Touchbugs: Actuated Tangibles on Multi-Touch Tables

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ABSTRACT

We present a novel approach to graspable interfaces using Touchbugs, actuated physical objects for interacting with interactive surface computing applications. Touchbugs are active tangibles that are able to move across surfaces by employing vibrating motors and can communicate with camera-based multi-touch surfaces using infrared LEDs. Touchbug's embedded inertial sensors and computational capabilities open a new interaction space by providing autonomous capabilities for tangibles that allow goal directed behavior.

Author Keywords

User interface device; actuated tangibles; interactive tabletops.

ACM Classification Keywords

H.5.2 [Information Interfaces and presentation]: User Interfaces - Haptic I/O.

INTRODUCTION

Tangible user interfaces (TUI) combine the dynamic qualities typical of digital information representations with physical affordances, i.e. "properties of an object that determine how it can be used" [5]. TUIs, in combination with multi-touch tables, provide passive haptic feedback for hand gestures and are augmented by a physical model for visual feedback. This allows people to interact with the input devices in the same way they interact with everyday objects, applying real world skills without the need for training or instructions. The benefits of these user interfaces include the simultaneous reduction of cognitive load placed on users (while they interact with an application) and simplification of the interaction itself. In contexts that are likely to include cognitive overload, time pressure, or stress, this may improve performance and even encourage improvisation and exploration [1].

Actuated TUIs allow data to be connected to, and represented by, physical objects (e.g. dynamic data can be linked to dynamics of the objects). They also facilitate more engaging, playful interaction and afford the use of movement as an expressive output modality. To date, approaches to connect actuated tangible user interfaces with interactive surfaces either require complex modification to, or augmentation of, the interactive surface hardware [4, 6, 8] or use constrained and relatively cumbersome tangible artefacts [2, 7, 10]. For example, Madgets are tangibles containing small magnets that are actuated using an array of electromagnets [8] (yielding a rather discontinuous movement). Marshall et al. [4] facilitate smoother and more accurate motion in their Ultra-Tangibles by applying ultrasound-based air pressure waves to actuate small lightweight objects on an interactive surface. In the few existing actuated tangible systems the possibilities for interaction are limited as the systems are essentially comprised of lightweight passive objects that are manipulated by an external applied force (i.e. electromagnetic or air pressure). Other designs have sought to enhance tangibles with wheels [2, 7, 10]; although wheeled objects are not entirely appropriate for direct interaction on interactive surfaces (i.e. they are not very robust and expose moving parts).

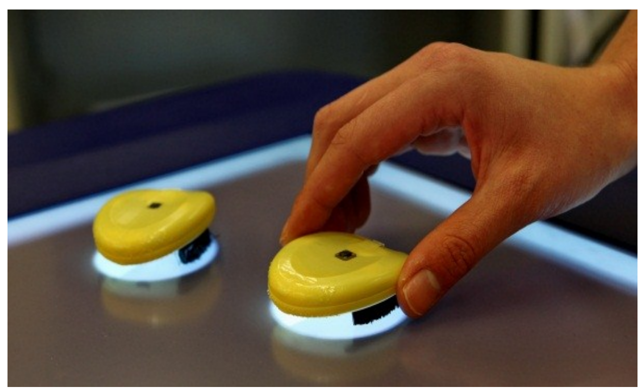

Figure 1. Touchbugs on a multi-touch table.

In this paper we present Touchbugs, an open source hardware and software framework for a novel actuated tangible technology [11]. Touchbugs are small tangibles that use directed bristles and vibration motors for actuation (giving them the ability to move independently). Their infrared LEDs allow multiple Touchbugs to both be spatially tracked (position and orientation) on optical multi-touch tables and to communicate information about their internal state to the table. Embedded inertial sensors, which capture displacement and orientation, provide rich opportunities for interaction design including direct physical manipulation, and symbolic and metaphorical gestures. This novel combination of sensing and actuation capabilities goes beyond simple changes of (virtual) states (e.g. by the use of buttons) offering significantly more potential of expressive interaction [1]. We present the design of Touchbugs and investigate the accuracy of the actuation in a number of experiments. Furthermore, we show how the embedded sensors can be used to stabilize the tangibles movement in an autonomous feedback loop.

MOTIVATION

Our aim was to develop a framework of autonomous, self-contained and controllable actuated tangibles. Our requirements for Touchbugs were: (i) that they are capable of smooth, continuous and controllable movement (both translational and rotational); (ii) that Touchbugs can sense their own movement and maintain internal state information independent of any external system; (iii) that the electronics are robust and compact and can readily enclosed by cases of different shapes and sizes; and (iv) that the integration of Touchbugs with optical multi-touch tables does not require hardware modifications or augmentations to the table.

TOUCHBUGS

A Touchbug consists of a 40×40mm printed-circuit-board (PCB), as shown in Figure 2, comprising a microcontroller, two vibrating motors, LEDs and several sensors. The PCB is located on two rows of bristles mounted at an angle of approximately 5° to the vertical (see Figure 1). A motor is mounted above each set of bristles, and the vibration generated by these motors causes a high frequency oscillating flexion of the bristles that results in a forward motion (or circular if just one motor is activated). LEDs on the underside of the Touchbug both allow optical multi-touch surfaces (i.e. FTIR or DI) to detect its position, and allow the Touchbug to transmit information to the table (see subsection *Detection on the table*). The embedded sensors (accelerometer and gyroscope) are used to stabilize the movement of the tangible and to sense physical interactions and manipulations (e.g. gestural manipulation). Custom bodies can be readily fabricated to enclose the PCB and the small and compact form factor of the PCB allows a wide variety of appearances and sizes. The Touchbugs shown in Figure 1 are 60×50×20mm; weigh 24g; and have a maximum (straight-line) velocity of 250mm/s.

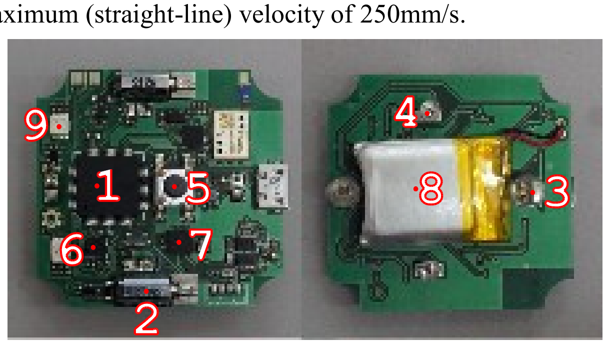

Figure 2. The Touchbugs PCB (upper and lower surface): (1) micro-controller; (2) left vibration motor; (3) rear LED; (4) right phototransistor; (5) button; (6) accelerometer; (7) gyroscope; (8) battery and (9) right colored LED.

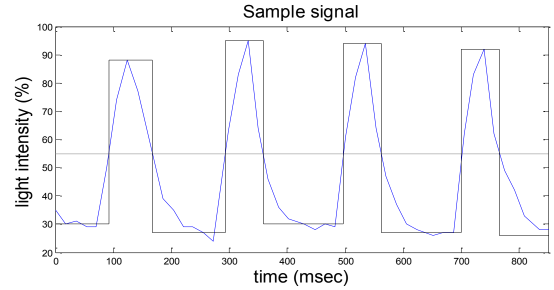

Figure 3. An illustration of the light signal which is sent by the tangibles LEDs.

Detection on the table

An optical multi-touch surface can detect and process the signal from a Touchbug's infrared emitters and thus receive information from them. As illustrated in Figure 3 both amplitude modulation and frequency modulation are employed to communicate information. The amplitude corresponds to the intensity of the infrared diode, and the frequency is the reciprocal of the amount of time between the signal peaks. Additional data (e.g. a button click) can be transmitted by actively modulating the pulse duration (pulse-width). Each LED transmits a distinct signal, which is detected by the camera of the interactive surface as a touch event. The fixed distance between these pseudo-touch events (generated by the LEDs), combined with unique signal frequencies for each LED, allows the detection and identification of multiple Touchbugs (up to half the number of touch events that the interactive surface API supports). Furthermore, by following conventions for setting the two frequencies (i.e. *left* < *right*), the orientation of the tangible can be sensed by the table (to a precision of less than 5°). Parts of the implementation rely on Touchbridge [3].

Actuating the tangibles

We experimented with various different kinds of materials, but discovered that fine and soft bristles worked best. Our final design utilized bristles from consumer off-the-shelf draught excluders that were trimmed to lengths from 7-17mm and attached to the underside of the PCB. Touchbugs can be steered using differential control of the two motors mounted on the top-side of the PCB above the bristles.

Due to factors such as irregular surfaces and slight differences in the lengths of bristles, the Touchbug is unlikely to move by default in a straight line, consequently a feedback control loop is required to stabilize the motion. While the process of control could be managed by the tabletop (indeed, it already measures a Touchbug's orientation), experiments showed that due to latency in the communication between a Touchbug and the table the required control loop could not be maintained. Instead we manage the control of a Touchbug on the tangible itself. A Touchbug senses its deviation from its initial orientation using the gyroscope. The gyroscope measures the angular velocity of the device around three perpendicular axes. However, the measured angular velocity is subject to noise resulting from the vibration of the motors. As illustrated in

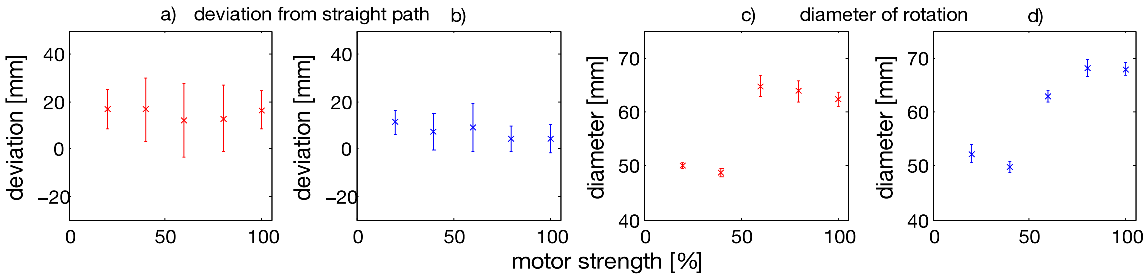

Figure 4. Results from two different experiments. The two leftmost graphs show the absolute deviation from a straight path for 5 different motor settings and 2 different lengths of bristles (red short, blue long). The two rightmost graphs show the diameter for circular motion (just one motor active).

Figure 5, this noise is normally distributed between ± 50°/s. As can been seen in Figure 5, when the tangible is rotating, the measurements significantly exceed this noise-level, although this can be a problem for extremely slow turn rates. We implemented a basic approach to direction control, in which a counter steering motion is induced if the angular velocity exceeds a certain threshold. This counter steering consists of increasing the strength (i.e. speed) of the inside motor (relative to the turn deviation), linearly to the absolute deviation from the initial orientation. This deviation is easily estimated by integrating the rotation measurements over time. Both the threshold from which to start compensating for drift as well as the coefficient that controls the strength of the counter steer, were estimated empirically to work best with medium speed motion.

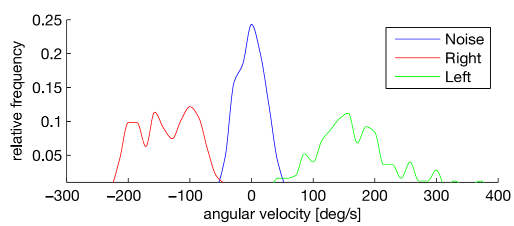

Figure 5. The distribution of angular velocity.

Steering the tangibles

A Touchbug has two phototransistors, one next to each set of bristles on the underside of the PCB (see component 4 in Figure 2). These point towards the interactive surface of the table and are sensitive to both visible and near infrared light. As the phototransistors are affected by ambient and infrared light – and due to the variability in ambient light levels – we restricted ourselves to displaying three light intensities on the surface which the Touchbugs can reliably detect and distinguish: black, grey and white. Displaying these colors is the mechanism by which the table can control the Touchbug. When a light level is detected, the Touchbug sets the strength (speed) of its corresponding motor accordingly. Using white, black and grey semi-circular patterns displayed directly under the Touchbugs, the table is able to start, stop and steer multiple tangibles at the same time. Different configurations of pattern result in different motions as illustrated in Figure 6. In retrospect, to improve the communication channel between the table and the Touchbugs, the phototransistors could have been replaced by ambient light sensors, which are only sensitive to visible light. This would increase the range of detectable intensity levels and therefore afford higher bandwidth and more reliable communication.

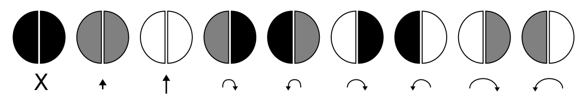

Figure 6. Semi-circles projected below the tangible that can be used for steering. Three colors result in 9 possible motions.

To steer the Touchbug to a specific target, first the angle between the direction of the Touchbug and the direction to the target is calculated using simple trigonometry. However, calculating this angle, rotating the Touchbug accordingly and starting a forward motion is bound to fail, as any rotating motion will also displace the device. Therefore a more sophisticated control mechanism is required. Given the estimated angle it is straight-forward to derive whether the device has to turn left or right to face the target. After initializing the turning motion, the angle between the current direction and the direction to the target is continuously estimated. Once this angle is below a certain threshold the forward motion is initiated. This procedure results in a smooth and natural, slightly curving path from the source position to the target.

EVALUATION OF THE ACTUATION

To assess Touchbug's movement abilities, we conducted two experiments. The first explored the accuracy of the automatic path correction based on the gyroscope measurements for different motor strength settings and bristle lengths. The tangibles were placed on a multi-touch table (SMART^{TM} table) and instructed to cross the available surface by following a straight-line path (10 runs for each motor setting and bristle length, 7mm and 17mm). The results are shown in Figure 4. Graphs (a) and (b) show the absolute deviation from the straight-line path measured after the device travelled for 500mm across the table. Long bristles (b) show less deviation from the path and also a smaller standard deviation compared to short bristles (a). Overall we have not found significant differences in the precision of the automatic path correction for different motor settings. Furthermore, the mean absolute deviation remained below 20mm for all bristle lengths and strength settings tested, less than the size of the actual PCB of the Touchbug.

The second experiment investigated how the motor strength influences the turn-rate of the device. The Touchbug was placed on the multi-touch table and instructed to turn in a circle (just one motor active, 10 runs per motor strength setting and bristle length). The diameter of the resulting circle was measured and the results are reported in Figure 4. Both the short bristles (c) and the long bristles (d) show a very similar relationship between diameter and motor strength setting. When increasing motor strength the diameter initially decreases, after which a sharp jump in circle diameter was observed. We believe this is due to the friction of the bristles on the surface. Up until a medium motor strength setting the friction of the inner, non-vibrating bristle exceeds the drag produced by the forward motion by the vibrating bristle, resulting in a sharp rotation. On higher motor settings the inner bristle begins to slide across the table resulting in a sharp increase in turn diameter.

Limitations of the system

Touchbugs have a number of clear limitations. The tangibles cannot rotate around their center, or move backwards and therefore can get stuck in the corners of a table. Another drawback is the optical tracking of the devices. The infrared diodes have a high intensity; nevertheless the tracking accuracy suffers when the lighting conditions change significantly. The number of Touchbugs that can be used simultaneously is constrained by the number of touch points that the multi-touch surface API can support. Although in theory there are no technical limitations on how many tangibles can be used, to date we have only used five simultaneously. Improvements in table hardware such as increasing the frame rate of the camera, along with more efficient algorithms would reduce latency and increase the bandwidth of the Touchbug-to-table optical communication.

INTERACTION CAPABILITIES

Due to the data set which is transmitted through the accelerometer and the gyroscope a wide range of additional features is in fact available. These sensors allow the recognition of simple motions (like tapping on the device) or gestures such as shaking, which could be used as a direct input or captured for later analysis [9]. Furthermore, we implemented the possibility to couple digital content to the Touchbug – such as 3D objects displayed on the table. When the user rotates the device in his hand, the digital object rotates according to the tangible. The device can also detect if it is laid on its back or if a user is holding it (using simple motion classification). In this case, the vibrating motors can be used as an output to provide variable haptic feedback or to attract the attention of the user. Furthermore, actuated tangibles also have the potential to support collaborative use across more than one remote table (or independent Touchbugs), for example, when a remote user working with the same system moves a tangible, changes can be reflected on a connected table (or Touchbug).

CONCLUSION

In this note we presented Touchbugs, a novel actuated tangible user interfaces framework which can communicate with interactive surfaces. We have characterized Touchbug's actuation and demonstrated its potential as an affordable yet uniquely expressive interaction device for optical multi-touch tables.

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