StickEar: Making Everyday Objects Respond to Sound

Kian Peen Yeo
yeokianpeen@sutd.edu.sg

Suranga Nanayakkara
suranga@sutd.edu.sg

Shanaka Ransiri
shanaka@sutd.edu.sg

Augmented Senses Group, International Design Center, Singapore University of Technology and Design.

Figure 1. StickEar prototype: (a) Deploy on an object. (b) Press to activate. (c) Rotate to tune. (d) Shake to reset (e) Redeploy on another object.

ABSTRACT

This paper present StickEar, a system consisting of a network of distributed 'Sticker-like' sound-based sensor nodes to propose a means of enabling sound-based interactions on everyday objects. StickEar encapsulate wireless sensor network technology into a form factor that is intuitive to reuse and redeploy. Each StickEar sensor node consists of a miniature sized microphone and speaker to provide sound-based input/output capabilities. We provide a discussion of interaction design space and hardware design space of StickEar that cuts across domains such as remote sound monitoring, remote triggering of sound, autonomous response to sound events, and controlling of digital devices using sound. We implemented three applications to demonstrate the unique interaction capabilities of StickEar.

Author Keywords

Distributed tangible user interfaces (dTUI), wireless sensor networks, sound based interactions

ACM Classification Keywords

H.5.2. User Interfaces: Interaction styles; K.4.2. Social Issues: Assistive technologies for persons with disabilities

General Terms

Design

INTRODUCTION

Spatial anchoring of visual information on physical objects through the use of paperbound materials is a common method for leaving tangible bits of information to facilitate non-verbal communication. Tagging objects and places with visual information using product labels, price tags, and signboards etc., has become a part of our daily lives. Often these visual tags are static and always visible. Sticky notes are special purpose visual tags used for temporal anchoring of visual information, with the flexibility of being redeployed to another object and space [28]. With StickEar, we propose a method to empower people with the ability to deploy acoustic tags on any objects or space, and be well informed of acoustic cues that may be produced by an object or a location.

We live in a world surrounded by sensors. They can either be embedded in a device that we carry around, or be a permanent installation at a location [37]. While having a portable feature-packed device (such as a mobile phone) with multiple sensors embedded may seem to be an 'all-round' solution for many applications, it might not be a cost effective solution when having to deploy multiple devices at various locations. Hence, dedicated low cost sensor devices are often deployed in large sensor networks [4]. Distributed sensor networks pose a different problem, as they are often seen as an expert device that can be complicated to set up and deploy [25]. They are often semi-permanent installations that are not meant to be redeployed on a frequent basis. With StickEar [40], we want to bring together the advantages of portability, accessibility and re-configurability into a single system.

With StickEar, users can simply 'stick' a StickEar sensor node onto an object to enable sound based interaction. The tangible user interface of StickEar allows users to interact with the device by pressing, turning and shaking (Figure 1). Contributions of this work include a discussion of the interaction space of StickEar, exploration of associated hardware design space, development and evaluation of the prototype system, and demonstration of a few examples of StickEar enabled applications.

RELATED WORK

Sound based Interactions

Sounds generated by everyday objects (e.g. doorbell, microwave oven, etc.) and sound in spaces (conversation, thunder etc.) act as important awareness cues for us to understand the state of the world around us [18]. In addition, sound is perhaps the most natural 'active' form of two-way communication since human hear and produce sound naturally [10]. The use of sound as a output for tangible interactions has been explored in various research areas [17, 1]. Scratch Input [15] for example, transforms the unique sound produced when dragging a fingernail on a textured surface into various gesture inputs to the surface. PingPongPlus [21] is a novel interface for digitally augmented cooperative play. It uses the sound from a ball

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hitting the table in a game of table tennis as an input to create a digital augmentation layer on the physical table. StickEar builds upon this concept of using sound as an input to transform objects into one that is interactive.

Tangible User Interfaces

Ishii and Ullmer proposed the concept of tangible bits as a means to bridge the gaps between the digital and physical world, as well as the foreground and background of human activities [20]. The use of dTUIs is demonstrated in Siftables, a research project which became a successful commercial product [27]. Siftables applies the technology and methodology from wireless sensor networks to a touch and gesture based TUI with graphical displays, allowing the physical interaction of digital information. In addition, Lucero et al. [24] implemented a network of mobile devices to demonstrate spacial and tangible interactions. In StickEar, we harness the idea of having wireless tangible bits but instead apply it on interactions with sound.

Connectivity

Interconnecting real-world objects in the digital domain provides an opportunity to perform collaborative and cooperative behaviours [12, 38]. Ninja Blocks [2] and Twine [3] are two commercial products that integrate wireless sensor monitoring into a cloud-based service over the Internet. They both feature an intuitive ‘rule-based’ configuration method to replace traditional programming for setting up the device. In addition, apart from the inbuilt sensors that come along with the device, they both allow external sensors to be connected through connectors. We recognize the potential of ‘Internet of Things’ [36], and the notion of these devices providing ‘just in time information’. With StickEars, we want to provide users with the ability to stay connected and be aware of their surroundings, and at the same time, make the experience intuitive through an inbuilt TUI on the device.

Augmented Objects

Augmenting objects with digital capabilities is getting increasingly popular as computing power gets cheaper and smaller [22, 26, 5]. A framework for object augmentation was proposed by Guerrero et al. [11], and some researchers have focused on building generic and extensible infrastructure to make smart objects [32, 19, 35, 34]. Sensor network technology for object augmentation is challenging and interesting to the extent of overshadowing its applications [30, 33]. However, recently, Sato et al. [31] proposed a novel capacitive sensing technology, Touché, to enhance touch gestures on everyday objects and a rich set of potential application domains. StickEar follows a similar approach where we present a method to augment objects based on sound and present a compelling set of potential StickEar-enabled applications.

INTERACTION DESIGN SPACE

Through the design of a sound-based wireless TUI that is easy to deploy and configure, we seek to explore possible interaction techniques and gain insights on novel applications enabled by this device. The interaction space of StickEar is broad, covering both input and output domains. We identified four possible interactions that support the redeployability nature and collaborative structure of one or more StickEars: (a) Remote monitoring of sound events; (b) Remote triggering of sound output; Autonomous response to sound events; (d) Sound as a controller.

Remote monitoring of sound events (input)

A StickEar can be attached to an object or to a specific space to ‘listen’ for sound events. Attaching StickEar facing an object would capture sounds on and very close to the object whereas attaching StickEar facing outwards would capture sound events from a much wider space. A user could change the range of detection by adjusting the sensitivity of StickEar. StickEar as an input device opens up many application possibilities including security monitoring, ubiquitous data collection [23], activity monitoring [39] and as an assistive tool for the deaf [18]. In addition, as an input sound-monitoring device, we see a potential of deploying multiple StickEars for applications such as sound source localization [13].

Remote triggering of sound output (output)

Misplacing objects can be a frustrating experience, and one would often hope that the object could somehow respond to your calls and tell you where it is. StickEar as an output device could act as a ‘voice’ for inanimate objects. Finding appropriate sounds that add to the affordances of an object [6] would make this interaction more interesting. StickEar can even be used to transform everyday objects into sound sources [8] and multiple StickEars could potentially collaborate to provide a multichannel audio output.

Autonomous response to sound events (input/output)

In this interaction space, a StickEar is used as an input and output device at the same time. A sound input event triggers an immediate sound output on the same StickEar. This interaction can be explained with an example of using StickEar as a baby monitor. StickEar is placed near a baby’s crib and configured to detect the sound of a crying baby. Upon detection, it responds immediately by playing a lullaby. This interaction could be based on the amplitude of the sound (exceeding a threshold) or, more interestingly, could be based on StickEar having the ability to perform classification of sound. Multiple StickEars in this interaction domain could be used to provide a better user experience for spaces such as museums and art exhibitions [16].

Sound as a controller (controller)

StickEar having the ability to perform classification of sound could function as a wireless controller using different sound inputs. For example, users could control personal digital devices or electrical appliances by snapping their fingers, tapping on StickEar or possibly ‘talking’ to it. Additionally, similar to PingPongPlus [21], a user would also be able to turn any surface into an interactive surface by attaching a single or multiple StickEars.

Apart from the above interactions, composite interactions between StickEars opens up new possibilities. One example scenario is where one StickEar is configured as an output device for locating objects, while another configured as an input device for sound event monitoring. A user triggers the alarm on one StickEars (configured as an output) but he/she is not in the range to hear the sound. However, another StickEar (configured as an input) within the vicinity can pick up this alarm sound and send a notification to the user informing him/her about the location of this sound event. This then allows a user to find an object from a remote location.

HARDWARE DESIGN SPACE

In the design of StickEar, our objective was to provide users with a device that enables sound based interactions with the environment. We want to emphasize on a wireless and portable device with a tangible user interface that is easy to deploy and configure. In this section, we will discuss the design space for possible hardware implementations that would support our proposed interactions.

Scope of recognition

We define two scopes of recognition: *level* and *class*. In its most basic configuration, the device is able to detect sound exceeding a user defined amplitude (*level*). This can be further sub-divided into two categories: localized detection of sound on or in close proximity to an object, or spatial detection of a particular space. Given the ability of the device to capture sound, it would be useful to be able to recognize a particular type of sound (e.g. clapping or knocking). As such, we define the second scope of recognition as the ability to recognize a certain type of sound (*class*).

Sound input measurement

We take into consideration two specific characteristics of sound (*amplitude* and *frequency*) for determining the required microphone hardware for sound measurement. The amplitude or loudness of sound is one factor that determines how far it can be heard from a distance. For example, softest sound a person can hear with normal hearing is 0 dB; normal conversation is about 60 dB; and baby screaming is about 110 dB. An amplifier circuit with tuneable gain settings gives users flexibility in detecting various sound *levels*. In terms of frequency, many common sounds at home fall in the range below $8kHz$ [10]. The sampling rate of the microphone signal should be at least $16kHz$ in order to capture these frequencies.

User input

A user physically interacts with the device to perform various tasks such as choosing between different modes of operation, tuning of sensitivity, executing or cancelling a selection and resetting. User inputs can be based on direct contact with the device such as pressing, turning, touching, shaking and bending. Indirect user inputs can be sound based, taking advantage of the microphone which is essential to the device. While a single capacitive touch screen would allow a user to perform these tasks through different touch gestures, it comes with high power consumption and large physical size. Use of traditional mechanical input devices such as push button switches and rotary encoders overcome some of these constraints. In addition, the affordances provided by these mechanical input devices and their corresponding functions are well established in many existing devices [9].

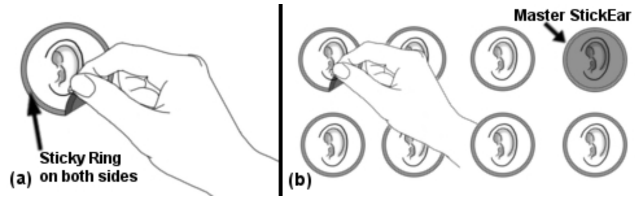

Figure 2. Envisioned form factor of futuristic StickEar

Output

Generally, feedback from StickEar to a user would be provided by using one or a combination of methods such as tactile, audio or visual. Audio and visual feedback in particular have an extended range while tactile feedback requires physical contact with the device itself. Audio feedback can be easily provided by a miniature speaker. Visual feedback in the form of display screens is popular because of the vast amount of information it can provide. However, the versatility of a single point light should not be underestimated. Harrison et al. [14] evaluated 24 different light behaviors from a single color light emitting diode (LED), of which eight were recommended for use in a mobile domain. With a tri-color LED, the amount of information that can be expressed can be multifold. For non-complex applications involving several different states, a single point light offers advantages in terms of power consumption and physical size.

Communication

Each StickEar could potentially have a direct internet access though a WIFI module built into it. Alternatively, connectivity could be achieved indirectly by establishing a local connection to a special StickEar that has an internet connection. Out of the numerous options for establishing wireless communication (bluetooth, WIFI, RF transceivers etc.), bluetooth and RF require low energy. However, an RF network with proprietary protocol might provide a computationally light weight and optimised solution in terms of power consumption and packet overhead.

Form factor

One of the motivations for StickEar came from the idea of sticky notes. Sticky notes come in a thin flexible paper material, with user inputs coming from an ink medium and providing an output that is visual based. Sticky notes unlike other writing mediums, offers a unique feature of being easily deployable through the use of a special non-permanent adhesive. The form factor of StickEar needs to be small, lightweight and possibly flexible too, so that it can be easily attached to flat or uneven surfaces using special reusable mounting tape or suction cup tape (Figure 2a). The electronics can be encapsulated in a waterproof flexible material that is acoustically transparent and users can interact with the device through touching, pressing and bending gestures. The device would be highly energy efficient and could harvest energy from its environment [29]. We envision

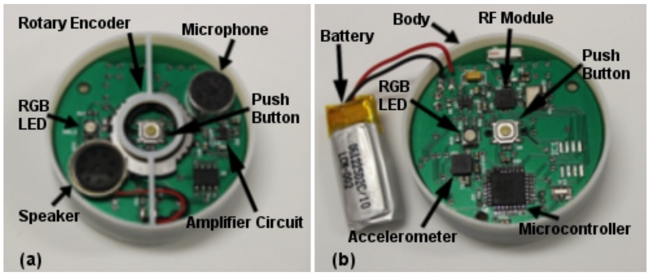

Figure 3. StickEar main board (a) front and (b) back.

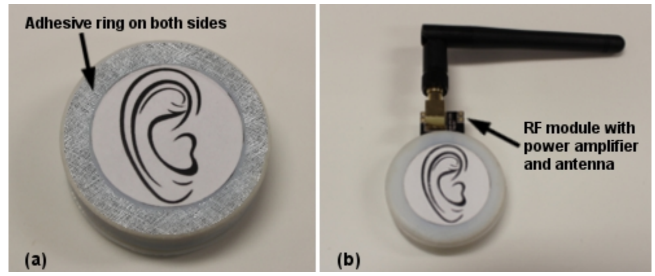

Figure 4. (a) StickEar sensor node. (b) Master StickEar

that future StickEars will come as a sheet of stickers where users simply peel them off to attach to different objects (Figure 2b). It is important to design this thin form factor with a thickness that would not fundamentally change the user interactions.

STICKEAR

Based on the hardware design considerations in the previous section, we developed a proof-of-concept prototype of StickEar. The system consists of multiple StickEar sensor nodes that are wirelessly interconnected. In addition, a 'master StickEar' is used for relaying messages from sensor nodes to other external devices, if necessary.

Hardware Implementation

StickEar sensor node

At the heart of the StickEar sensor node is an ATMEGA328 8-bit microcontroller running at 8 MHz. A 3.3V lithium polymer battery provides power to the device. Inputs to the sensor node include a microphone, rotary encoder, push button switch and an accelerometer. A tri-color LED and speaker are used for visual and audio feedback respectively. Wireless connectivity between sensor nodes is provided by an nRF24L01 2.4 GHz radio transceiver. Hardware design of StickEar sensor node is shown in Figure 3.

Sound Acquisition: An omni-directional electret microphone with a sensitivity of -44 dB is used for capturing sound. An op-amp circuit configured as an inverting amplifier is used to amplify the signal from the microphone so as to maximize its dynamic range. In addition, the signal gain can be adjusted programmatically using a digital potentiometer. The amplified signal is then sampled at $20kHz$ by the microcontroller, allowing frequencies up to $10kHz$ to be measured accurately.

Input: In the current prototype, a user interacts with StickEar through three basic input gestures. By rotating a cylindrical ring sandwiched between the top and bottom faceplates (connected to a rotary encoder), a user can choose between different modes of operation as well as adjust the sensitivity. A push button switch located at the center of both the front and back of StickEar allows the detection of the pressing gesture. A 3-axis accelerometer (ADXL335) is used to detect a shaking gesture, which is associated with resetting the device to its main function selection menu.

Output: Two types of output feedback are available to the user. Visual output is provided by a tri-color LED located on both the front and back of the device. Different colors are used to represent a different mode of operation. Thus as a user cycles through the main mode selection menu, StickEar will light up with a corresponding color. A periodic blinking light sequence is used to indicate the occurrence of an event on the device. Also, a change in intensity of the light output provides an indication when adjusting the sensitivity. Audio output from a miniature speaker is used when StickEar functions as an output device to a remote sound triggering application.

Form Factor: Current prototype version of the StickEar sensor node is a rounded shaped 3D printed plastic case (Figure 4a). The outer casing is designed such that it has a flat front and rear surface with reusable ring shaped adhesive along the perimeter of both sides. This allows the StickEar to be easily deployed and redeployed on different objects.To differentiate between localized and spatial hearing, an ear pictogram is printed on one side of the casing to indicate hearing directionality.

Master StickEar

The master StickEar uses an nRF24L01 transceiver with a power amplifier. It has a similar form factor to a StickEar sensor node except a more powerful RF antenna (Figure 4b) for an extended range of communication with other StickEar sensor nodes. A Bluetooth module in the master StickEar allows communication with a Bluetooth enabled computing device. We recognize the limitations with range in Bluetooth connectivity, but this current implementation is sufficient to demonstrate the interactions we are proposing. In the next design iteration, we would extend the connectivity of StickEars to be Internet enabled through a master StickEar that has an embedded WIFI module.

EXAMPLE STICKEAR APPLICATIONS

Based on the previous discussion on interaction design space, we developed three specific applications to demonstrate the capabilities enabled by the device. These applications allow StickEar to function as an input device, output device and/or a remote controller.

ObjectListener

In this particular application, StickEar operates as a remote input device, providing a notification to a user upon detecting a sound. An application on a Samsung Galaxy Nexus smartphone (service running in the background) was developed to establish pairing with the master StickEar for receiving notifications from sensor nodes. Setting up StickEar as an object listener is simple, as a user only needs to attach StickEar to the object (Figure 5a), initiate a one-time

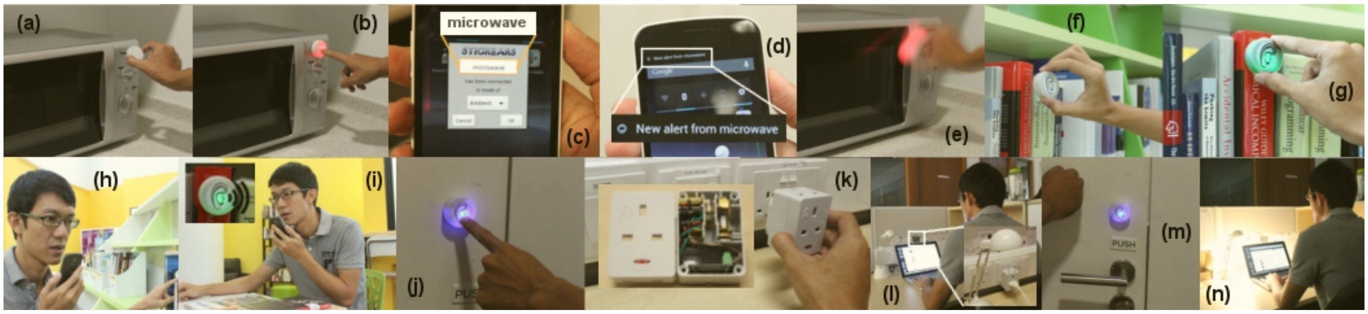

Figure 5. StickEar enabled interactions. (a) Deploying StickEar on a microwave; (b) Press to pair with the smartphone application; (c) Enter a text label and notification type; (d) Receiving an ambient alert form the microwave; (e) Unsticking and shaking to reset; (f) Redeploying on a bookshelf; (g) Rotating to select 'ObjectFinder' mode; (h) Assigning a voice tag; (i) Voice command to find an object (StickEar triggers an alarm); (j) Augmenting a door as a remote controller; (k) Augmented plug that receives notifications from 'master' StickEar; (l) Table lamp is connected to the Augmented plug; (m) Sound event on the door; (n) Table lamp lights up.

pairing request by manually triggering a sound event on the object for the first time (Figure 5b). This pairing request message is relayed to the smartphone application via the master StickEar. In response to the pairing request, a user provides a text entry (Figure 5c) to label the object which is then stored together with the wireless ID of the sensor node in the phone database. In addition, the user has the option to choose to receive either an alert (pop-up message on the screen) or ambient notification (task bar message) for subsequent sound events on that object (Figure 5d). To reuse and redeploy StickEar, a user simply detaches it from the object and gives it a shake to remove its association with the object (Figure 5e).

ObjectFinder

StickEar when used as an output device, can function as an object finder by producing a sound output that can be remotely triggered by a user. We developed another application on the same smartphone to enable StickEar as an object finder. An object can be tagged with a sound by attaching StickEar to the object (Figure 5f), selecting it to operate in output mode and initiate a pairing request to the mobile device by pressing on the exterior face plate of StickEar. Upon receiving the pairing request on the mobile application, the user can assign a voice tag to the object by speaking into the phone (Figure 5g), in which a speech to text service (Google Voice) will convert the voice tag into text, which is then stored in the application's database. To locate the object at a later time, the user can simply launch the application on his or her device and issue a voice command (Figure 5h). This then triggers an alarm sound output on the corresponding StickEar sensor node (Figure 5i).

LightController

In the last application example, we developed a sound awareness tool [18] for the deaf. We demonstrate this by modifying an electrical adaptor plug, adding the same RF module used in StickEar sensor nodes together with a microcontroller and a relay switch (Figure 5k). A deaf user connects the power supply of the device (in this case a table lamp – Figure 5*l*) into the modified plug and deploys a StickEar sensor node to an object or a location (Figure 5j). Whenever the sensor node detects a sound event (Figure 5m), it activates the relay on the plug turning the device on to inform the user (Figure 5n).

DISCUSSION AND CONCLUSION

In our preliminary experiments, we noticed that the external casing contributed to a drop in the sensitivity of sound reception of StickEar. Extending this range with a higher gain value on the amplifier would be challenging as it would also decrease the signal to noise ratio. It was difficult to implement advanced classification algorithms due to limited speed and memory of the microcontroller used. There was a need to balance between processing speed and power consumption, as a faster microcontroller would have high power requirements. However, initial experiments shows that, with limited speed and memory resources, StickEar can be trained to detect impulsive sounds.

In multi-user scenarios, to prevent data from being sent to a wrong master StickEar, a sensor node can be easily paired to the master by perhaps tapping both together to indicate their primary association. In terms of interactions, we plan to develop a comprehensive conceptual interaction model of the device. It is important to note that the social, economical and ethical effects of extensive integration of ubiquitous computing into our everyday life with devices like StickEar is yet to be determined [7]. We plan to conduct a user study to understand how users would react to some of the suggested applications, and possibly see if they would come up with any other novel interactions.

We would consider the possibility of a flexible multi-layered printed circuit board design to bring StickEar closer to a more sticker-like form factor. If an external casing is necessary to water-proof the electronic components, the casing can be printed on flexible material. It would be interesting to explore the acoustic properties of the casing material, having an acoustic transparent material on one side and an acoustic shielding material on the other. Alternatively, the use of directional microphones can be considered. Using a faster and more powerful microcontroller or digital signal processing chip would perhaps open up more possibilities given that it would be possible to have higher sampling rates and more complex algorithms for signal processing. To overcome the problem of power usage with a faster microcontroller, the firmware could be designed to be interrupt driven and set to low power mode during idle states. While the form factor of the current StickEar prototype is far from being a true thin sticker-like device as we envision for the future, the device was sufficient to provide us with capabilities to explore various possible sound based interactions.

In this paper, we presented StickEar as a tangible bit that can be redeployed and reused easily for sound-based interaction with everyday objects. Based on the explorations of the interaction and hardware design space, we implemented and evaluated a functional prototype of the StickEar system. StickEar enabled interactions were demonstrated by developing three specific example applications. We envision StickEar to be an empowering personal device that anyone would carry and use everyday to augment objects and spaces.

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