

Wearable Sensors: Opportunities and Challenges for Low-Cost Health Care

Richard R. Fletcher, *Member, IEEE*, Ming-Zher Poh, *Student Member, IEEE* and Hoda Eydgahi

Abstract —Wearable sensors enable long-term continuous physiological monitoring, which is important for the treatment and management of many chronic illnesses, neurological disorders, and mental health issues. Examples include: diabetes, autism spectrum disorder (ASD), depression, drug addiction, and anxiety disorders. In this paper, we present a few mobile health technologies developed by our group and also discuss emerging opportunities as well as existing challenges. Technologies presented include wearable sensors for electrodermal activity (EDA) and mobile plethysmography as well as mobile phones and the supporting wireless network architecture.

Index Terms — biomedical monitoring, wearable sensors, telemedicine, mobile health, low-cost health care.

I. INTRODUCTION AND MOTIVATION

THE definition of health care, and the way it is delivered, is currently undergoing great change, particularly in the United States. Throughout the world, there is increasing need for ambulatory monitoring of physiology to enable medical interventions and therapies outside of the clinical setting [1]. The application areas are numerous, but include the following:

- Autism Spectrum Disorders (ASD) – there is increasing interest in early-age detection of ASD as well as to create better therapies [2].
- Disaster relief/battlefield medical care – Recent earthquakes around the world, as well as ongoing wars, demonstrate the existing need for better low-cost, portable, and scalable physiology sensors [3].
- Elder care – there is a need to perform unobtrusive monitoring of elder people at home or in nursing homes [4].
- Behavioral therapy – continuous long term monitoring of physiology is needed for treatment of conditions such as drug addiction and obesity issues.
- Anxiety disorders – there are huge topics in mental

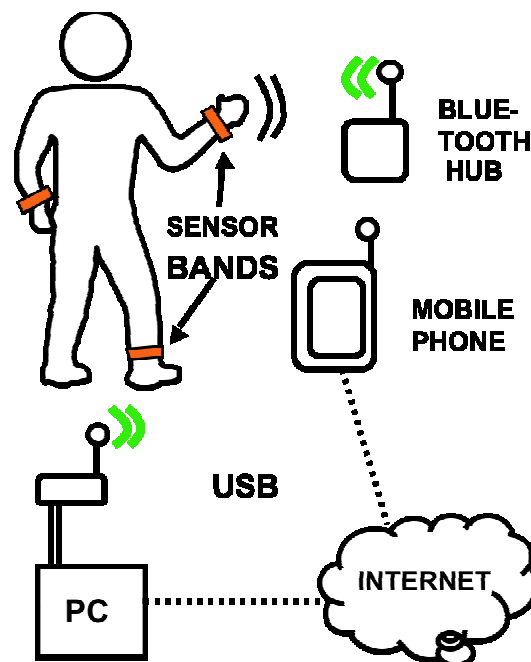


Fig. 1. Sample network architecture for mobile health monitoring system.

health, such as anxiety disorders, where continuous physiology monitoring would provide a vital complement to clinical visits [5].

- Diabetes – Being able to monitor the physiological indicators of extreme levels of sugar/insulin is of great interest, particularly to the elderly population [6].

From a cost perspective, the primary goal has been to move health care away from where it is most expensive (clinic, emergency room) and move toward *preventative* measures and outpatient monitoring. The motivation is to create technologies that will enable us to continuously monitor our health and track our progress in all stages of life and disease.

As health monitoring becomes part of the fabric of everyday life, there is a need for technologies that are comfortable, simple to use, unobtrusive, and also provide privacy and security. Wearable sensors, mobile phones, web cameras, and online social networks are all part of the future *health support system*.

Future forms of medical interventions will likely involve not just pharmacology but also electronic devices. For example, a future doctor may “prescribe” a treatment that

Manuscript received April 24, 2010. This work was supported by the MIT Media Lab Consortium and the Nancy Lurie Marks Family Foundation.

R. R. Fletcher is with the Media Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139 (e-mail: fletcher@media.mit.edu)

M. Z. Poh is with the Harvard-MIT Division of Health Sciences and Technology and the Media Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139 (e-mail: zher@mit.edu).

H. Eydgahi is with the Electrical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA 02139 (e-mail: hoda@mit.edu)



Fig. 2. Sensor band incorporating electrically conductive fabric electrodes.

includes both medicines as well electronic devices (physiology sensors, webcam, mobile phone, etc.). The patient would then go to an electronic appliance store (e.g. Best Buy, Walmart) to fulfill the electronic portion of his “prescription.” If the patient needs help installing the sensors at his home, the patient can hire the store’s health care team to do a professional installation. A variety of companies will offer services to manage the health information in our home, which may be paid like any other utility service such as phone or Internet service.

In this paper, we present several technologies developed by our group and discuss some progress and challenges towards achieving the vision of ubiquitous low-cost health care infrastructure.

II. WEARABLE SENSORS

Wearable sensors have been successfully integrated into clothing garments as well as fashion accessories such as hats, wrist bands, socks, shoes, eyeglasses and headphones. These systems often include temperature sensors and accelerometers, which are often used to monitor and classify a person’s physical activity. In addition to these, our group has explored sensors that are fundamental to psychophysiology and understanding of human emotion. Two general categories of sensors being developed by our group are described below.

A. Electrodermal Activity (EDA)

Electrodermal activity (also known as skin conductance or galvanic skin response) directly correlates to the *sympathetic* nervous system activity and thus provides a powerful tool for monitoring arousal and certain aspects of autonomic regulation [7, 8].

EDA sensors are promising for providing people with Autism Spectrum Disorder (ASD) a means of measuring stress or anxiety in situations where these feelings cannot be communicated verbally or socially. EDA sensors can thus provide feedback to caregivers and to the patients themselves to help understand specific causes of stress or anxiety and

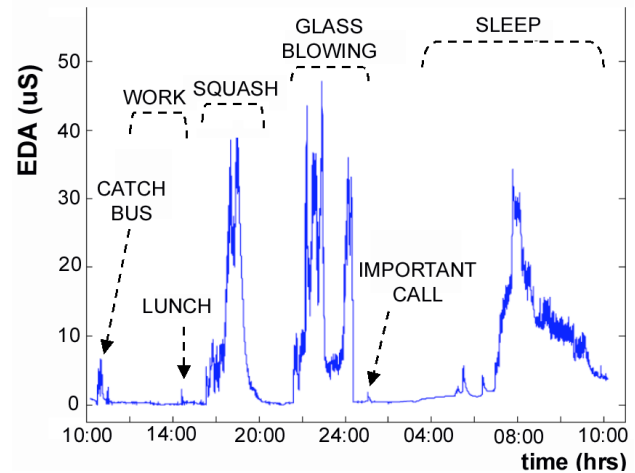


Fig. 3. Sample EDA data collected for 24-hour period.

help prevent negative behaviors or “meltdowns” [2].

EDA activity has also been shown to correlate with other disorders and activities that involve the sympathetic nervous system. Active areas of research for EDA include sleep disorders, epileptic seizure detection, and detection of diabetic shock, among others.

Although EDA is usually measured from the fingertips, meaningful EDA data can also be collected from the wrists and ankles, which are the preferred sites for mobile measurement of EDA [9]. The measurement of EDA is a good match for wearable sensors because it requires relatively low power and the circuitry is relatively simple. In addition, the relatively high resistance of the skin enables the use of non-ideal conducting materials, such as electrically conductive fabrics, as interconnects. Shown in Figure 2 are wrist bands with embedded EDA sensors that incorporate electrically conductive fabric [10].

In Figure 3, we show sample EDA data collected over a 24-hour period. It is interesting to note that the EDA signal includes exhibits a characteristic structure during sleep.

B. Mobile Photoplethysmography (PPG)

In order to measure *parasympathetic* as well as sympathetic aspect of the autonomic nervous system, we have also devoted significant research activity to mobile measurement of heart rate and heart rate variability [11].

Several different measurement methods have been investigated, including electromagnetic methods. This work is ongoing. However, much of our work has been devoted to developing new form factors for photoplethysmography (PPG), which detects the blood volume pulse by measuring the relative absorption of near infrared light over perfused skin. Since oxygenated and de-oxygenated blood exhibit different light absorption, the measurement at two wavelengths can be used to calculate the relative oxygen saturation in the blood (SpO_2) [12].

In addition to a wrist band form factor, we have explored other body locations and other form factors for PPG heart rate measurement. Shown in Figure 3 is a sample PPG

sensor that can be worn on ear or incorporated into the earpiece of other common consumer devices such as a Bluetooth mobile phone earpiece [13] or earphones [14].

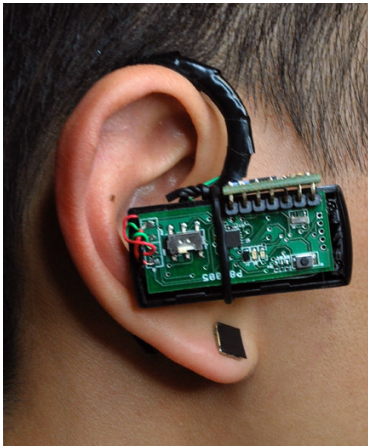


Fig. 4. Mobile photoplethysmography (PPG) sensor integrated into earring and wireless earpiece.

III. WIRELESS CONNECTIVITY

For many applications, real-time wireless connectivity to the wearable sensors is not required. In this case, the data can be logged locally on the sensor module itself for many hours or days.

However, for many emerging applications, there is an interest to provide *real-time interventions* to the patient. In this case, it is often necessary for multiple wearable sensors to communicate with an external computer (such as a mobile phone) that can receive the sensor data and automatically classify certain events based on a pattern-recognition or machine-learning algorithm in order to provide some type of real-time intervention in the form of an alert, message to the user, or a text message to a remote caregiver. In this case real-time wireless connectivity is essential.

A. Bluetooth

Certainly for mobile phone applications, Bluetooth connectivity is preferred, and Bluetooth radio modules (e.g. Roving Networks) are readily available. Unfortunately, Bluetooth has several important limitations including relatively high power consumption (50-100mW). Also, the master-slave protocol only supports up to 7 slaves with one master node.

An additional inconvenience of Bluetooth is the handshaking required to establish the connection. If the radio signal is temporarily dropped (due to occlusion or multipath), the host (master) must explicitly re-establish the connection.

B. “Zigbee” (IEEE 802.15.4)

In cases where more than 7 sensor nodes are needed or when extreme low power is required, a different radio is used based on the IEEE 802.15.4 physical layer protocol. Since

this protocol is ad-hoc and peer-to-peer, a larger number of nodes can be supported. The MAC layer protocol implemented in these radios enable them to move gracefully in and out of the local sensor network without breaking the flow of communications. Furthermore, these radios require less than 1 mW to communicate over a 30 meter range, which is perfectly adequate for mobile health applications.

If a PC is used as the base station, a USB receiver is employed to collect the data (Figure 1). However, for mobile phone integration, we have designed a Bluetooth hub (called PAN-HUB) which contains both an 802.15.4 radio and a Bluetooth radio. The PAN-HUB essentially creates an 802.15.4 Personal Area Network and then aggregates and relays the information to a Bluetooth stream going to the mobile phone.

C. RFID

For certain applications, inexpensive passive RFID tags can be used to identify people, places, and things. In collaboration with a corporate sponsor (Becton-Dickinson) we created a medication compliance monitoring system using RFID tagged pill bottles.

More recently, we have explored the use of RFID tags as a wearable sensor for patient identification. In a recent project [15], we have used RFID ankle bracelets as a means of automatically identifying infants in a large pneumonia infant immunization study in Karachi, Pakistan. To date, the technology has successfully been used to track more than 2000 infants over the course of two years in over 26 clinics in the study area. For the purpose of the study, special mobile phones were used which contained an embedded RFID NFC reader (Nokia E61).

IV. ONGOING CHALLENGES

Although many new technologies have emerged to support health monitoring and telemedicine, many challenges still remain before this technology can find widespread use. A few of these are discussed below.

A. Differences in Objectives

The discussion of mobile health technologies and telemedicine is often clouded by the existence of many competing technologies and different design objectives. Even among a single common platform, there are different opinions regarding how the system should be used.

An engineering team, for example, may prefer to compress the data and use low-duty-cycle transmission in order to save power; the clinical team, on the other hand, would prefer to see large amounts of data collected at a high sampling rate in real-time. Since the clinical use of these sensors will vary greatly, there is a need for wearable sensors that can be easily programmed or reconfigured by the end user.

B. Power Consumption

Long-term continuous monitoring will require creative system design as well as commercially available solutions.

Although many low-power designs have been published in academia, few of these ideas have been commercialized. Industry is often caught in a chicken-egg problem waiting for the market demand to justify new product development. For example, a lower-power alternative to Bluetooth, Bluetooth Low Energy (formerly called Wibree) has existed for several years but has not succeeded in being adopted by mainstream mobile phone manufacturers.

Fortunately, advances in the semiconductor industry continue to produce lower-power integrated circuits and battery technology. Also, energy harvesting technology now provides additional means to extend battery life.

C. Lack of Mobile Health Data Standards

Many groups in academia as well as industry are developing solutions for mobile health and telemedicine. However, few systems are interoperable with each other. The Continua Health Alliance (www.continuaalliance.org) was formed as an industry consortium to help address this need; however, these organizations are often financially inaccessible to academic developers.

It is hoped that wireless standards such as Bluetooth, Wi-Fi and openly available drivers will enable some degree of interoperability and competition among device makers.

D. Validation and Performance Standards

Given the proliferation of mobile health technologies, it is sometimes difficult to compare one device to another. It would be useful to create a way to set metrics or validate devices (without needing to get FDA or government certification). The medical industry is generally biased towards maximizing performance and cost, but in the low-cost consumer health market, it is necessary to determine the appropriate level of performance.

From an engineering perspective, for example, it is often difficult to determine when a 12-lead ECG device is needed, when a 5-lead or 2-lead ECG may be sufficient. Many products are considered “toys” by doctors, but at the same time, it is not practical to employ a \$5,000 machine for a simple measurement in the home. Obviously, a great deal of interdisciplinary dialogue and collaboration will be required between doctors and engineers in order to help determine the appropriate level of performance and cost that will meet the needs of future health interventions.

V. CONCLUSION AND FUTURE OUTLOOK

Advances in electronics, data algorithms, wireless standards, battery technology, materials science are enabling many new forms of wearable sensors and low-cost health care systems that can be applied to a wide variety of medical interventions and therapies.

Wearable sensors complement other emerging technologies for continuous health monitoring, including instrumented furniture and smart cameras [16].

The proper use of these technologies outside of the clinic,

however, is still at a very early stage. As the health care industry shifts to adopt new models for medical interventions and therapies, it will be important for the research community (not just industry) to help shape the future standards, metrics, and practices in this new domain.

VI. ACKNOWLEDGEMENTS

Authors would like to thank the Affective Computing group at the MIT Media Lab as well as collaborators for help in advancing all aspects of the technology.

REFERENCES

- [1] P. Bonato, "Wearable sensors/systems and their impact on biomedical engineering," *IEEE Eng Med Biol Mag*, vol. 22, pp. 18-20, May-Jun 2003.
- [2] R. Picard, "Future affective technology for autism and emotion communication," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 364, p. 3575, 2009.
- [3] T. Gao, T. Massey, L. Selavo, D. Crawford, B. Chen, K. Lorincz, V. Shnayder, L. Hauenstein, F. Dabiri, and J. Jeng, "The advanced health and disaster aid network: A light-weight wireless medical system for triage," *IEEE Trans Biomed Circuits Syst*, vol. 1, p. 203ñ216, 2007.
- [4] C. Scanaill, S. Carew, P. Barralon, N. Noury, D. Lyons, and G. Lyons, "A review of approaches to mobility telemonitoring of the elderly in their living environment," *Annals of Biomedical Engineering*, vol. 34, pp. 547-563, 2006.
- [5] F. Wilhelm and W. Roth, "The somatic symptom paradox in DSM-IV anxiety disorders: suggestions for a clinical focus in psychophysiology," *Biological Psychology*, vol. 57, pp. 105-140, 2001.
- [6] R. Merrell, "The Interaction of Technology and Diabetes Care," *Diabetes Technology & Therapeutics*, vol. 5, pp. 467-469, 2003.
- [7] W. Boucsein, *Electrodermal activity*. New York: Plenum Press, 1992.
- [8] H. D. Critchley, "Electrodermal responses: what happens in the brain," *Neuroscientist*, vol. 8, pp. 132-42, Apr 2002.
- [9] M. Z. Poh, N. Swenson, and R. Picard, "A Wearable Sensor for Unobtrusive, Long-term Assessment of Electrodermal Activity," *IEEE Trans Biomed Eng*, vol. 57, pp. 1243-1252, 2010.
- [10] R. Fletcher, K. Dobson, M. Goodwin, H. Eydgahi, O. Wilder-Smith, D. Fernholz, Y. Kuboyama, E. Hedman, M. Z. Poh, and R. Picard, "iCalm: Wearable Sensor and Network Architecture for Wirelessly Communicating and Logging Autonomic Activity," *IEEE Trans Inf Technol Biomed*, vol. 14, pp. 215-223, 2010.
- [11] M. Malik, J. Bigger, A. Camm, R. Kleiger, A. Malliani, A. Moss, and P. Schwartz, "Heart rate variability: Standards of measurement, physiological interpretation, and clinical use," *European Heart Journal*, vol. 17, p. 354, 1996.
- [12] C. M. Alexander, L. E. Teller, and J. B. Gross, "Principles of pulse oximetry: theoretical and practical considerations," *Anesth Analg*, vol. 68, pp. 368-76, Mar 1989.
- [13] M. Z. Poh, N. C. Swenson, and R. Picard, "Motion-tolerant magnetic earring sensor and wireless earpiece for wearable photoplethysmography," *IEEE Trans Inf Technol Biomed*, Epub 2010 Feb.
- [14] M. Z. Poh, K. Kim, A. Goessling, N. Swenson, and R. Picard, "Sensor Earphones and Mobile Application for Non-obtrusive Health Monitoring," in *Proc. IEEE Int. Symp. Wearable Computers (ISWC)*, 2009.
- [15] A. Marcus, G. Davidzon, D. Law, N. Verma, R. Fletcher, A. Khan, and L. Sarmanta, "Using NFC-enabled Mobile Phones for Public Health in Developing Countries," in *Proc. IEEE Conf. Near-Field Communication (NFC)*, , 2009.
- [16] M. Z. Poh, D.J. McDuff, R.W.Picard, "Non-contact Automated Cardiac Pulse Measurements Using Video Imaging and Blind Source Separation," in *Optics Express*, vol 18, No 10. 2010.