Skin Buttons: Cheap, Small, Low-Power and Clickable Fixed-Icon Laser Projections

Gierad Laput Robert Xiao Xiang 'Anthony' Chen Scott E. Hudson Chris Harrison

Human-Computer Interaction Institute
Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh PA 15213
{gierad.laput, brx, xiangchen, scott.hudson, chris.harrison}@cs.cmu.edu

ABSTRACT
Smartwatches are a promising new interactive platform, but their small size makes even basic actions cumbersome. Hence, there is a great need for approaches that expand the interactive envelope around smartwatches, allowing human input to escape the small physical confines of the device. We propose using tiny projectors integrated into the smartwatch to render icons on the user's skin. These icons can be made touch sensitive, significantly expanding the interactive region without increasing device size. Through a series of experiments, we show that these "skin buttons" can have high touch accuracy and recognizability, while being low cost and power-efficient.

ACM Classification: H.5.2 [Information interfaces and presentation]: User Interfaces - Input devices and strategies.

Author Keywords: Wearable devices; around device interaction; sensors; ADI; on-body computing; mobile computing; interaction techniques; touch input; smartwatch.

INTRODUCTION
Smartwatches are an emerging computational form factor, made commercially viable by recent advances in miniaturization and battery technology. However, because they are small and our fingers are relatively large, their interfaces tend to be simplistic. Touchscreen smartwatches allow the watch face to be used for a multitude of interfaces, providing flexibility that physical buttons cannot, but suffer from lack of tactile feedback and finger occlusion. These issues would be partially mitigated if we could simply provide more space for interaction. However, simply making smartwatches larger is not an option, as this would make them more obtrusive. Thus one possible approach is to appropriate surface area around the watch for interaction.

To achieve this, we propose using tiny projectors that can be integrated into a smartwatch. These render icons onto the user's skin – for example, notification icons could be projected for missed calls or new messages (Figure 1). Infrared (IR) proximity sensors complement these projectors to enable touch sensitivity. For example, tapping a pulsating text message icon could allow users to quickly jump to that message. In addition to providing a projection surface, the skin also provides useful tactile feedback.

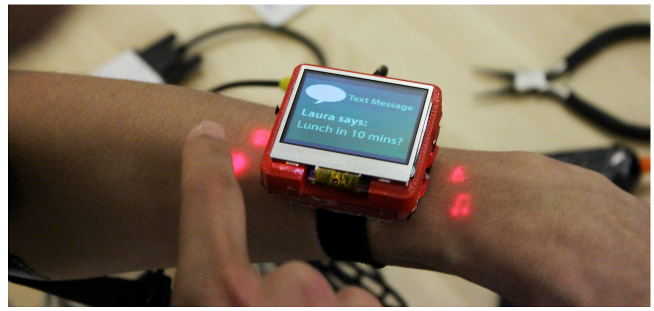

Figure 1. Skin Buttons are touch-sensitive projected icons. Here, application-centric buttons are projected: email, notification, music player and heart. Tapping an icon launches the corresponding application.

We make the following contributions: (1) an approach providing around-device, on-body input with projected, graphical feedback, which augments a smartwatch's small screen with lightweight peripheral icons; (2) the design and implementation of the prototype hardware system and icon set; (3) an evaluation of the system's feasibility: power consumption, size, and cost; and (4) a user study of its usability: recognizability, visibility, and accuracy.

RELATED WORK
Enabling rich interactions on small devices has been a stubborn HCI problem, leading to a wide variety of approaches being considered. One strategy is to make better use of limited screen real estate through better software and interaction techniques (e.g., [8]). Alternatively, other parts of the watch itself can be used for input, such as the bezel [2,20], band [19,24], underside [3], and face [29].

More related to this work are approaches that provide input beyond the physical confines of the device. For example, Nenya [1] and iRing [22] proposed using rings as an interactive accessory, capturing input such as rotation on the finger. Abracadabra [9] used a finger-worn magnet and magnetometer for in-air finger tracking and gesturing. GestureWatch [15] use IR proximity sensors to sense gestures above the display. SideSight [4] used IR proximity sensors along the sides of the device to detect the position of one or more proximate fingers, enabling peripheral multitouch

UIST '14, October 05 – 08, 2014, Honolulu, HI, USA.

ACM 978-1-4503-3069-5/14/10 $15.00.
http://dx.doi.org/10.1145/2642918.2647356

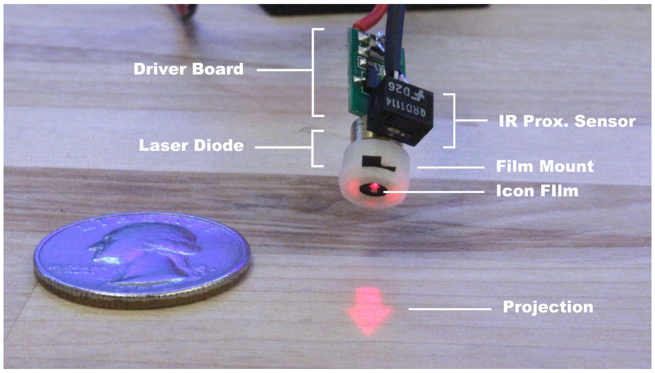

Figure 2. Close-up of a single Skin Button projector.

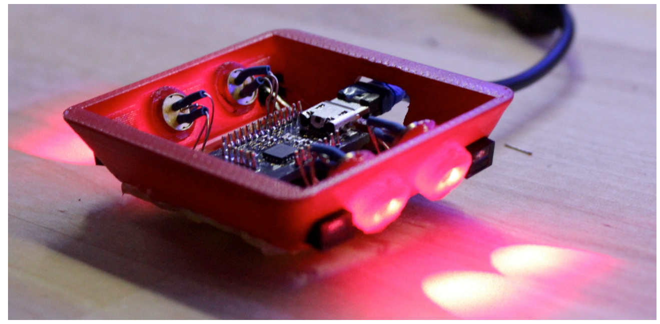

Figure 3. Internal view of our prototype. Note the projectors fitted into 20° angled ports on the sides of the enclosure. Also, note the extent of the projected light (no films inserted).

actions, such as pan, zoom and rotate. These free-space interactions often fall under the category of "around device" interaction, which has evolved into a significant area of study (see e.g., [13]).

Lastly, our work was also inspired by research into wearable and "on-body" systems. A wide variety of sensing techniques have been evaluated, from bioacoustics [11] and electromyography (EMG) [25], to computer vision [7,14, 30] and ultrasound. Of note, SonarWatch [17] and PUB [18] used oblique ultrasonic rangefinders to localize finger inputs on the forearm. SenSkin [21] measures shear forces using two armbands to enable trackpad-like interactions on the skin. Another approach entirely is for interfaces to be implanted under the skin [12]. Finally, there is a growing body of literature that looks at how to design touch interfaces and gestures for the skin [26,27].

IMPLEMENTATION

Our prototype smartwatch contains four fixed-icon laser projectors, described subsequently, with accompanying infrared proximity sensors. These are connected to a Femtoduino board, which communicates over USB with a host computer. Similarly, a 1.5-inch, 280x220 TFT LCD display is driven from the host computer. We used an external computer to facilitate prototyping, though a commercial implementation would be self-contained.

Fixed-Icon Laser Projectors

We chose 5 mW red laser diodes (650 nm) for our projectors (Figure 2). We removed the collimating lens, enabling the diodes to output a cone of light (Figure 3). By using lasers (i.e., coherent light), we achieve focus-free projection, which is crucial as the oblique angle of the emitter produces widely variable distances to the skin surface. Further, this eliminated the need for lenses, which reduced size, cost and complexity. The laser diodes were driven by standard automatic power control (APC) circuitry, with brightness controlled using pulse width modulation (PWM). This allows for a wide range of expressive light behaviors [10].

To create static image projections, we rendered icons to photographic film at 5780 DPI (an "8K process"). The best results were achieved by using black-and-white film stock (Figure 4). These films are placed 3mm in front of the laser emitter aperture (Figure 2). Our 3D printed enclosure contains precise openings for our emitters and icon films, ensuring correct and stable projection geometry (Figure 3). The resulting field of view is 62° horizontally and 17° vertically, which is ideal for short range, oblique projection.

Surface Calibration

The projectors are mounted in the smartwatch chassis at 20º from horizontal. The light from the laser diode first passes through a circular aperture 4 mm in diameter (Figure 2). This circle of light expands broadly across the skin surface, resulting in a parabolic cone of light (Figure 3). The film, placed between the diode and the aperture, must be carefully designed so that the projected icon will appear correct on the skin surface, taking into account the oblique projection angle and the curvature of the arm (Figures 4 and 5).

To generate the perspective-corrected images on our film, we performed a calibration procedure to establish the projector pose relative to the skin. We used a mannequin arm (Figure 5) to model a human arm and provide a fixed calibration target. We repeated the procedure for all four projectors, producing films specific to each.

The calibration process models the appearance of the icon onto the skin as a projective transformation. Rays are imagined casting out from the projector, through the film, and onto a resulting point on the skin. To establish the initial correspondence between skin points and film points, we printed a film containing an evenly spaced 5x5 grid of points. The resulting pattern projection was measured to derive "skin coordinates" corresponding to the film's grid points. These coordinate pairs were fed into OpenCV's camera calibration routine, which provided the pose, focal and nonlinear distortion parameters of the projector. Finally, we used these parameters to transform the icon images from skin coordinates to film coordinates. A comparison of calibrated and uncalibrated icons is shown in Figures 4 and 5.

Luminance Correction

Our current films are binary in nature, in that they are either clear or opaque to the laser light. Because our laser light is not collimated, it diminishes in intensity as the square of the distance, producing widely variable luminance across the skin. We therefore experimented with gradated (grayscale)

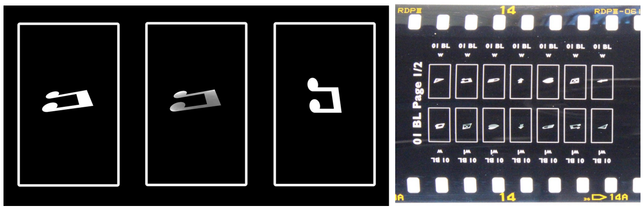

Figure 4. Left: Example icons: perspective-corrected, perspective- and luminance-corrected, and uncorrected. Right: icons rendered onto film (bottom row luminance corrected).

films, in which we selectively darken regions of the film to produce a more even luminance distribution. We measured the approximate visual intensity of the laser light at each point on the skin using a camera, and then darkened the film correspondingly to balance the intensity. The resulting icons from this process can be seen in Figure 4, bottom-right.

Unfortunately, we found the results to be suboptimal. The icons were substantially dimmer, as the light was attenuated over the majority of the icon. This made icons less visible, requiring more power output to achieve equivalent brightness. Additionally, from a visual perception standpoint, humans are generally less sensitive to smooth changes in luminance [28]. Instead, the hard edges between lit and unlit areas (i.e., icon edges) are most noticeable, and so we found it more desirable to exaggerate this difference by employing maximum illumination, regardless of luminance regularity.

Touch Sensing

To capture touch events, we use a Fairchild QRD1114 phototransistor/emitter (Figure 2), which measures the intensity of reflected infrared light from proximate surfaces up to 3 cm away. Infrared proximity sensing of this type has been used in many applications, including input devices (see e.g. [4,15]). For our purposes, these sensors are paired with a laser projector and oriented obliquely to the skin. To compensate for ambient infrared light, we capture two sensor values, once with the IR emitter active and once without. These values are then subtracted to get a better estimate of proximate reflections. Additionally, to help reject false positives, we also use an accelerometer, which disables touch sensing while the arms are in significant motion.

Although this infrared sensing approach is not novel, we are not aware of any work that uses such sensors on the skin in this fashion. SideSight [4] is most similar from a configuration perspective, using oblique infrared proximity sensing to detect fingers on either side of a device when situated on a table. Also related is Digits [14], which used an oblique infrared line laser and 2D camera to estimate 3D hand pose.

Compared with mechanical buttons, skin buttons could be made very small (potentially a single IC), yet still provide large, comfortable input. Conversely, mechanical buttons cannot provide notifications (no output), are not solid state (durability issues), and must be large enough for fingers.

Size, Weight and Cost

We built our Skin Button projectors from off-the-shelf components costing roughly $5 each. In volume, we anticipate the price to be $1 or less. Our prototype projector, seen in Figure 2, is approximately 8x10x19 mm, occupies less than 0.4 cm^3 of space, and weighs less than 3 g. With tighter integration, we do not foresee significant obstacles to shrinking this by a factor of two or more. The biggest gains to be made are by moving the laser driver onto the smartwatch mainboard PCB, sharing some components, and switching to surface mount components. In the future, a single dedicated IC could handle all of the sensors.

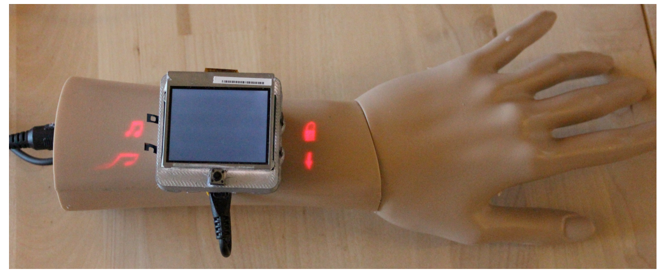

Figure 5. A mannequin was used for rapid prototyping. Note that the top-left icon ("music") is perspective-corrected while the bottom-left icon is not, leading to distortion.

ICON SET DESIGN STRATEGIES

Over the course of several months of ideation, development and user testing, it became clear that skin button icon sets fell into one of three primary use strategies. In the next section, we offer an example application for each approach.

Application Centric – This approach dedicates Skin Buttons for key applications or actions, such as launching the phone app or triggering a voice search (example set in Figure 1).

Navigation Centric - Skin Buttons could also be used primarily for navigation. For example: up, down, select, and back (Figure 6). This is also the (physical) button set used in the Pebble Smartwatch. The general nature of these buttons means they could be used for input across a wide variety of applications, from music players to contact lists.

Screen-Coupled – It is also possible to associate Skin Buttons with on-screen labels (Figure 7), enabling flexible and fully generalized use, more akin to a touchscreen. Actions could range from app launching on the home screen to playback controls in a music app. Importantly, these labels could be much smaller than an equivalent on-screen touch button, allowing more of the screen to be used for content.

EXAMPLE APPLICATIONS

To demonstrate the immediate potential of our approach, we created three proof-of-concept applications, seen in Figures 1, 6 and 7 (see also Video Figure). These illustrate the three strategies described in the previous section.

Today's smartwatches are used extensively for notifications. Additionally, most devices have a "home" screen, from which to access key functionality. *Application-centric* Skin Buttons could augment both of these features by offering easily accessible application icons. As an example, we fitted our prototype with four application icons: email, notifications, music player, and favorites (Figure 1). These

Figure 6. Music Player application features a navigation-centric icon set. Clockwise from top right: up arrow, down arrow, circle (select), back arrow.

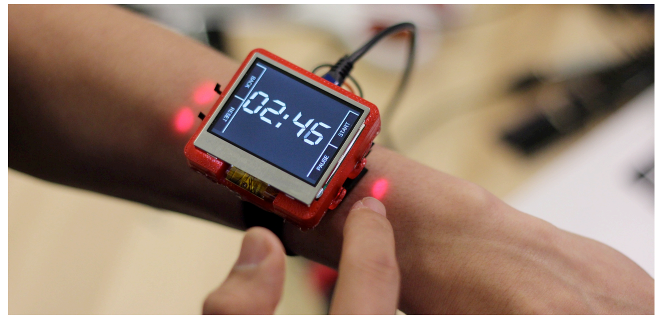

Figure 7. In our clock app, users can set an alarm and change watch faces. In stopwatch mode, seen here, users can start, resume/pause, reset, or return to the clock.

icons can be tapped to quickly launch the corresponding application. Additionally, icons can pulse, flash or have other light behaviors [10] to indicate that e.g., a missed phone call, or that a text message has been received.

We also created a music player that used our *navigation-centric* icon set (Figure 6). 'Up' and 'down' buttons are used to scroll, the 'select' button enters a sub-list (e.g., playlist or album) or activates an item (e.g., play a song), and 'back' traverses up through the hierarchical interface.

Finally, as a demonstration of application-specific, *screen-coupled* Skin Buttons, we created a clock application. When in the clock mode, buttons allow the user to customize the 'watchface', toggle the 'alarm', set the 'alarm time', and enter 'stopwatch' mode (Figure 7). When in stopwatch mode, there are buttons to 'start', 'pause/resume', 'reset', and go 'back' to clock mode.

EVALUATION

To assess the performance of Skin Buttons, we ran a series of small, targeted experiments, which took approximately 30 minutes in total. We recruited 20 participants (7 female, mean age 24), who were given $10 for their involvement in the study. To assess if posture had an effect on use, ten participants completed the study standing, while the other ten were seated. The experiment was performed under normal office ambient lighting conditions. For the experiment, we used email, up-arrow, music, and heart icons.

As our prototype was calibrated assuming the watch was worn on the left wrist, only participants who reported they would wear a watch in this fashion were recruited. In addition to standard demographics information, participants also completed the Fitzpatrick Scale questionnaire [6], which provides a schema for skin color (types I to VI, ranging from lightest to darkest skin color). We had the following breakdown: Type II, III, IV, V and VI had 4, 4, 7, 2, and 3 participants respectively, representing almost the entire spectrum of skin tones. The experimenter also recorded hairiness and any other notable skin features (e.g., wrinkliness, freckle density) for later analysis.

Projected Icon Recognizability

Our first experiment sought to assess if icons had enough *fidelity* to be recognizable when projected on the skin. After participants put on our smartwatch prototype, all four Skin Buttons were illuminated at an intensity determined to be comfortable in piloting. The experimenter then announced the icon names (e.g. "the email icon") in random order, asking the participant to point out each icon as it was announced. For the arrow icon, the experimenter additionally asked the participant to identify the direction it was facing.

Out of 80 recognition trials, participants pointed to the wrong target two times, yielding an overall recognition accuracy of 98%. All participants correctly identified the arrow icon, but two misidentified the direction. We believe these results suggest our prototype icon design and projection fidelity is reasonably robust. Following the recognition trials, we asked participants two Likert-scale questions: "I could easily recognize the different projected icons" and "After a few days of use, I believe I could easily recognize the different projected icons" (1–Strongly disagree, 5-Strongly agree). These elicited average scores of 3.7 and 4.6 respectively (SD=1.0 and 0.49).

Projection Visibility

Next, we wished to investigate the more general question of *visibility*. Put simply: at what level of brightness can the projection be seen and what level is sufficient to enable reliable use in typical lighting conditions? To answers these questions, we allowed participants to adjust the brightness of the Skin Buttons using arrow keys on a laptop. Participants were asked to find three levels of brightness:

- "I can just barely see that the icons are active at this level of brightness" (*barely*)
- "I can comfortably see that the icons are active at this level of brightness" (*comfortable*)
- "I would generally never need an icon to be stronger than this level of brightness" (*high*)

Participants were able to adjust and revisit the three questions until they were satisfied with their selected levels of brightness. When participants indicated they were done, our software recorded the corresponding duty cycles of the laser projectors. We found that barely visible icons required an average duty cycle of 10.0% (SD=3.6%), comfortable visibility required 17.3% (SD=6.2%), and high visibility required 27.9% (SD=10.7%).

Touch Sensing Accuracy
To assess the touch sensing accuracy of our approach, we had our participants "click" our four Skin Buttons 25 times each in a random order. Participants were told to simply "click the icon" without any further guidance. Before performing the trials, participants practiced with the system for two minutes. There were two possible error modes: 1) another skin button was inadvertently triggered or 2) the click was not detected. In the latter case, the experimenter recorded the false negative and the participant clicked again. In total, our 20 participants provided 2000 click trials, of which 2.8% (56 trials) had false negatives. When a finger tap was detected, the system was 96.9% accurate in triggering the intended button. Anecdotally, 99%+ accuracy appears achievable if people can use the device for a longer period than the study permitted.

Power Consumption
Our approach has to two distinct processes that consume power: touch sensing and projection. For reference, the Samsung Galaxy Gear (2013) contains a 1200 mWh battery.

As noted previously, the touch-sensing scheme we employ takes two samples, one with and one without IR illumination. This process takes approximately 40 µs. Our prototype smartwatch polls these sensors at 50 Hz, resulting in 1.0 mW of power draw per sensor. Even if active continually for 24 hours, this would drain less than 2% of the battery.

The power draw of our projectors depends on their intensity, which we vary using pulse width modulation (PWM). In our projection visibility experiment, we found that 17.3% was the mean duty cycle (SD=6.2%) needed to achieve a "comfortable" level of brightness. This equates to a power consumption of 19.9 mW when active, including both the laser diode and driver circuitry. In other words, each hour, a projected icon would consume roughly 1.7% of a Galaxy Gear's battery. Icons that are "barely" visible require roughly half the power, only 11.5 mW. Pulsing or flashing an icon could cut power consumption in half or more.

Importantly, if Skin Buttons allow interactions to proceed without turning on the main display (e.g., by flashing the phone icon to convey a "missed call" instead of activating the LCD), they have the potential to extend battery life. It should also be noted that these numbers should be treated as an upper bound, as tighter integration and further refinement would undoubtedly reduce power consumption.

Skin Color and Other Effects
There were no statistically significant effects regarding gender, age, hairiness, skin color, or standing vs. sitting. As such, the above experimental results were combined.

Interview
At the end of the study, we conducted an open-ended interview with participants to elicit their feedback. Overall, we found that participants found the concept compelling and useful. Seven had tried smartwatches in the past; all but two had discontinued use due to a poor user experience. With respect to touching the skin for interaction, users generally thought Skin Buttons were "cool" and "satisfyingly responsive." One participant mentioned that "touching buttons on her skin" made the smartwatch experience "more intimate." Several participants commented on the visual appearance of icons, suggesting the recognizability was affected by "negative space", "simplicity of shape", "exaggerated features", "brightness", and good "reuse [of] symbolic conventions."

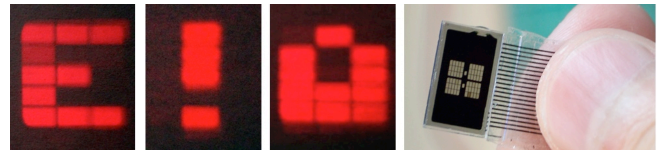

Figure 8. By substituting film for a very small liquid crystal display, it is possible to project primitive dynamic icons, including characters, symbols and system icons (e.g. a battery). Far right: the LCD we used, which contains four LCD blocks, each 3x5 pixels in resolution.

LIMITATIONS AND FUTURE WORK
The major limitation of our current prototype is the use of fixed projected icons. Dynamic projection is certainly more desirable, and so we performed an early experiment to explore this approach. We repurposed a small LCD module with an active area consisting of four 1.8x2.2 mm 3x5 pixel arrays (Figure 8). Using an LED as a light source, we were able to project various icons. Due to the limited resolution, these are not perspective-corrected. Small, high-resolution LCDs (e.g. 32x32) could allow for perspective-corrected, high-resolution, dynamic icons in the near future.

Diffraction gratings are another option for static icon projection. We experimented with these early on, but found the output to be poor at short throw distances. We hope to design our own diffraction gratings in the future – these have high setup costs, but are very low cost to manufacture in volume. Additionally, our current prototype is monochromatic (red); moving to full color is interesting, but comes at the cost of increased size. Regarding size, we believe further miniaturization is possible (see "implementation").

The use of fixed icons also means that projection calibrations must be "one-size-fits-all". We noted during our experiments that the icon appearances were primarily affected by the projection angle, rather than the curvature of the arm. Nevertheless, there may well be incompatible arm geometries; e.g. icon sets would have to be modified for watches that are worn on the right arm.

There are also challenges in achieving high fidelity projected output on the skin. Foremost, light hitting the skin causes subdermal light scattering [16], which increases local illumination, thus decreasing contrast. Additionally, at the scales at which we are operating, the fine details in our icons can produce light interference effects. Moreover, laser light tends to produce a speckle pattern, which can make the icons appear to "sparkle", reducing the visibility and identifiability of the icon [5]. Despeckling methods exist that can reduce this effect (see e.g., [23]), but future work is needed to see if these techniques are compatible with small devices.

Finally, the IR proximity sensors we use can be inadvertently triggered by movement or flexing of the arm and wrist, and also by proximate clothing and jewelry. We attempt to mitigate the former by using an accelerometer to reject touch input while in motion, but outside of the lab, this will be a greater challenge. Sensor fusion, e.g., by combining IR touch sensing with bio-acoustics, may be the best way forward, and we plan to explore this in future work.

ACKNOWLEDGEMENTS

This work was generously supported by grants from Yahoo! InMind, Google and NSF (IIS-1217929), as well as fellowships from Qualcomm, Disney and NSERC of Canada.

CONCLUSION

Skin Buttons are low cost, very small projectors that can render a fixed image onto the skin at an oblique angle. These properties make them suitable for inclusion into smartwatches, where they can extend the interactive area beyond the small screen. We further added touch sensitivity through infrared proximity sensing, enabling interactive touch functionality. We described our proof-of-concept implementation and results from our study, which show that the projections are easily recognized, easily clicked, and have power requirements approaching commercial feasibility.

REFERENCES

1. Ashbrook, D., Baudisch, P. and White, S. Nenya: subtle and eyes-free mobile input with a magnetically-tracked finger ring. In *Proc. CHI '11*, 2043-2046.
2. Ashbrook, D., Lyons, K. and Starner, T. An investigation into round touchscreen wristwatch interaction. In *Proc. MobileHCI '08*, 311-314.
3. Baudisch, P. and Chu, G. Back-of-device interaction allows creating very small touch devices. *Proc. CHI '09*, 1923-1932.
4. Butler, A., Izadi, S. and Hodges, S. SideSight: multi-"touch" interaction around small devices. In *Proc. UIST '08*, 201-204.
5. Dainty, C. (Ed). Laser Speckle and Related Phenomena. *Topics in Applied Physics*, Vol. 9, 1975, Springer.
6. Fitzpatrick, T. B. Soleil et peau. *Journal de Médecine Esthétique*, Vol. 2, 1975, pp. 33–34.
7. Gustafson, S., Holz, C. and Baudisch, P. Imaginary phone: learning imaginary interfaces by transferring spatial memory from a familiar device. In *Proc. UIST '11*, 283-292.
8. Gutwin, C. and Fedak, C. Interacting with big interfaces on small screens: a comparison of fisheye, zoom, and panning techniques. In *Proc. GI '04*, 145-152.
9. Harrison, C. and Hudson, S. Abracadabra: wireless, high-precision, and unpowered finger input for very small mobile devices. In *Proc. UIST '09*, 121-124.
10. Harrison, C., Horstman, J., Hsieh, G. and Hudson, S. E. Unlocking the Expressivity of Point Lights. In *Proc. CHI '12*, 1683-1692.
11. Harrison, C., Tan, D. and Morris, D. Skinput: appropriating the body as an input surface. In *Proc. CHI '10*, 453-462.
12. Holz, C., Grossman, T., Fitzmaurice, G. and Agur, A. Implanted user interfaces. In *Proc. CHI '12*, 503-512.
13. Jones, B., Sodhi, R., Forsyth, D., Bailey, B. and Maciocci, G. Around device interaction for multiscale navigation. In *Proc. MobileHCI '12*, 83-92.
14. Kim, D., Hilliges, O., Izadi, S., Butler, A., Chen, J., Oikonomidis, I. and Olivier, P. Digits: freehand 3D interactions anywhere using a wrist-worn gloveless sensor. In *Proc. UIST '12*, 167-176.
15. Kim, J., He, J., Lyons, K. and Starner, T. The Gesture Watch: A Wireless Contact-free Gesture based Wrist Interface. In *Proc. ISWC '07*, 1-8.
16. Krishnaswamy, A. and Baranoski, G. A Biophysically-Based Spectral Model of Light Interaction with Human Skin. *Computer Graphics Forum*, 22(6), 2004, pp. 331-340.
17. Liang, R., Lin, S., Su, C., Cheng, K., Chen, B. and Yang, D. SonarWatch: appropriating the forearm as a slider bar. In *SIGGRAPH Asia 2011*, Emerging Technologies, Article 5.
18. Lin, S., Su, C., Cheng, K., Liang, R., Kuo, T. and Chen, B. PUB - point upon body: exploring eyes-free interaction and methods on an arm. In *Proc. UIST '11*, 481-488.
19. Lyons, K., Nguyen, D., Ashbrook, D. and White, S. Facet: a multi-segment wrist worn system. In *Proc. UIST '12*, 123-130.
20. Oakley, I. and Lee, D. Interaction on the edge: offset sensing for small devices. In *Proc. CHI '14*, 169-178.
21. Ogata, M., Sugiura, Y., Makino, Y., Inami, M. and Imai, M. SenSkin: adapting skin as a soft interface. In *Proc. UIST '13*, 539-544.
22. Ogata, M., Sugiura, Y., Osawa, H. and Imai, M. iRing: intelligent ring using infrared reflection. In *Proc. UIST '12*, 131-136.
23. Pan, J. and Shih, C. Speckle reduction and maintaining contrast in a LASER pico-projector using a vibrating symmetric diffuser. *Optics Express,* 22(6), 2014, 6464-6477.
24. Perrault, S., Lecolinet, E., Eagan, J. and Guiard, Y. WatchIt: simple gestures and eyes-free interaction for wristwatches and bracelets. In *Proc. CHI '13*, 1451-1460.
25. Saponas, D., Tan, D., Morris, D., Balakrishnan, R., Turner, J. and Landay, J. Enabling always-available input with muscle-computer interfaces. In *Proc. UIST '09*, 167-176.
26. Wagner, J., Nancel, M., Gustafson, S., Huot, S. and Mackay, W. Body-centric design space for multi-surface interaction. In *Proc. CHI '13*, 1299-1308.
27. Weigel, M., Mehta, V. and Steimle, J. More Than Touch: Understanding How People Use Skin as an Input Surface for Mobile Computing. In *Proc. CHI '14*.
28. Wolfe, J.M., Kluender, K.R., Levi, D.M., Bartoshuk, L.M, Herz, R.S., Klatzky, R.L. and Lederman, S.J. (2006). *Sensation and Perception*. Sinauer Associates, Sunderland, MA.
29. Xiao, R., Laput, G., and Harrison, C. Expanding the input expressivity of smartwatches with mechanical pan, twist, tilt and click. In *Proc. CHI '14*, 193-196.
30. Yamamoto, G. and Sato, K. PALMbit: A Body Interface utilizing Light Projection onto Palms. *Jour. of The Inst. of Image Info. and Tele. Eng.*, 61(6), 2007, pp. 797-804.