Septimu²: Earphones for Continuous and Non-Intrusive Physiological and Environmental Monitoring

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ABSTRACT
Mobile phones have become an ideal platform for physiological and environmental sensing. A number of research and commercial smartphone “accessories” have emerged in recent years that try to extend the sensing capabilities of a mobile phone. However, the major drawback of these devices is that they either require the user to act in some specific way or change their lifestyle and habit to some extent. In this demo, we present Septimu V2 (Septimu²) – a novel non-intrusive physiological and environmental sensing platform which is fully embedded in a conventional earphone, works with existing smartphones, and does not require the user to change habits in any way. Septimu² is a continuation of [1], and integrates a suite of new sensors. In addition to 3-axis accelerometer and gyroscope, Septimu² incorporates remote IR temperature sensor, IR LED, IR photodiode and two additional microphones. The baseboard performs signal condition and sends the data to cellphone via Bluetooth. Septimu² enables a number of applications, including heart-rate monitoring, fine grained posture detection, and external sound source localization and classification.

Categories and Subject Descriptors
C.3 [**Special-purpose and Application-based Systems**]: Real-time and embedded system

General Terms
Measurement, Performance, Design, Experimentation.

Keywords
Physiological Sensing, Environmental Sensing, Earphone.

1. INTRODUCTION
Smartphones are becoming increasingly popular as a platform for sensing applications such as mobile health and environmental monitoring. However, the functions and performances of sensors integrated inside smartphones are limited. To overcome this limitation, much research has been done on developing various accessories for mobile phones. However, they often require changing the habits of users. For example, a wristband needs to be worn by the users for heart monitoring to function. This could significantly alter the lifestyle of users.

In this demo, we present Septimu² – a custom-designed earphone-based sensor platform that provides physiological and environmental monitoring. The special-made ear buds integrates many sensors: 3-axis accelerometer, gyroscope, remote IR temperature sensor, IR LED, IR photodiode and several microphones. The IMU could track the trajectory of heads; IR remote sensor could be used to measure body temperature; the combination of IR LED and photo diode could measure heart rate; three spatially separated microphones are used for binaural recording and augment reality applications. With so many sensors available, it is very convenient for people to develop many exciting applications. For example, we have shown a demo using an older version of the hardware to track head posture of the user and to measure the heart rate using the internal-facing microphone [1]. In this demo, we focus on the new design and showcase some functionality enabled by newly embedded sensors.

2. SYSTEM OVERVIEW
Septimu² consists of two components, a pair of circular sensor boards with diameters of 9mm located inside the earphones, and a baseboard inline with the earphone cord. The system diagram is shown in Figure1.

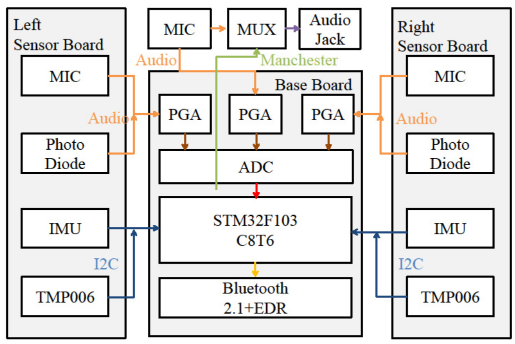

Figure 1. SEPTIMU² System diagram

From the diagram we could find that analog signals from the microphone and IR photo diode are fed into a Programmable Gain Amplifier (PGA), then digitalize by an Analog to Digital Converter (ADC). The IMU and temperature sensor are connected to the I2C bus directly. The digital signal is handled by the STM32 ARM Cortex-M3 microcontroller and data is transmitted to the smartphone via Bluetooth.

3. DESIGN CHOICES

To preserve both the form-factor and functionalities of a traditional earphone, we mounted the IR sensors on the rubber cover of the ear buds, two microphones facing outwards of the earphones, temperature and IMU sensors inside the earphone. The user simply needs to put on the earphone as usual. Septimu^2 will take physiological and environmental data automatically. The whole system is shown in Figure 2.

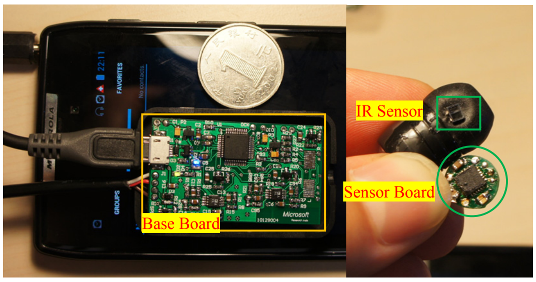

Figure 2. Hardware Overview

3.1 IR Diodes and Photodiodes

Previous method of using microphones inside the ear canal to measure heart rate is susceptible to noise [1]. If the noise is much higher than the heartbeat signal, even advanced filtering algorithm could fail to precisely separate useful signal from noise, which will cause error in heart rate measurement [2]. To improve accuracy, we use IR LED and photodiode for heart rate detection [3, 4].

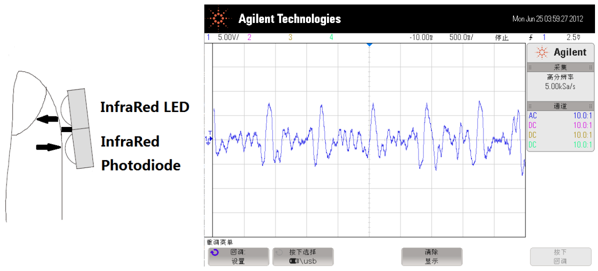

Figure 3. Using IR to measure heart beat

Its principle is shown in Figure 3. Part of the infrared light will be reflected by the skin (e.g., finger or ear canal) and then received by an infrared photodiode. When the heart pumps blood to the capillaries, the IR photodiode will receive more light; when the blood flow back to the heart, less light will be received by the photodiode. This signal is then amplified by the PGA to recover the heart rate.

3.2 Temperature Sensors and Microphones

To detect body temperature, we use a MEMS-based IR to sense temperature from a distance. Due to the desire of small size, we choose MEMS-based microphone chips from TI – TMP006, which is 1.6mm^2 in size. TMP006 produces digital sound signal, which has higher SNR and uniform sound pressure response curve when compared with traditional electret condenser-based microphones.

3.3 IMU Sensors

To integrate IMU inside the extremely small footprint of the sensor boards while still ensuring performance, we chose MPU6050, which has a rotational resolution of 0.0076 degree per second and acceleration resolution of 6.10E-5g/s. In addition, it consumes only 3.6mA.

3.4 Wireless Connectivity

To transmit multi-channel high-fidelity sound to the smartphone, the audio jack interface [5] is not enough. We therefore further add the Bluetooth (with Enhanced Data Rate) interface. To reduce the power consumption of Bluetooth module, we turn it on only when needed (i.e. to transmit high rate data such as sound signal), and revert to the audio jack interface for lower rate data like heartbeat event or those detected from IMU readings.

4. FIRMWARE AND API

The sampling rates for microphones and photo diodes are different, requiring several timers for ADC. We also use DMA to reduce the load of MCU. After receiving the IMU data from the baseboard, Kalman filtering is applied to get the position and posture of the head. Also, the cellphone will perform TDOA algorithm to estimate the source of sound. Based on this, we developed several APIs for developers. They could get the heart rate or posture, and high-fidelity samples of sound.

5. DEMO SCRIPTS

1) **Safe listening**: In this demo, the user is prompted with a list of classes of sounds (e.g. human voice, fire alarm, etc.); she selects one or more that she wants to be aware of. While she is listening to music, if a pre-selected type of sound appears, this sound is overlaid on her music, and alerts her. Potential applications include safe listening while walking during traffic.

2) **Mobile Health**: In this demo, the user wears Septimu^2 and listens to music. Her phone will display and record her heart rate and posture in real-time.

REFERENCES

[1] D. Hong, B. Zhang, Q. Li, S.M.S. Nirjon, R.F. Dickerson, G. Shen, X. Jiang, and J.A. Stankovic. Demo: SEPTIMU - continuous in-situ human wellness monitoring and feedback using sensors embedded in earphones. In Proceedings of IPSN. 2012.

[2] S. Nirjon, R. Dickerson, Q. Li, P. Asare, J. Stankovic, D. Hong, B. Zhang, G. Shen, X. Jiang, and F. Zhao. MusicalHeart: A Hearty Way of Listening to Music. ACM Sensys, to appear, Nov. 2012.

[3] Ming-Zher Poh, Nicholas C. Swenson, and Rosalind W. Picard. 2010. Motion-tolerant magnetic earring sensor and wireless earpiece for wearable photoplethysmography. Trans. Info. Tech. Biomed. 14, 3 (May 2010)

[4] V. Chan and S. Underwood. A single-chip pulsoximeter design using the MSP430. Application Report, 2005, Texas Instruments Incorporated.

[5] Y-S. Kuo, S. Verma, T. Schmid, and P. Dutta. Hijacking power and bandwidth from the mobile phone's audio interface. In Proceedings of the First ACM Symposium on Computing for Development (ACM DEV '10).