Vibkinesis: Notification by Direct Tap and ‘Dying Message’ Using Vibronic Movement Controllable Smartphones

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ABSTRACT

We propose Vibkinesis, a smartphone that can control its angle and directions of movement and rotation. By separately controlling the vibration motors attached to it, the smartphone can move on a table in the direction it chooses. Vibkinesis can inform a user of a message received when the user is away from the smartphone by changing its orientation, e.g., the smartphone has rotated 90° to the left before the user returns to the smartphone. With this capability, Vibkinesis can notify the user of a message even if the battery is discharged. We also extend the sensing area of Vibkinesis by using an omni-directional lens so that the smartphone tracks the surrounding objects. This allows Vibkinesis to tap the user’s hand. These novel interactions expand the mobile device’s movement area, notification channels, and notification time span.

Author Keywords

Smartphone; mobile device; notification; vibration; mobile sensing.

ACM Classification Keywords

H.5.m. Information interfaces and presentation: Miscellaneous.

INTRODUCTION

Smartphones can notify users of different events, such as phone calls and received emails, through screen alerts, sounds, or vibrations. Recently, several novel methods have been proposed to enrich information output using new materials and devices, e.g., by bending the body of a smartphone [9], moving its surface [23], and expanding its body [14]. These technologies augment the information channels available between mobile devices and users.

There are other methods that do not require the physical appearance of the smartphone to change. inFORM [8] demonstrates an application that transports a mobile phone

to a user when the mobile phone receives an incoming call. In the commercial field, several types of robots that transport smartphones are sold [1, 3]. These mechanical fields and robot methods rely on a fixed table or floor because of issues with their mobility. In other words, such methods satisfy a different goal from ours in this paper because they do not involve self-contained mobile devices.

Figure 1. Vibkinesis concept of self-moving smartphone. The user notices by Vibkinesis (a) direct tap, and (b) changed orientation.

We propose Vibkinesis, a self-contained smartphone that can move on a tabletop by vibrating. The smartphone controls four pairs of attached vibrating motors that allow it to slide on a flat surface. Vibkinesis changes its orientation by rotating and relocating, as shown in Figure 1. Furthermore, Vibkinesis can directly contact a user. Obviously, such a method of freely moving smartphones can be achieved through robots [1, 3], or by attaching several tires, motors, servo-motors, and a microcontroller to the phone. However, from the perspective of mobility and compatibility, we believe Vibkinesis is satisfactory implementation because it requires only eight small vibrators and a microcontroller. This setup does not negatively affect the smartphone’s mobility. Moreover, the peculiarity of the system’s entire appearance is important in daily use, especially for mobile systems, because such systems are used in public. Vibkinesis looks like a smartphone with a small thick case. Thus, it is different from robotic phones or smartphones with tires.

By allowing smartphones to move freely on a tabletop,

* The term “Dying Message” in the title is the last message written by a dying character in Japanese mystery novels and comics.

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UIST '14, October 05 – 08, 2014, Honolulu, HI, USA.
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<http://dx.doi.org/10.1145/2642918.2647365>

users can obtain information through a new channel. For example, if a user is working while listening to music through headphones (thereby losing the smartphone's aural channel), he/she can become aware of an incoming phone call through a *direct tap* from the smartphone (using the haptic channel). Moreover, and to the best of our knowledge, previous methods proposing self-contained mobile devices have not addressed situations where the battery of a mobile device is discharged and the device is not able to notify the user of messages or other events. We could not find studies that addressed such a limitation, although all mobile devices have a battery limit. We propose a solution to this issue through a novel capability of Vibkinesis: the smartphone persists in a rotated orientation even after the battery has discharged, as though it had written a last message.

It is well known that mobile devices move due to the embedded vibrators. Cycloramic [2] uses this effect to rotate a phone 360° in order to capture panoramic images. However, there is no method to control the angle of rotation of the phone, or its direction of movement and rotation. In this paper, we propose several practical notifications through two-dimensional movement and rotation methods by using eight vibration motors. Another contribution of Vibkinesis is a new focal point for mobile devices and a solution: notification using its orientation even after the battery has discharged.

RELATED WORK

Notification Methods of Mobile Devices

Traditional sound and haptic notifications are well reviewed in [10]. Recently, several other notification methods have been proposed for mobile devices in addition to screen displays, sounds, and vibrations. MorePhone [9] bends the phone's surface such that the user is aware of the device's change, even when wearing headphones. Surflex [6] also changes its shape by bending. Shape-changing Mobiles [14] change their protuberance such that users can notice whether devices are leaning to the front or back. Take Me By The Hand [13] changes the shape and weight gravity point of a mobile phone for eyes-free navigation.

Several methods use vibrators to obtain more complete information, especially as feedback. Ambient Touch [19] produces complicated vibrating patterns so that the user can obtain more information than from simple vibrations. Haptic-emoticon [18] provides a continuous two-dimensional haptic feedback using nine discrete vibrators located at the bottom of the phone. Sahami has proposed embedding six vibrators for navigation [24]. Brown et al. propose sending messages to the user through vibrators attached to his/her arm [4]. SemFeel [29] provides feedback with regard to the user's operation through multiple vibrators attached to the bottom of the device. Users can thus sense the part of the display that they touch without looking at it. These navigation or feedback methods are

used when a user holds the device. On the contrary, the vibration motors of Vibkinesis are activated when the device is on a surface (not held by a user). Thus, Vibkinesis does not focus on direct vibrotactile stimuli.

Changing Device Shape

Shape-changing devices in the field of Human-computer Interaction have been developed to alter the functions and affordances. The mechanisms and categories of shape-changing interfaces are well documented in [7, 21]. As in MorePhone [9], a shape-memory alloy is used to change the shape of a device [12, 20]. Morphees [22] also use shape-memory alloys but focus on functions related to usability, such as changing into a prehensile shape. The aforementioned devices are able to shape-change provided they receive electrical power. This includes shape-memory alloys, which can bend only when powered by electricity. Therefore, shape-changing mobile devices can notify users only if they are charged.

Sensing Methods of Mobile Devices

Sensing the environment is necessary for mobile interfaces to perform appropriate actions. Hinckley et al. propose rotating the displayed image depending on the tilt of the device [15]. SideSight [5] allows the user multi-touch interactions around the device using two arrays of infrared (IR) proximity sensors. PaperPhone [17] recognizes bending gestures using a flexible electronic paper display. Harrison et al. propose using a small RGB light and sensor to detect the material on which a mobile device is resting for placement-aware mobile computing [11]. Surround-see [28] uses an omni-directional lens to view the surrounding environment, such as the user's proximity or hand gestures. Vibkinesis employs the same setup as that of Surround-see for the smartphone to move toward a user's hand to notify him/her about an event.

There also exist sensing techniques that only use the default sensors in a device. TinyMotion [27] senses the user's actions using a camera image. Accelerometers are used to detect touch and tap gestures [25, 30], including foot gestures [26], when the phone is in a user's pocket. VibroTactor [16] determines the location of the smartphone using vibrations and sound echoes. For most of these methods, sensing technologies are used to detect the user's actions. The exception is VibroTactor, which can determine the location when the smartphone is placed on a surface.

IMPLEMENTATION

Vibration-controlling Hardware and Software

Our Vibkinesis prototype is implemented using a Sony Xperia Z with three plastic cases, eight Tokyo Parts Industrial vibration motors FM34F, and a microcontroller ATmega328P on an Arduino Nano. The four pairs of vibrators are attached to a base case using double-sided tape, and an Arduino Nano is attached in a similar manner (Figure 2, middle). Another cover case is attached to the

base case in an inverted position using tape, and the smartphone is placed on top of the mount case (Figure 2, right). The smartphone and the Arduino Nano are connected by a USB host cable for power and serial communication. Applications that run on Android OS are programmed using Processing for Android with libraries for serial communication and camera image processing. In this setup, the measured energy supplied by Arduino Nano is approximately $3.1\text{ V} \times 60\text{ mA} = 0.18\text{ W}$ for each vibrator. Each pair behaves independently, and thus the maximum electrical requirement at one time is $0.18\text{ W} \times 2 = 0.36\text{ W}$.

The combinations of vibrators and movements for the current Vibkinesis setup are shown in Figure 2 (left). In any implementation, it is difficult to move the device exactly in a straight line. However, this issue is not critical because the software can correct the direction of movement of the device by rotating it.

We assume that the rotation and direction of movement of Vibkinesis depend on the turning directions of the eccentric wheel motors in the attached vibrators. The applied power from the weights in the motors alters depending on their positions. When a weight goes through the inside of the device, the effect of this applied power is slightly weakened; when going through outside, the power remains. In this way, when the motors at the top turn to the left, the device rotates to the left; the device rotates to the right when the bottom motors turn to the right. We also assume the left and right motor pairs' power lean to one side, and then the device moves roughly in the opposite directions.

Figure 2. Vibkinesis hardware setup. Front view shows combinations of each activated two-vibrator set and movement/rotation directions.

For our first prototype, we mounted a vibrator on each edge of the base case (for a total of four motors). However, the power of the vibrations was not sufficient to move the smartphone. We then used two vibrators for each direction, following which the system moved as intended for Vibkinesis. The entire system, including the weight of the smartphone (146 g), weighs 231 g, and its thickness is 31 mm (including the smartphone's thickness of 7.9 mm). Technically, this setup will be implemented in a

smartphone because vibrators are commonly embedded in smartphones; the smartphone typically acts as the microcontroller in such setups. Our prototype is sufficient to exemplify the idea underlying Vibkinesis. However, a light-weight setup is recommended.

Other options for implementing vibration control are as follows:

1) Wi-Fi using XBee instead of a USB host cable for data communication with the microcontroller: a clear limitation of our current prototype is the USB cable connection. XBee eliminates the physical connection between the smartphone and the Arduino Nano; however, an additional battery is required for the microcontroller. A USB host cable can be used for both power supply and data communication. If we use XBee and an additional battery, the total weight of the system increases and its mobility consequently decreases. Moreover, we would then be required to separately charge the smartphone and the additional battery. For these reasons, and for mobility and simplicity of daily use, we chose the USB host cable for our proof-of-concept prototype.

2) Stronger vibrators can reduce the number of motors needed. However, the fewer motors in this case require higher voltage, due to which it becomes necessary to add another battery. This means that the system requires a more complicated circuit using field-effect transistors (FETs) with resistances. The vibration motors we use for the current prototype require 2.5 to 3.5 V, which is supplied by the USB host cable; therefore, the system is lighter. Obviously, stronger motors can carry a heavier system, but its mobility suffers. Consequently, we chose light motors.

Sensing Rotation Angle

In order for the smartphone to stop vibrating when it rotates to a certain degree, e.g., 90° , it is necessary to measure the extent to which the smartphone turns after it starts vibrating. We had some options for sensors, such as the three-dimensional accelerometer, a magnetic field sensor (compass), and a camera. Moreover, if we develop Vibkinesis as a tabletop interface, we can use external sensors, such as Kinect. However, our concept of Vibkinesis is as a self-contained mobile system; thus, we selected embedded sensors. We chose to use a compass because it would simply return the direction that the smartphone is facing.

Our prototype exhibits robustness with regard to the angle of rotation. Even if the smartphone accidentally rotates to an excessive degree when, for example, someone strikes the table when the smartphone is vibrating, Vibkinesis detects the exceedance, and then rotates accordingly in the opposite direction. In this manner, a different notification can be avoided.

A limitation of the compass is that it is influenced by surrounding magnetic objects, including magnets from the mounted vibration motors. However, we experimentally

confirmed that the magnetic force of the eight small vibrators is not sufficiently strong to considerably alter the compass direction. Furthermore, and for practical purposes, the smartphone's compass function can be used without trouble in the presence of some magnetic forces, such as audio speakers or the TV. Therefore, using the compass to detect the angle of rotation is of no consequence for incremental rotations of 45° or 90° .

More sophisticated sensing methods can be used, for example, the optical flow processing of camera images. In use cases of Vibkinesis, the smartphone always rests on a surface; its front camera thus faces the ceiling and the rear camera faces the surface (this requires clear cases). Thus, the smartphone can calculate the angle at which it rotates by observing the ceiling or the surface. Our current prototype uses the compass only because it is sufficient to show our concept of rotation notification. However, integration with other smart methods can help improve its angle precision.

Sensing Direction of User's Hand

Vibkinesis can move to tap a user's hand on a table by detecting the direction of the hand. Following the detection technique of Surround-see [28], we attached an omni-directional lens, Kogeto, which enhances the field-of-view to 360° in the horizontal plane, to the front camera of the smartphone using double-sided tape. Of course, more sophisticated methods are available. However, simple RGB thresholds are sufficient to detect skin color for the proof-of-concept of Vibkinesis. When a user is working at a table, e.g., performing paperwork or conducting tasks using a PC, his/her hands are located at the lower position of sensed images. We can avoid the user's face/neck region by using only the lower two-thirds of the images. Vibkinesis senses 1280×720 pixel images at 10 fps, and then verifies skin color per 10 pixels. Vibkinesis assumes that the gravity point of the skin-colored pixels is the direction of the user's hand. In the *direct tap* application, Vibkinesis controls the vibrators' ON/OFF function until it reaches the hand.

This sensing method has limitations in accordance with those of common computer vision, e.g., light effect, the skin color of naked forearms, individual skin color, and surrounding objects that have a color parameter close to that of the human skin. There are several solutions that use additional items, for instance, wearing a tracking marker on a wrist or a finger, using a depth sensor, or attaching a non-contact thermometer. An omni-directional lens can detect the user's hand without problem for the purpose of exhibiting our Vibkinesis concept. However, the aforementioned alternatives might improve detection accuracy.

Measurement

We tested two types of measurements – rotating times and moving times – on three types of surfaces – wood, glass, and plastic. The rotation time for each surface is calculated as the average of rotating the device by 45° on

that surface five times to the right and to the left, for a total of 30 times. The movement time is measured similarly, as the average of moving the device 5 cm five times to the right and to the left, on each surface. We test the flatness of each surface using a spirit level. The smoothest surface is glass, followed by plastic.

Figure 3 shows that the rotation time is shortest on the wood surface. This means that a certain level of grip helps the rotation of Vibkinesis. On the contrary, the time taken to move is not significantly different for other surfaces. These data show that Vibkinesis can work on surfaces that we commonly use. Moreover, we confirmed that only an extremely strong frictional force, e.g., that on a carpet, can prevent movement.

Figure 3. (Left) Rotation times and (Right) movement times on each type of surface.

SAMPLE APPLICATIONS AND CAPABILITIES

We developed applications for different scenarios to show the capabilities of Vibkinesis.

Informing by Tapping (Direct Tap)

Sometimes, users might not notice smartphone alarms even when in close proximity to the phone. Vibkinesis informs the user of notifications by tapping the user's hand, in the same manner as being tapped by another person.

A simple direct tap, which constitutes moving to the user's hand then continuing to vibrate, is effective for a user wearing headphones. Moreover, Vibkinesis can move away from the user, and thus provides a repeat of tapping and moving away. An irregular tapping pattern might be more effective because the user is more likely to notice an irregular stimulus than a regular one.

Hand detection and movement to the user's hand are ineffective in case of obstacles (e.g., objects between the user's hand and the phone, or when the phone rests on an object, such as a book, placed on the surface). Moreover, if the phone and the user's hand are on the same surface, normal vibration transfers through the surface to the hand. However, this detection is influenced by parameters, such as how efficiently the table transfers vibrations, or the extent to which the user's hands move. Thus, tapping the hand is more *direct* for the user's tactile perception, under the condition that the phone can reach the hand.

Notification by Rotation (Dying Message)

When users are away from their smartphones, they obviously cannot observe any notifications, such as messages. Thus, once they return, they have to actively check their phones to see if they have a pending notification; otherwise, they risk missing it. Commonly, several solutions are adopted, such as displaying the message until the user can verify missed messages, or providing a notification at regular time intervals.

Vibkinesis adds a new notification channel: changing its orientation by rotating. If the smartphone has rotated, say, by 90° to the left when the user returns, the user might notice its abnormal appearance. In this application, the user can configure the combination of messages and rotation (direction and angle). For example, rotating 45° to the right per email received, or rotating 180° when a call from a designated person is received.

Vibkinesis can notify the user even after the smartphone's battery has been discharged. This is the capability of our proposal most distinct from other related work. For example, users should recharge the battery of their device if they expect important communication, such as an email. However, users sometimes do not notice that the battery has discharged. This is especially true when the user is away from the device. In such situations, displaying a message, such as "Remaining battery: X%," or using other alerts, is useless. Previous methods, including using shape-memory alloys, did not address and solve this problem. Obviously, alert-forever methods (displaying, alarming, and vibrating) cannot be used in this situation. Vibkinesis proposes another solution: informing the user of messages missed by its orientation change, even after the battery has discharged.

Vibkinesis also provides multiple data: that the battery is discharged, and there are (or there are not) important messages pending perusal. For example, if the battery was discharged and no messages were received, Vibkinesis rotates by a certain degree (e.g., 90° to the right); if the battery was discharged after receiving a call from a person identified by the user as important, Vibkinesis rotates by a certain additional degree (e.g., plus 45° , for a total of 135°). In this way, users can determine whether they have to recharge the battery as soon as possible.

DISCUSSION

Rotation Noticeability

We demonstrated our current prototype to several people at our university. Almost all individuals responded positively to our basic idea: if the smartphone had rotated 90° in their absence, they would have noticed the abnormal orientation. On the other hand, one of the people said that he would not be aware of the rotation because he always placed his smartphone in random orientations. However, he also indicated that he might notice if the device had rotated 180° because there is no reason to place a device on a table in an entirely inverted orientation. As this person mentioned, the

rotating resolution is important to notice. Attaching different messages to high resolutions, e.g., at every 5° rotations, the messages are difficult to distinguish. On the contrary, significantly low resolutions, e.g., 180° as the person suggested, can only be attached to few different messages. Therefore, it is necessary to investigate the best resolution for Vibkinesis.

Battery Life

The battery discharges faster with Vibkinesis because of the USB host power supply, the image processing, and the magnetic sensing. The problem of battery life cannot be considered independently of mobile systems. However, application designs help solve such problems, similar to Vibkinesis' dying message. With Vibkinesis, the user does not have to worry about remaining battery even if there is an important message.

Physical Limitations

Physical conditions, such as leaning and surface friction, influence the movement of Vibkinesis. In our operational verification of the prototype, the smartphone was not able to move along a steep slope that we intentionally created. Further, surfaces with very high or very low friction disturb its movement. Not all surfaces are suitable for Vibkinesis, but it can be used on flat surfaces made of wood, glass, and plastic, such as those used for daily work.

CONCLUSION AND FUTURE WORK

In this paper, we proposed Vibkinesis, a smartphone that notifies users by changing its orientation and by direct tapping. We built a proof-of-concept prototype by controlling vibronic movement. We introduced the capabilities of Vibkinesis in certain situations: when the user is away from the smartphone, after the battery is discharged, and when the user cannot hear the smartphone's alarm.

For our future work, we will investigate the rotation angle resolution most suited for Vibkinesis applications. Moreover, surface conditions should be tested more extensively. We will also look to develop other capabilities in Vibkinesis. For example, another approach to solve the problem of the battery being nearly discharged is to move to a wireless charging sheet. Further, we plan to test the usability of Vibkinesis in daily use after developing a more sophisticated, light-weight, and powerful version. The power of the current prototype is not sufficiently strong to move objects around it. If Vibkinesis had more power available, it can make its appearance more abnormal to inform the user of an important notification. For example, if stationery, cups, or other objects on the table have fallen to the floor while Vibkinesis is still on the table, the user would very likely notice the extraordinary circumstances. Vibkinesis will be able to create such notifications by interacting with the real world, which cannot be performed through screen displays, sounds, or simple vibrations.

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