Earables for Personal-Scale Behavior Analytics

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The rise of consumer wearables promises to have a profound impact on people's lives by going beyond counting steps. Wearables such as eSense—an in-ear multisensory stereo device—for personal-scale behavior analytics could help accelerate our understanding of a wide range of human activities in a nonintrusive manner.

The era of wearables has arrived. As more established forms of wearables such as timepieces, rings, and pendants get a digital makeover, they are reshaping our everyday experiences with new, useful, exciting, and sometimes entertaining services. Millions of people now wear commercial wearables on a daily basis to quantify their physical activity, social lifestyle, and health.[1] However, for wearables to have a broader impact on our lives, next-generation consumer wearables must expand their monitoring capabilities beyond a narrow set of exercise-related physical activities.

One of the barriers for modern wearables in modeling richer and broader human activities is the limited diversity of the embedded sensors. Inertial sensors, such as gyroscopes, are constrained to track motion activities; microphones are primarily limited to conversational activity sensing; and radio-wave-based sensing primarily works for proxemic context detection. Also, many noncommercial academic endeavors exploring newer wearables with ambitious modeling targets suffer from poor ergonomics, limiting large-scale studies and experimental trials. We argue that one way to address these challenges is to leverage a form factor with an already established function and augment it with diverse, established sensing modalities while maintaining its ergonomics and comfort. Indeed, several recent wearable initiatives, including smart eyeglasses[2] and smart wristbands,[3] aimed at modeling medical-grade biomarkers but allowed open data access to spur new research. We envision that wearables equipped with multimodal sensing and real-time data accessibility could foster new research leading toward a comprehensive understanding of various human behavioral traits in a nonintrusive manner. Such understanding will uncover opportunities for new and useful applications in the areas of precise, predictive, and personalized medicine; digital, physical, mental, and social well-being; cognitive assistance; and sensory human communication experiences.

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To this end, we present eSense, an in-ear multi-sensory high definition wireless stereo device in an aesthetically pleasing and ergonomically comfortable form factor. eSense offers a set of APIs to allow developers to record real-time data streams of different sensors and to reconfigure different system parameters suitable for behavioral inferences. We briefly discuss the system's design and development and its potential in a wide range of research studies and applications in personal-scale behavior analytics.

DESIGN DYNAMICS

Wearables with many embedded sensors are now mainstream. Many of these wearables manifest in traditional forms—for example, a wristband, smartwatch, or pendant. As such, a new wearable form demands careful design assessment from multiple perspectives including ergonomics, aesthetics, functionality, and interaction usability. We have chosen the wireless earbud for efficient, robust, and multimodal sensing of behavioral attributes for the following benefits:

- *Established functionality*. Earbuds are already integrated into people's lives, and provide access to high-definition music during work, commuting, and exercise. Earbuds also allow people to make hands-free calls. eSense, first and foremost, is a comfortable earpiece capable of producing a high-definition wireless audio experience in a compelling form, but it has added sensing functionalities. Consequently, eSense seamlessly augments established earpieces without demanding changes to users' current behaviors.
- *Unique placement.* The ear is a relatively stationary part of the body, so placement of a sensing unit in the ear offers two concrete benefits. First, due to the stationary nature, sensory signals (accelerometer, gyroscope, audio, and so on) are less susceptible to motion artifacts and external noises. So, sensor data carries accurate and precise information concerning recognition of physical and conversational activities in comparison to other wearable devices such as those worn on the wrist. Such signal clarity has a profound impact on the robustness of sensory models. Second, placement in the ear enables earables to monitor head and mouth movements, in addition to whole-body movements, in a noninvasive way. This unique capability creates opportunities for many novel applications in the areas of personal health, dietary monitoring, and attention management.
- *Privacy-preserving interaction.* Earbuds are intimate and discreet, enabling users to have immediate and hands-free access to information in a privacy-preserving and socially acceptable way. Other wearable form factors typically demand explicit actions and attention from users, but earbuds can deliver auditory information even when a user is mindfully engaged in a physical or social activity.

Wireless earbuds provide users with freedom of movement and hands-free interaction, minimizing situational disability and fragmentation of attention. In addition, earables can be worn for many hours without any impact on primary motor or cognitive activities. These advantages collectively shaped our design decision to select the earbud as an ideal wearable platform for personal-scale behavior analytics.

eSENSE

eSense is designed to be able to track a set of head- and mouth-related behavioral activities including speaking, eating, drinking, shaking, and nodding, as well as a set of whole-body movements. Automatically tracking these activities has profound value to various applications in the areas of quantified lifestyle, computational social science, healthcare, and well-being. While these application areas benefit from a diverse range of sensory signals including audio, motion, orientation, photoplethysmogram (PPG), temperature, and galvanic skin response, we designed eSense with three sensory channels—audio, motion, and Bluetooth Low Energy (BLE) radio. Three aspects influenced this design decision: the physical dimension of the eSense printed circuit board to maintain the aesthetics and comfort, the minimization of signal interference from adjacent sensors, and the maximization of battery life to offer the primary functional service: high-definition music playback.

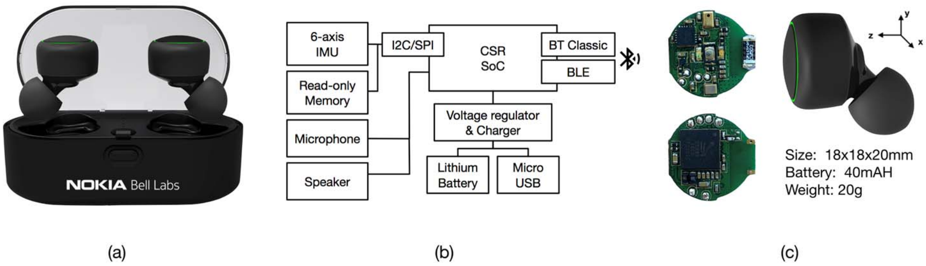

Figure 1. eSense system. (a) Audio, motion, and Bluetooth Low Energy radio sensing are powered by a CSR processor and a 40-mAH battery. (b) Schematic design. (c) Front and back of the printed circuit board.

Hardware

Two main concerns drove the hardware design of eSense (see Figure 1): physical size and functional requirements. Physically, we wanted eSense to equal the size of a standard wireless earbud (including battery, electronics, and all outside connections) to ensure that it could be worn naturally with comfort. Functionally, we wanted eSense to permit reprogramming the sensors and recharging of the battery by users. Taking both of these concerns into account, we used a custom-designed 15 × 15 × 3 mm PCB. eSense is composed of a Qualcomm CSR8670, a programmable Bluetooth dual-mode flash audio system-on-chip (SoC) with one microphone; a TDK MPU6050 six-axis inertial measurement unit (IMU) including a three-axis accelerometer, a three-axis gyroscope, a digital motion processor, and a two-state button; a circular LED; associated power regulation; and battery-charging circuitry. There is no internal storage or real-time clock. We opted for an ultra-thin 40-mAh LiPo battery to provide the system with power. This battery offers a reasonable energy profile: 3.0 h of inertial sensing at 50 Hz and 1.2 h for simultaneous audio sensing at 16 kHz and inertial sensing at 50 Hz. The carrier casing is equipped with an external battery enabling recharging of eSense earbuds on the go. Each earbud weights 20 g and is 18 × 20 × 20 mm.

Firmware

We developed an energy-aware firmware that implements the classic Bluetooth stack including the Advanced Audio Distribution Profile (A2DP) for high-definition audio streaming, and mono channel recording. The firmware also implements the full BLE radio stack for delivering the accelerometer and gyroscope data and configuring different parameters. A set of BLE characteristics expose these functionalities for setting the sampling rate and duty cycle of the microphone and IMU, setting the advertisement packet interval and connection interval of BLE, and receiving the sensor data. Also, we have designed standard BLE characteristics for receiving the battery voltage and advertisement packets. In our design, continuous bi-directional audio streaming uses classical Bluetooth, and motion data streaming uses BLE. To accommodate simultaneous audio and motion data transfer, eSense implements a multiplexing protocol transparently without requiring any modification to the host device stack. Finally, to enable continuous proximity sensing, eSense broadcasts advertisement packets continuously, and the advertisement interval can be configured programmatically to maintain a right balance between battery life and application requirements.

Middleware

To support application development with eSense, we have created a thin middleware for the iOS and Android operating systems, and Node.js middleware for desktop platforms. This middleware lets developers connect to and configure eSense and ingest sensory data in real time. It also offers a set of predefined audio- and movement-based context primitives that developers can readily use in their applications in an event-driven manner.

SIGNAL CHARACTERISTICS

We have experimentally explored the differential characteristics of the BLE, audio, and inertial signals captured by eSense. Comparing eSense to two other forms, a smartphone and a smartwatch, we looked at several key factors that impact behavior analytics pipelines including sampling variability, the signal-to-noise ratio (SNR), placement invariance, and sensitivity to motion artifacts. The experimental results suggest that eSense is robust in modeling these signals and in most conditions demonstrates comparable and often superior performance in signal stability and noise sensitivity.

Figure 2 shows the SNR of motion and audio signals received under identical physical activity conditions—sitting, standing, and walking—for eSense, a LG Urbane 2 smartwatch, and a Google Nexus 6 smartphone in the pocket. For inertial sensors, we derived the SNR by computing the power ratio of the signal and noise in decibel (dB) scale. The noise profile—electrical noise and sensor biases—was obtained from the stationary states of the devices. We computed the SNR for audio signals by the power ratio of the signal and noise in the context of speech during different physical activities. We obtained the noise profile in the absence of speech signals during these activities and before calculating the SNR in dB scale; this noise was removed from the recorded signal through spectral subtraction. For inertial sensing, we observe that the earbud and smartwatch carry more information than a smartphone about the target physical activities. With respect to audio sensing, the earbud provides the highest SNR in all physical activity conditions owing to the device's unique placement, which is less affected by the acoustic profile of human activities.

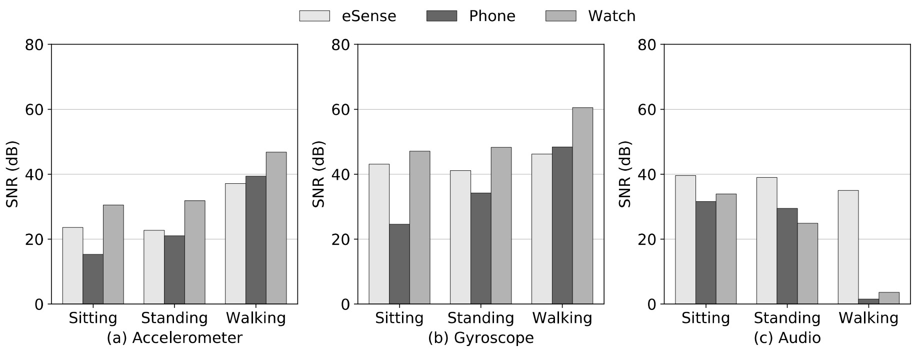

Figure 2. Signal-to-noise ratio (SNR) of accelerometer, gyroscope, and microphone signals of eSense, a smartphone, and a smartwatch under different activity conditions. eSense's earbud captures differential signals in all cases.

APPLICATION LANDSCAPE

The most plausible consumer-focused applications for multisensory wearables such as eSense are smart music players that can react to social and emotional contexts, fitness trackers, and affective communication tools. Building upon many academic research efforts, several commercial-grade earbuds today such as Bragi's The Dash, Bose SoundSport, Jabra Elite Sport, and Sony Xperia offer a superior noise-cancelling music experience augmented with fitness coaching. Two other active application areas that are gaining momentum are in-ear personal assistants and real-time language translators. A number of crowdfunded projects are currently exploring these services with wearables.

There are, however, many other application areas in which we envision earables providing significant benefits. In fact, over the past two decades, seminal research in the ubiquitous computing and wearable computing domains has sought to achieve useful, engaging, and sometimes ambitious behavioral analytics with ear-worn sensing devices including continuous monitoring of cardiovascular function, heart rate and stress,[4,5] measurement of oxygen consumption and blood flow,[6] tracking eating episodes,[7] dietary and swallowing activities,[8,9] and several other biomarkers. Here we briefly look at potential applications for eSense and similar earables in these areas.

Health and Well-being

eSense can be effectively used to monitor head- and mouth-related behavioral activities including speaking, eating, drinking, shaking, and nodding, as well as a set of whole-body movements. It can also be extended to detect more minute head and neck movements to augment various clinical medicine applications related to neck and head injury. Moreover, with eSense conversational activity monitoring capabilities, social interactions can be quantified that to further help treat different mental health conditions and provide well-being feedback. Figure 3 shows a workplace well-being application that models eSense sensory streams for a variety of physical, digital, and social well-being metrics[10] and provides personalized and actionable feedback in conversational and visual representations.

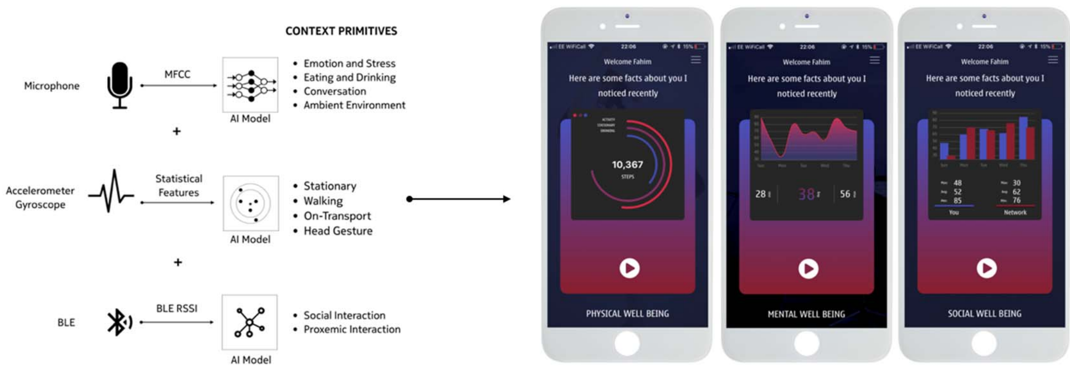

Figure 3. A personalized well-being feedback app for eSense that captures physical, mental, and social well-being at the workplace.

Cognitive Assistant

In recent years, we have seen the emergence of conversational agents such as Siri, Cortana, and Google Assistant into mainstream use by millions of users on a daily basis. However, these agents are not yet capable of understanding users' physical, social, and environmental contexts. We envision that a platform such as eSense will pave the path for these agents to be hyperaware of their users' context, and thereby be able to offer personalized services more persuasively and integrate with our inner cognition loop seamlessly. Also, subtle gestures such as nodding or shaking can act as semi-implicit interaction techniques with these agents. Such cognitive agents will be extremely beneficial for the mobile workforce (for example, field service professionals and retail workers) as well as structured-workplace workers (for example, office workers and call center workers) by providing them with situational guidance and activity-aware recommendations, enabling them to adhere workplace safety and regulations precisely.

Driving Behavior Monitoring

One specialized behavior analytics application that eSense can be used for is to track drivers' head movements to ensure that drivers are awake, alert, and looking in the right direction. The hands-free and immediate interaction affordance of eSense can also be leveraged as a contextual communication interface to provide drivers with relevant information about their routes, and to prevent them from reading texts while driving.

eSense could pave the path for conversational agents to be hyperaware of their users' context, and thereby be able to offer personalized services more persuasively and integrate with our inner cognition loop seamlessly.

Contextual Notification Management

Timely delivery of notifications on mobile devices has been an active area of study in the past few years. Researchers have primarily focused on understanding the receptivity of mobile notifications and predicting opportune moments to deliver notifications to optimize metrics such as response time, engagement, and emotion. eSense's ability to understand situational context could be incorporated into designing effective notification delivery mechanisms in the future.

Lifelogging

eSense could also enable lifelogging using nonvision modalities. While today's lifelogging applications are primarily vision based, audio, motion, and proximity sensing can collectively identify and capture users' memorable and vital everyday events and can help them intuitively recall their past experiences.

Computational Social Science Research

There is a rich body of literature on tracking face-to-face interactions and the impact of the space on enabling them. These works often apply to controlled environments and settings such as offices. eSense could be used as a platform to conducting such studies at scale, thereby opening up opportunities for new insights in computational social science.

CONCLUSION

Wearable devices such as eSense hold enormous potential in accelerating our understanding of a wide range of human activities in a nonintrusive manner. As such, we plan to share this platform with ubiquitous computing researchers and create an open data repository for eSense-driven research and research on other wearables. Academic researchers are encouraged to visit http://www.esense.io and register their interest in participating in an early access pilot project in the fourth quarter of 2018 using donated eSense units, associated software libraries, and a data-sharing platform. We will also showcase eSense at the 2018 UbiComp and ISWC conferences. We expect that these efforts will collectively help our community to achieve the next breakthroughs in wearable sensing systems, especially in understanding the dynamics of human behavior in the real world.

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