A Technique for Touch Force Sensing using a Waterproof Device's Built-in Barometer

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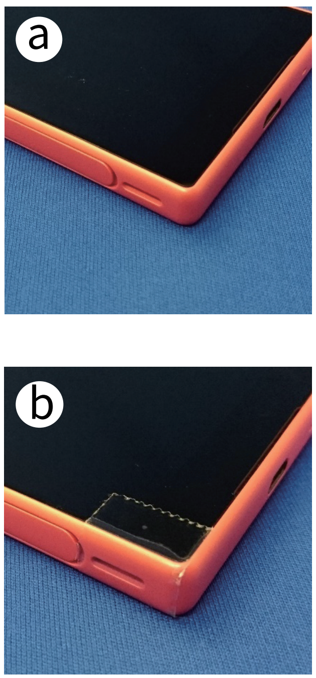

Figure 1: Device conditions. a) non-tape condition. b) with-tape condition.

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Abstract

We present BaroTouch, a technique that leverages a waterproof mobile device's built-in barometer to measure the touch force. When an airtight waterproof device is touched, the distorted surface changes the air pressure inside that device and thus changes the built-in barometer value. Although this change varies under different airtightness conditions, our technique can measure the touch force independent of the airtightness conditions. To investigate BaroTouch's characteristics, we conducted three experiments. First, since the change in the barometer value varies under different airtightness conditions, we evaluated BaroTouch's characteristics under two levels of airtightness conditions. Second, we investigated the relationship between the sensor value and the touch positions or forces and found that the touch screen increased approximately in a linear manner. Last, in a controlled user study with 10 participants, the participants could exert three levels of touch force with an accuracy of over 92.2% accuracy using BaroTouch.

Author Keywords

Force input; pressure sensing; touch screen; smartphone; smartwatch.

ACM Classification Keywords

H.5.2. [Information Interfaces and Presentation (e.g. HCI)]: Input devices and strategies (e.g., mouse, touchscreen);

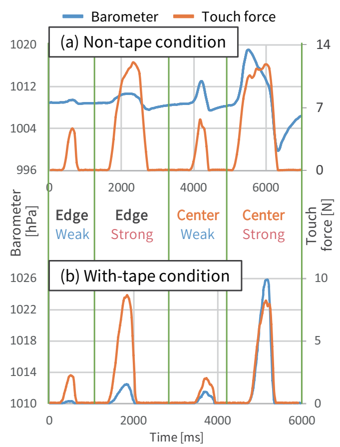

Figure 2: Waveforms of the air pressure and touch force in the waterproof device when it was touched at different touch positions and different touch forces. a) Non-tape condition. b) With-tape condition.

Introduction

We present BaroTouch, a technique that leverages a waterproof mobile device's built-in barometer to measure the touch force. It measures the touch force a user exerts on the touch screen without a force sensor by observing the changes in the barometer value when the user touches on the touch screen. Our technique does not need machine learning for sensing and is a passive technique; thus, it could be lightweight.

To investigate BaroTouch's characteristics, we conducted three experiments. First, since the changes in the barometer value varies under different airtightness conditions of the waterproof device, we evaluated BaroTouch's characteristics under two levels of airtightness conditions. Second, since the magnitude of the change in the air pressure varies for different touch positions and different touch forces, we investigated the force-sensitivity characteristics of each touch position and each touch force. Last, we conducted a controlled user study to investigate the number of levels of touch force that users can exert with BaroTouch.

Related Work

Many touch force sensing techniques have been proposed to expand touch interaction.

Touch Force Sensing on Mobile Devices with Additional Equipment

Some techniques of force sensing by additional equipment have been suggested to expand touch interactions on a mobile device. For example, Acoustruments [6] can measure touch force when a pipe, which connects a smartphone's microphone and speaker, is touched. Force Gestures [3] attached force sensors to the case of a mobile device to measure the touch force on its touch screen. Ono et al. [9] analyzed the resonant properties of a smartphone to recognize a touch force using a smartphone case attached with a vibration speaker and a piezoelectric microphone. In contrast to these approaches, BaroTouch realizes touch force sensing by only a built-in barometer.

Touch Force Sensing on Smartphones using Built-in Sensors

Techniques that only use a smartphone's built-in sensors to measure touch force on its touch screen have been proposed. For example, GripSense [2] measures touch force by vibrating the smartphone and observing the diminished gyroscope readings. ForceTap [4] is a technique for sensing the tapping force based on the acceleration value from the built-in accelerometer. ForcePhone [11] measures touch force by using a smartphone's built-in microphone and speakers with ultrasonic sensing and machine learning. VibPress [5] measures touch force by using a smartphone's built-in accelerometer and vibration motor. In contrast to the above work, no prior work has investigated the use of a smartphone's built-in barometer for sensing touch force. Moreover, BaroTouch does not need machine learning; it measures touch force with a simple conversion from the air pressure to touch force. In addition, BaroTouch is a passive sensing technique and thus could be lightweight, in contrast to active sensing techniques such as those in [5, 11].

Other Touch Force Sensing Techniques

Expressive Touch [10] is a method for measuring tapping force on a tabletop touch screen by using the peak amplitude of the sound waves generated by finger taps. Dietz et al. [1] measures key pressing force by using a modified flexible membrane keyboard. Pressing the Flesh [7] measures touch force on any surface by observing the color changes in the fingertips and nails using a camera. Emoballoon [8] is a touch gesture recognition technique on a balloon, which has an inner barometer and a microphone. In contrast to these studies, our method focuses on measuring touch force on a mobile device by using its built-in barometer.

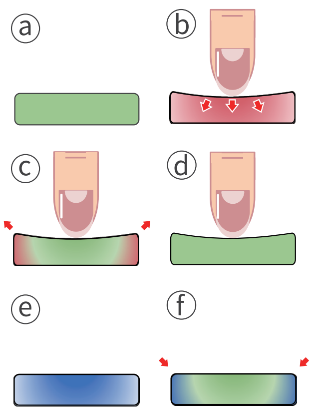

Figure 3: Changes of the air pressure inside the waterproof device. a) Before touch. b) Right after touch. c) During touch. d) A period of time after touch. e) Right after the finger leaves. f) Long after the finger leaves.

BaroTouch

BaroTouch is a technique that leverages a waterproof device's built-in barometer to measure the touch force a user exerts on the touch screen. When the touch screen is touched, its distorted surface compresses. Since this changes depends on the airtightness, we built an algorithm to measure the touch force under different airtightness conditions.

Process for Changes in The Barometer

Since BaroTouch measures touch force by observing the changes in the device's inner air, which depends on its airtightness, we investigated the characteristics of this change. We prepared the following two waterproof smartphones (device condition): one whose lanyard hole is sealed with tape (with-tape condition, Figure 1a) and one that is not sealed (non-tape condition, Figure 1b).The smartphones were SONY Xperia Z5 Compact (Waterproof rating: IPX5/8, barometer: Alps Electric HSPPAD038). We also attached a force sensor (Interlink Electronics FSR402) to the touch screen to measure the finger's touch force.

Figure 2 shows the waveforms of the barometer value and the force sensor values under the two device conditions. Under non-tape condition (Figure 2a), the barometer value greatly increased at first, then decreased, and finally recovered when the touch screen was released. This waveform was generated because the device's inner air flowed out/in when the device distorted/recovered, as shown in Figure 2a). Moreover, Figure 2b shows that the transformations in Figures 3c and Figure 3e only occur under the non-tape condition because the device's inner air under the with-tape condition was not exchangeable owing to its high airtightness.

Algorithm

Since the change in the barometer value differs under the two device conditions, as mentioned above, we designed an algorithm to measure the touch force during the touch, as expressed by the following equations:

$$
\begin{aligned}
b_{lp}[n] &= b_{lp}[n-1] \times (1-\alpha) + b_{raw}[n] \times \alpha && (1) \\
b_{hp}[n] &= b_{raw}[n] - b_{lp}[n] && (2) \\
b_{sum}[n] &= \sum_{i=0}^{n} b_{hp}[i] && (3)
\end{aligned}
$$

where b_{raw} is the raw barometer value, b_{lp} is the low-passed value of raw barometer value, b_{hp} is the high-passed value of raw barometer value; b_{sum} is the integral value of b_{hp}, and α is a constant equal to 0.015. Our current implementation processes the barometer value with this algorithm at 200 Hz.

In this algorithm, we use a high-pass filter to eliminate the atmospheric pressure (see Equations 1 and 2). Next, we use an integral approach to reduce the effect generated by the device's inner air that flows out/in (see Equation 3). We define the b_{sum} during the touch as the measured force. When the user releases a finger from the touch screen, b_{sum} is reset to zero.

Figures 4 and 5 show the results of the algorithm under the two airtightness conditions. Figures 4a and 5a show the touch force measured by force sensors (i.e., the reference force); Figures 4d and 5d show the measured force. As shown in these figures, the measured force is more similar to the reference force than the raw barometer value.

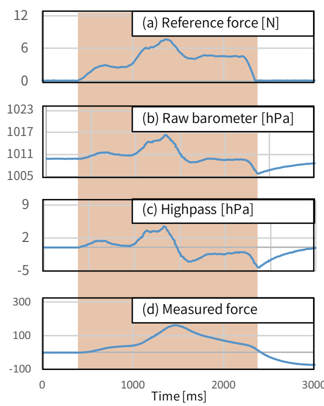

Figure 4: Response of the device when it was touched under the non-tape condition.

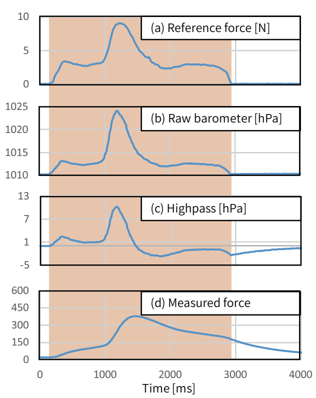

Figure 5: Response of the device when it was touched under the with-tape condition.

Force-Sensitivity of Different Touch Positions and Forces

In order to clarify BaroTouch's force-sensitivity, we investigated the relationship between the barometer value and touch positions and between the barometer value and touch forces. In this investigation, we used the same smartphones as the first experiment.

Procedure

The experiment was carried out in a room where the windows and doors were all closed. The atmospheric pressure of the experimental environment was 1008.02 hPa at the start. In this experiment, we placed weights on a device's touch screen and recorded the air pressure (i.e., b_{sum}). In the force-sensitivity investigation of touch positions, we divided the device's touch screen into 6 rows $\times$ 3 columns of areas, placed a 50 g weight (radius = 1 cm, force = 15.92 gf/cm^2) at the center of each divided area, and recorded the largest b_{sum}.

In the force-sensitivity investigation of touch positions, we divided the touch screen into 6 rows $\times$ 3 columns of areas, placed a 50 g weight (radius = 1 cm, force = 15.92 gf/cm^2) at the center of each divided area, and recoded the largest b_{sum}. In the force-sensitivity investigation of touch forces, we placed 10 g, 20 g, 50 g, 100 g, 200 g, 500 g, and 1000 g weights on a pedestal, as shown in Figure 6 (radius = 1 cm, weight = 4.33 g) to unify the contact area sizes for all weights. We then placed the pedestal at the center and upper-left side of the touch screens of the two smartphones and recorded the largest b_{sum}. Since we placed the weights 10 times for each of the investigations, the total number of trials was 360 (2 device conditions $\times$ 18 areas $\times$ 10 times) for the force-sensitivity investigation of touch positions, and 280 (2 device conditions $\times$ 2 locations $\times$ 7 different weights $\times$ 10 times) for the force-sensitivity investigation of touch force.

Results and Discussion

Figure 7 shows the results of the force-sensitivity investigation of touch positions. From Figure 7, we can know that the maximum value of the experimental device's center part was larger for each condition. We think that this is because the center part of the device had greater distortion than the edge parts. By using this characteristic and the touch position, we may be able to measure touch forces that do not depend on the touch positions.

Figure 9 shows the results of the force-sensitivity investigation of touch force. This shows that the value increases in proportion to the weight. Moreover, a comparison of Figures 9a and 9b reveals that the non-tape condition exhibited leakage of the air with in the device. Furthermore, since the same characteristic was observed at both the center and upper-left side of the touch screen, the entire touch screen would share this characteristic.

User Study of Different Levels of Touch Force

We conducted a controlled user study to evaluate how many levels of touch force a user can exert with BaroTouch. In this study, we used two conditions and executed the application, as shown in Figure 10. We measured an accuracy of 2–6 force levels.

Participants

10 graduate and undergraduate students with ages of 21–24 were recruited (5 male, 5 female). All the participants used their smartphones in their daily lives (usage time: 36–96 months, average: 55 months) and were all right-handed. Two of the participants have used smartphones with force-sensitive touch (usage time: 6–7 months). We paid each participant 820 yen as an honorarium to each participant when he/she completed the study.

Figure 6: Pedestal.

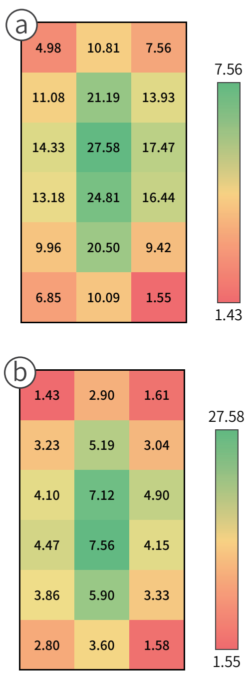

Figure 7: Force-sensitivity characteristic at each touch position: a) non-tape condition. b) with-tape condition.

Experimental Environment

The experiment was carried out in a room where all of the windows and doors were closed. The average atmospheric pressure of the room was 996.40 hPa (976.08–1002.24 hPa). We used the same smartphones as the first experiment.

Procedure

Participants were asked to remain sitting in chairs throughout the experiment. Firstly, the experimenter gave an introduction to the participant. After this, the participant was instructed to answer a demographic questionnaire about the participant. Then, we measured the pinch strength of the participant's right thumb using a pinch gauge (Baseline ER HiRes hydraulic pinch gauge). The average finger pinch strength among the participants was 7.25 kg (SD $=$ 2.99 kg).

The experimenter presented the application shown in Figure 10 to the participant and explained its usage. Then, the participant was asked to touch the button displayed at the center of the experimental device strongly for 5 times and weakly for 5 times. We recorded the largest strongly b_{sum} of each touch. Calibration was achieved by setting the average b_{sum} of strong touches as the upper limit, and that of the weak touches as the lower limit, calibration was done.

In order to counterbalance the order effect, we divided the participants into two groups, letting one of them performed the tasks under the non-tape condition firstly and the other group performed tasks under the with-tape condition first. Under each device condition, a participant was assigned all 5 dividing conditions (i.e., 2–6 blocks) by a Latin square. Under one dividing condition, the participant performed a practice session and a test session. In the practice session, we displayed 12 targets randomly. In the test session, 60 targets were displayed in a random order, with the same occurrence times for each target. If a trial was failed, the next target was displayed. The experiment was carried out with a short break (>3minutes) between the two device conditions. Consequently, one participant completed 660 trials (2 device conditions $\times$ 5 blocks $\times$ (12 $+$ 60 trials)) during the experiment. After the experiment, we asked every participant to fill out a free-form questionnaire: which device was easier to use. The entire experiment, from the prior explanation of the last questionnaire, took approximately 40 minutes for each participant.

Results and Discussion

Figure 8 shows the success rate for each device condition and dividing condition. We used a paired t-test for each dividing condition to examine if the results under two device conditions were significantly different. As a result, under the 6 blocks dividing condition, the with-tape condition shows a significantly higher success rate than the non-tape condition. Furthermore, under the 3 blocks dividing condition, which is used in peek and pop function with 3D Touch on an Apple iPhone, the non-tape and with-tape conditions have the success rate of 92.2% and 94.5%, respectively.

From the results of the questionnaires, eight of the ten participants answered that it was easier to control the force levels under the with-tape condition. In contrast, two participants said that the non-tape condition was easier. They also commented that they felt the green level meter was too sensitive to make it reach the target block. As a reason for that, under the non-tape condition, the range between the upper and lower limits was too narrow because the changes in the device's inner air pressure was small from their calibration.

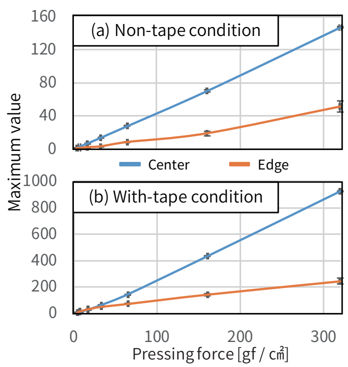

Figure 9: Force-sensitivity characteristic of each touch force: a) non-tape condition. b) with-tape condition.

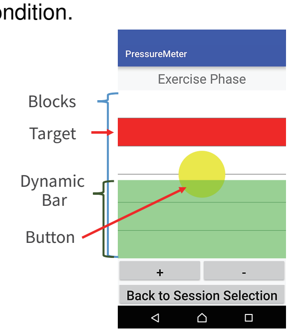

Figure 10: Application used to investigate how many levels of touch force a user can exert. The application divides the screen between the upper and lower limits identically into 2–6 blocks. The participant touches the yellow button and adjusts the touch force so that the top edge of the green level meter remains inside the red target.

Conclusions and Future Work

We presented BaroTouch, a technique for measuring the touch force from the change in the built-in barometer value due to a user's finger touching a waterproof device's touch screen. The results of our user study showed accuracies of 97.8% (non-tape condition) and 95.8% (with-tape condition) accuracy. For six levels, the accuracy decreased to 78.6% (non-tape condition) and 85.5% (with-tape condition), respectively.

Future research should investigate our technique using smartphones with other IPX ratings. We will investigate other waterproof devices such as tablets and smartwatches.

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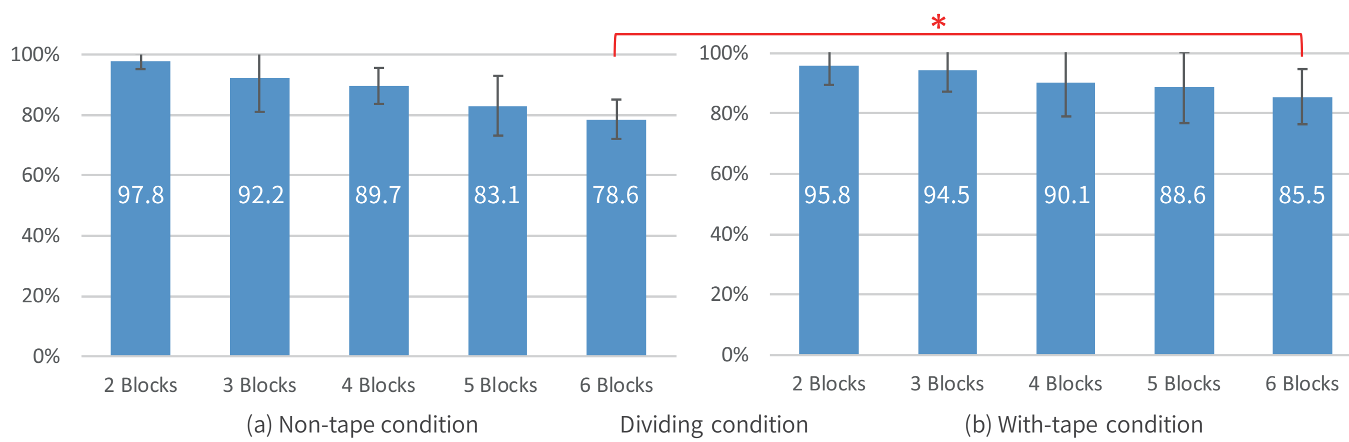

Figure 8: Success rate for each device condition and each dividing condition. Error bars represent standard deviations. ($*$:$p < 0.05$)

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