Abstract

Smartwatches can be used independently from smartphones, but input tasks like messaging are cumbersome due to the small display size. Parts of the display are hidden during interaction, which can lead to incorrect input. For simplicity, instead of general text input a small set of answer options are often provided, but these are limited and impersonal. In contrast, free-form drawings can answer messages in a very personal way, but are difficult to produce on small displays. To enable precise drawing input on smartwatches we present a magnetic stylus that is tracked on the back of the hand. In an evaluation of several algorithms we show that 3D position estimation with a $7.5 \times 20$ mm magnet reaches a worst-case 6% relative position error on the back of the hand. Furthermore, the results of a user study are presented, which show that in the case of drawing applications the presented technique is faster and more precise than direct finger input.

Author Keywords

Digital Pens, Mobile Interaction, Around-Device Interaction

CCS Concepts

+Human-centered computing → Interaction devices;
  Ubiquitous and mobile devices;
Introduction
Modern smartwatches are mainly used in sporting activities, health tracking, and with simple interactions such as answering phone calls, navigation, or music control. Due to their functionality of phone-independent mobile communication they can be used in a variety of applications, but face challenges associated with the small interaction area of the touch display. For example, tasks like text messaging are still difficult, because the finger covers several keys and users cannot see what they are actually typing [18].

To address this challenge, many researchers proposed novel interaction designs based on software and hardware prototypes to improve the usability of ultra small touchscreens. As an alternative option to typing, drawing is a very personal way to reply to incoming messages or to create, for example, an individualized digital birthday card [16]. However, drawing requires very precise input, which amplifies the challenges of small displays, e.g., with regard to the fat finger problem [35].

Interactions in the spatial vicinity of a display are particularly suitable to solve occlusion problems on tiny devices. To this end we developed a pen-based input device at the size of a conventional pen that allows cursor-like input on the back of the hand. The pen contains a capacitive pen-tip sensor to detect touch events on the hand and a permanent magnet to allow the smartwatch magnetometer to track the position of the pen.

This paper evaluates tracking algorithms and derives optimal parameters to enable precise paintings on smartwatch displays. In addition, the results of an initial user study are presented to prove the concept and to evaluate the performance compared to direct finger input on smartwatch displays.

Related Work
Methods for counteracting the fat finger problem on tiny displays can be divided into software and hardware approaches. By extending the software of the device, simple interaction techniques can be realized that do not require further equipment. To name a few, by enlarging areas of interest, precise input can be generated [18, 23, 26]. Also, splitting the keyboard into smaller parts has been explored [7, 8, 14, 27], as well as tap and gesture typing [12], cursor entry [31], or one-handed input via moving the wrist [10].

In order to avoid occluding the display, additional hardware can extend the interaction space. There are approaches that add hardware to the finger segments [3, 6, 24, 13, 28, 34, 36, 38], sense the wristband or smartwatch bezel for input [11, 21, 25, 29, 33, 40], or use a movable mechanical display for simple interactions like pan, twist, tilt, and click [39]. Other proposals add touch sensitive wire into clothing [29], use the skin [22] and the back of the hand for input [4, 17], or enable mid-air interactions around the device [15, 20, 32]. Several projects use magnetic field sensing [3, 6, 15, 20, 24, 28, 34], which has also been applied on stylus pens [1, 41]. There has also been research on finding optimized algorithms for permanent magnets with different shapes for tracking in 2D [5] and using magnetometer arrays around the device for 3D position estimation [9].

However, these implementations do not optimize tracking for precise interactions, like drawing on the back of the hand. For this purpose, Wu et al. combine a monocular camera and a 6-DoF motion tracking sensor to achieve very precise drawings [37]. Without position tracking, Schrapel et al. have shown that high recognition rates on handwritten digits can be achieved with stylus pens [30]. Both tech-
niques use paper as the interaction area and do not consider the back of the hand for input.

While previous work focused on general interactions, we show how the back of the hand can be used to enable precise cursor-like input and demonstrate how the interaction can be optimized for painting with digital pens.

**Position Tracking**

Since painting requires a particularly high tracking precision, we evaluate known algorithms for magnetic tracking.

**Algorithm Selection**

To identify the best tracking algorithm, three different approaches from related work \[1, 5, 9, 20, 41\] were implemented on a Huawei Watch 2. In the selection process for the most suitable tracking algorithm, the intended use with a stylus pen was especially considered. The three candidate algorithms we considered were the ones by Abe et al. \[1\], by Camacho and Sosa \[5\], and by Yoon et al. \[41\].

We first chose the 2D tracking algorithm by Abe et al. \[1\], assuming that the back of the hand approximates a flat plane. When all influences of terrestrial magnetism are constant, the magnetic moment can be eliminated using Coulomb's law, and a root-finding problem remains. In contrast to Abe et al., who apply the bisection method, we use Newton's method on all algorithms, as it requires less computational power, which is advantageous for mobile devices. While Abe et al. only consider the height of the magnet \[1\] Camacho and Sosa also use its shape in their equations \[5\]. Since cylindrical shapes can easily be embedded in stylus pens, this shape and approach was selected.

Furthermore, we investigated the 3D tracking algorithm by Yoon et al. \[41\] which was used in various projects \[9, 20\]. In contrast to the other chosen methods, this approach takes into account the magnetic moment, which determines the orientation of the magnet. However, the orientation of the magnet in three dimensions is required, which Yoon et al. calculate using an additional magnetometer \[41\] and Fan et al. \[9\] as well as McIntosh et al. \[20\] by placing several magnetometers around the interaction surface.

**Algorithm Evaluation**

To examine the optimal magnetic parameters and to evaluate the performance of the selected algorithms with the magnetometer embedded in the watch, a preliminary experiment was conducted. Based on the dimensions chosen by Abe et al. \[1\], cylindrical magnets with a diameter of 8 mm and heights of 16, 20, and 32 mm with a fixed magnetization degree of N48 were selected. Since a higher magnetization results in a higher magnetic flux density, a magnet with a diameter of 7.5 mm and a length of 20 mm with a magnetization of N52 was also used in the experiments.

The first experiment was intended to measure the accuracy of the algorithms in 2D space. The Huawei Watch 2 was placed in a planar coordinate system with the embedded 9-DOF smartwatch IMU in the origin. Within the proposed interaction area the cylindrical permanent magnet (diameter 8 mm, height 20 mm) was moved in 1 cm steps within a grid of 4 to 12 cm in x-direction and -5 to 1 cm in y-direction. The grid size was selected according to the average of anthropometric measurements of the back of the hand \[2\]. At each position, with the magnet's north pole towards the ground, the calculated distance was logged for all three algorithms. Deviations, resulting from inaccurate magnet orientation tracking for the 3D tracking algorithm were eliminated due to the chosen test setting.

A second experiment was conducted to investigate the optimal magnetic parameters. The previous test was repeated for different magnets with the 3D tracking algorithm. Based
on the results, the two most promising magnets were evaluated again in an tilt angle of 45°, which corresponds to a more realistic usage for stylus pens. Based on the final selection, the influence of the magnet's offset in z-direction was then investigated by measuring the positions again with an offset of 5, 10, 15, and 20 mm on the z-axis.

### Tracking Results

The general algorithm accuracy comparison Figure 5a shows that 3D tracking clearly outperforms 2D approaches even on a planar surface. Likewise, the back of the hand does not offer a completely flat surface, making 3D position determination particularly suitable for the intended application. We observed that the 2D algorithm by Camacho and Sosa [5] achieves more stable error rates than Abe et al. by incorporating the shape of the magnet into the calculations. However, a post-hoc test with Bonferroni correction showed no significant differences between the 2D algorithms while both differ significantly from 3D tracking.

Figure 5b shows that the strength of the magnetic field has a major impact on accuracy. If the magnetic field is too weak, the algorithm cannot find an optimal solution at every position within the interaction area. As a result the magnet [8×16 mm; N48] can only be used within a radius of 5 cm on the proposed interaction area. Conversely, if the magnetic field is too strong (see [8×32 mm; N48]), the magnetometer becomes saturated, which leads to inaccurate results. Furthermore, the watch itself has a magnetic mounting for the charging cable that influences the embedded sensor. Although this constant factor can be eliminated from the measurements, it still has an influence on saturation and noise that results in less accurate position tracking. A post-hoc test with Bonferroni correction could also show a significant difference between the magnet with a size of 8x32 mm and the other magnets.

For the two remaining magnets, Figure 5c shows that an inclination also affects the positioning accuracy. It can be assumed that the magnet of the smartwatch mounting here also influences the tracking algorithm. Due to the slightly higher flux density of the magnet [7.5×20 mm; N52] accurate positions can still be calculated, while the other magnet [8×20 mm; N48] is limited to a radius of 4 cm.

Figure 5d shows the influence of the z-position on the computed 2D position. A relatively stable accuracy is achieved over the full range, whereby an offset starting from 10 mm differs significantly compared to the initial position, according to a post-hoc test with Bonferroni correction.

This is due to the fact that the magnetic flux density decreases with increasing distance. Therefore it is important to consider the outliers, which up to 15 mm achieve a maximum relative error of 6 % within the proposed interaction area. Figure 4 visualizes the tracking performance over the intended interaction area. Since the absolute error increases with a rising distance, direct mapping of the position data results in inaccurate positioning of the cursor on the watch. Therefore we use indirect mapping.

### Prototype

From the previous evaluation we conclude that a cylindrical magnet [7.5×20 mm; N52] is able to track the position over the back of the hand with a maximum relative position error of 6 %. The found dimensions fit into a conventional pen, which is important to achieve a natural writing experience. In addition to the small form factor, accurate interaction is also required. For this purpose, a touch sensor (AT42QT1010) on the PCB is connected to the pen tip, which communicates its state to the smartwatch via Bluetooth Low Energy (version 5) upon contact with the skin. The round shape of the pen tip and the gold plating ensure...
a comfortable touch experience and an optimal contact with the skin even in an inclined position. Figure 6 shows the individual components.

A 6-DOF IMU (BMI160) is integrated to measure the orientation of the stylus, which requires an initial calibration on first use. For this purpose the prototype must be held perpendicular to the back of the hand for one second. Based on the sensor data measured at 100 Hz, the position is then calibrated with Madgwick’s AHRS [19]. A magnetometer (BMM150) was also installed for test purposes, which cannot be used for orientation estimations due to the strong magnetic field. This leads to an accumulated drift over time, which, however, does not noticeably influence the accuracy due to the low-noise sensor data over the short duration of an interaction [41]. To alleviate such tracking drifts, an indirect mapping is applied which does not require further calibration. In addition, it is thereby not necessary to further adjust the tracking area to the size of the hand.

The 7.5×20 mm magnet is mounted at a distance of 15 mm from the pen tip, also serving as a pen handle that restricts the degrees of freedom in which the pen is held. This is advantageous as the corresponding yaw angle of the prototype can only be calculated using a magnetometer. In addition, the pen’s center of gravity is shifted further towards the tip, which positively affects the writing comfort. In total the prototype has a weight of 18 g, of which 12 g are used for the 180 mAh battery. It can be continuously operated for 12 hours without recharging the battery.

For demonstration purposes an example painting application was implemented on the Huawei Watch 2. A cursor on the display shows the current position. As soon as the pen tip touches the back of the hand, a line is drawn.

User Study
A small user study was conducted to compare the pen-based interaction on the back of the hand with direct finger input for target acquisition and drawing interactions on tiny displays. Twelve volunteers aged 18 to 52 years (mean age $x = 29.0, \sigma = 11.7$), including 4 women and 8 men were recruited. All participants were right-handed and 6 of them owned a smartwatch.

After an initial questionnaire with demographic questions a short introduction was given by the demonstrator. The participants could then test the application as long as they wanted to get familiar with the interaction technique.

Then a pointing experiment was performed to test how precise and fast users can select randomly displayed targets with a radius $r=10$ px (1 mm). After ten trials with the finger and ten trials with the pen, each participant had to select ten names from vertically aligned random lists with each technique. The objective was to compare list scrolling by drawing with the pen on the back of the hand against scrolling on the display with the index finger. Together, both experiments provide an insight into how quickly and precisely users can interact with each technique.

A final experiment was intended to find out how accurately both methods can be used to create drawings. For this purpose, the participants had to trace various shapes as accurately as possible. A periodic rectangle function was displayed in three levels of difficulty, i.e., with three, four and five repetitions, as shown in Figure 7. Additionally, two letters (M, ß) had to be drawn. All variants of drawings were presented in random order and measurements of time and position were taken from the beginning of the drawing. The whole study took about 45 minutes on average.
Results

The results of the user study are visualized in Figure 8. The upper graph (a) shows the results of the pointing experiment. While the finger can be used to interact much faster, a higher error rate occurs than with the stylus. This behaviour also appears in the list experiment Figure 8b. Both results together can be seen as an indicator that both interaction techniques are rather inappropriate for complex tasks like Web browsing on the smartwatch. However, some participants remarked that they prefer the pen as they could not see the items in the list during the finger input condition.

Of greater relevance is the third part of the study, which is visualized in graphs (c) and (d). The error rate visible in (c), calculated with dynamic time warping (DTW), shows that more precise lines can be drawn with the pen. Especially with increasing difficulty it is noticeable that smaller deviations from the templates can be achieved with the pen. This is also evident in the letters M and ß. A post-hoc test with Bonferroni correction showed significant differences between finger and stylus input on all methods except for the easy and medium templates.

In contrast, the task completion times shown in Figure 8d indicate that the participants have drawn the letters particularly quickly with the finger, whereas they spent more time with the stylus and drew more accurately. When tracing the rectangle templates the participants were much faster with the pen, even for the most difficult condition. We explain this with the observation that tracing with the finger is more difficult, as the displayed template is covered by the finger. This results in a longer time needed for drawing and a larger error with the finger than with the stylus. Here as well, a post-hoc test with Bonferroni correction showed significant differences between both input methods for all templates.

In general, we find that for drawing applications indirect pen input on the back of the hand is substantially faster and more precise than direct finger input. In addition, we asked the participants about their impressions. In general, the participants found the interaction on the back of their hands intuitive and pleasant. They stated that they could imagine using such a device for drawings, web apps and games, despite the small display.

Conclusion

We proposed an interaction technique and device for drawing on the back of the hand for ultra small wrist-worn displays. By integrating a magnet in a stylus, the position relative to a magnetometer can be determined with high precision. Different dimensions and magnetic field strengths were tested with the result that a magnet with a dimension of 7.5×20 mm and a magnetization degree of NS2 achieves acceptable results on the Huawei Watch 2. Furthermore, different algorithms were evaluated regarding their accuracy in the interaction space, which showed that the 3D position determination is significantly more accurate. An initial user study served to evaluate the field of application. It showed that by using the stylus, more precise interactions can be made than with the finger. Contrarily, the interaction time increases with the pen. However, the study shows that for applications like drawing on a tiny screen, direct finger input leads to higher error rates and higher task completion times than indirect pen input on the back of the hand.

In the future we plan to identify further interactions that are particularly suitable for pen-based input on the back of the hand. Additional tests are necessary, e.g., to optimize the approach for interactions like web browsing, gaming, or keyboard input. We will also investigate whether this technology can be used for authentication and handwriting recognition on the back of the hand.

Figure 8: Evaluation of the study parts across all participants.
REFERENCES


