also envision that input could be customized to reflect both the user's preferences and the application context. However, the current main limitation of the proposed system is that users might inadvertently change their artwork while attempting to touch the canvas for a tool selection. This issue could be easily addressed by disabling painting on short taps, or by enabling tool selection only when two or more fingers touch the screen. In sums, we believe that this approach could improve many applications and common mobile tasks such as selecting, copying and pasting text, by minimizing the need for menu selections. The tool selection scenario is shown in Figure 1.a.

4.2 Augmented passwords

Graphical passwords, such as the Android pattern lock, are among the most common authentication methods for mobile devices and tablets [4]. Their popularity is due to their high usability – graphical passwords are memorable, fast and easy to use. However, they are also more exposed to attacks based on simple observation, such as shoulder surfing. VibRing presents an opportunity to address this issue and still maintain the usability benefits of graphical passwords. The ring, in fact, can augment the password space by transferring to a device additional non-visual information transmitted through touch.

As an example, we implemented an authentication scheme based on the Android pattern lock [4], where the secret information is the combination of the graphical lock pattern with an invisible identification number transmitted from the finger to the device using vibration patterns (Figure 1.b). The user, prior authentication, simply makes a selection on the smart-ring. While inputting the graphical pattern, VibRing transmits the secret selection, through encoded vibrations, to the touched device, and the combination of both information is used to grant or deny authentication. By augmenting the graphical pattern lock with an additional factor (the selection on the smart-ring) we achieve a two-factor authentication that maintains the large password entropy of graphical passwords, but also enhances the security against observation attacks.

4.3 Multi-user recognition

Currently available touchscreen devices cannot distinguish who is the author of a specific touch gesture and simply assume that the input was performed by a legitimate owner. It is therefore impossible to discern exactly who is interacting with the device. There are, however, many practical situations in which multiple users share the view of the same device and contribute to its control with individual direct touches. In this situation, it is essential to be able to distinguish the identities of whom performed the input gesture. Our system supports such disambiguation of users, and, differently from prior work [5, 8], it works with currently available unmodified off-the-shelf devices.

As an example for this scenario, we built an application of a multiplayer chess game with players located in front of each other (Figure 1.c). When, for example, the white player attempts to move a piece, the system determines if the selection is legitimate (i.e. if it is a white piece) and where the piece can be placed by highlighting the possible movements. In this particular case, the user is not required before every move to make a specific input selection using VibRing, but a fixed disambiguating frequency pattern can be chosen before the game starts. Alternatively, we envision that VibRing could have presets pre-installed that would correspond to unique user IDs. In the future, this approach could be applied not only for turn-based games, but also to applications that require disambiguating simultaneous input gestures from different users.

4.4 Device pairing

User recognition is also the key to multiple-device pairing. In fact, researchers demonstrated that it is possible for a user to hold two devices and have the system perform an implicit pairing between the two [24], or to press a button on each device and have the system handle the pairing [16]. VibRing presents the opportunity for a similar pairing mechanism, but it also has the advantage that it can differentiate multiple simultaneous pairings performed by different users on multiple devices.

To explore this interaction space, we developed an application that allows users to share images across devices by simply touching them, similarly to the SPARSH system [13]. As illustrated in Figure 1.d, when a user touches an image on one device, the image is

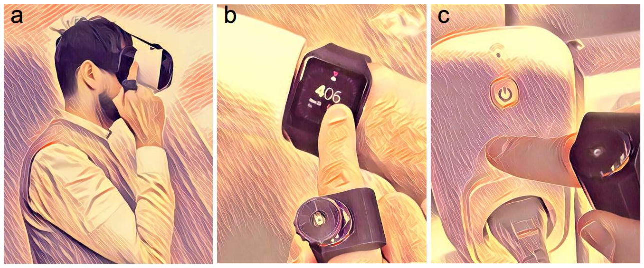

Figure 4. Scenarios of future applications using devices with limited screen space or no screens: head-mounted displays (a), smartwatches (b) and Internet Of Things devices (c).

copied on a clipboard and it is associated to a specific vibration pattern. The image can then be pasted to the same device or to other devices in the same network. Moreover, differently from previous work, simultaneous pairings can happen between multiple devices and with multiple users, disambiguated by their rings. For the prototype, we used the Open Sound Control (OSC) protocol for data transmission across devices. In our prototype, users can select through the VibRing dial a specific vibration pattern ID or, such as in the case of multi-user recognition, these IDs can be permanently associated with a specific ring using presets.

5. DISCUSSION AND FUTURE WORK

Being able to disambiguate users or specific operational modes by simply touching a capacitive screen opens a new range of personalized interactions with mobile devices. Menu selections can be simplified and content presentation can be personalized according to the current user. Additionally, multiple devices can be easily paired, and a hidden information channel can increase the security of data sensitive applications. In this paper, we demonstrated that these objectives can be achieved by simply using a wearable smart-ring capable of encoding and transmitting messages through structured vibration patterns.

The main limitation of our approach, however, is that the current prototype does not reliably work when multiple users simultaneously touch the screen. In fact, ERM motors limit the spectrum of usable frequencies for communication due to their long lag times. Moreover, off-the-shelf mobile devices, such as the Android tablet used in this work, do not allow precise sampling rates for accelerometers, but rather depend on the CPU load at run-time. This problem could, however, be solved by modifying the device kernel as explained in [10], or using Linear Resonant Actuator (LRA) motors for generating the vibration patterns. Future work will investigate these possibilities. A second main limitation of this work is that we did not validate our technique with a user study. Although empirical preliminary investigations with users did not reveal specific usability concerns with the vibration patterns or the ring interface, a user study is required for validating this interaction technique and the user performance. However, the most promising future direction of research is in trying to combine this technology with devices that have limited input capabilities, such as devices with small screens or no screen at all. Therefore, we plan to investigate the usage of VibRing with head-mounted displays, smart-watches and IoT (Internet of Things) devices (Figure 4).

In conclusions, in this paper we presented a system based on a wearable smart-ring (VibRing) that allows touch disambiguation on devices with a capacitive screen and a built-in accelerometer. We explored the interaction space afforded by such technology and gave practical examples of how this system allows us to achieve input selection without relying on menus, to augment graphical passwords with invisible information and to recognize users and devices. Future work will be devoted to both improving this technology and applying it to other wearable and smart devices with limited input capabilities and small screens, such as smartwatches, head-mounted displays and IoT devices.

6. ACKNOWLEDGMENTS

This paper was supported by the MSIP, Korea, under the G- ITRC support program (IITP-2016-R6812-16-0001) supervised by the IITP.

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