34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Development of a Wearable System Integrated with Novel Biomedical Sensors for Ubiquitous Healthcare

Kevin Hung, C.C. Lee, W.M. Chan, Sheung-On Choy, and Paul Kwok

Abstract— **The world's ageing population has led to an urgent need for long-term and patient-centered healthcare solutions. Hence, there is a growing need for wearable systems for physiologic monitoring. While various biosignals are monitored with traditional approaches, it is worthwhile to investigate alternative sensing techniques in order to improve accessibility and understanding of patients' conditions. This paper presents our laboratory's development of such a wearable system, which makes use of unconventional techniques for physiologic monitoring. With its integrated textile electrocardiogram (ECG) electrodes, intelligent finger-ring photoplethysmogram (PPG) sensor, miniaturized optical fiber-based temperature sensor, eye dynamics monitor, global positioning system (GPS) module, and wireless capability, it demonstrates a feasible solution for ubiquitous healthcare.**

I. Introduction

With the increasing life expectancy and decreasing fertility, ageing of the world's population is now profound and pervasive. By Year 2050, the number of persons aged sixty or above is projected to two billion, and in more developed regions, nearly one-third of the population will be in this age group [1]. Since prevalence of chronic conditions among the elderly is higher than in the younger population, there is an urgent need to allocate more resources in long-term healthcare. Chronic diseases are becoming the world's leading causes of death, and this situation is inducing social problems and escalating healthcare costs. In response to these impacts, there has been increasing interest in mobile health (m-health) systems for ambulatory and personalized monitoring. To enhance mobility and ubiquitousness of these applications, various parties have developed wearable sensors and systems that monitor different biosignals [2-4], aiming at providing easy-to-use and affordable solutions for serving the chronic and elderly populations. While various physiologic features are monitored with traditional approaches, it is worthwhile to investigate other indicators and acquisition methods in order to improve accessibility of the users' health conditions. This paper presents the development of such a wearable system in our laboratory. It is integrated with textile electrocardiogram (ECG) electrodes, a finger-ring photoplethysmogram (PPG) sensor, optical fiber-based temperature sensor, eye dynamics monitor, global positioning system (GPS) module and Bluetooth connectivity. The novelty of this work lies in several domains: 1.) automated search for an optimal PPG sensing location by the intelligent finger-ring sensor, 2.) miniaturization of optical fiber Bragg grating (FBG) sensor for wearable application, and 3.) use of pupillary dynamics to complement monitoring of cardiovascular variability. The system, built in the form of a shirt, demonstrates how ubiquitous healthcare can be realized using the abovementioned unconventional techniques.

Manuscript received March 29, 2012. This work was supported by The Open University of Hong Kong under the R&D Fund (Project Number 09/2.2).

Kevin Hung is with the School of Science & Technology, The Open University of Hong Kong (OUHK), 30 Good Shepherd Street, Hong Kong (phone: 852-2768-6865; fax: 852-2789-1170; e-mail: khung@ouhk.edu.hk).

C.C. Lee (e-mail: cclee@ouhk.edu.hk), W.M. Chan (e-mail: wamchan@ouhk.edu.hk), Sheung-On Choy (e-mail: sochoy@ouhk.edu.hk) and Paul Kwok (e-mail: ckkwok@ouhk.edu.hk) are with OUHK.

II. Methodology

A. System Overview

Figure 1 is an overall block diagram of the wearable system. It consists of the corresponding subsystems for GPS, Bluetooth, and monitoring of ECG, PPG, body temperature, and eye dynamics. Their operations are controlled by a battery-operated 8-bit microcontroller (MCU) (Atmel AVR). The MCU also serves as a patient-worn station which captures the signals from the subsystems, packages them into a single data format, and wirelessly sends them to a nearby PC via Bluetooth connection. Figure 2 is the outlook of the system integrated in a "smart shirt" prototype. The finger-ring PPG sensor and eye sensor are extensions of the shirt. The following describes the subsystems.

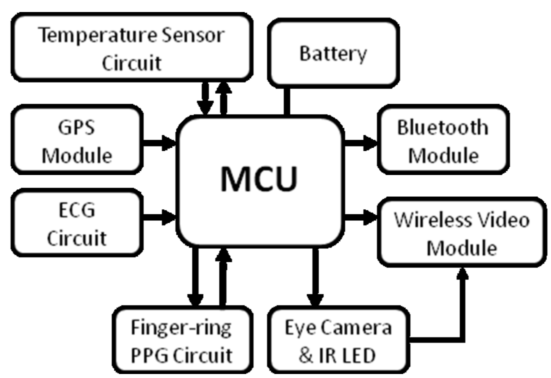

Fig. 1. Block diagram of the wearable system for ubiquitous monitoring.

B. ECG-Monitoring Subsystem

As shown in Figure 3, patches of textile ECG electrodes, which were made from conductive fabric (Shieldex MedTex™ P-130), and their flexible connections (fabrick.it ribbon, 0.3Ω/m tinsel wire) were woven into the inside surface of the shirt prototype. The other end of the ribbon was fed into an instrumentation amplifier (Texas Instrument INA128) with gain of about 1000, followed by a first-order bandpass filter

978-1-4577-1787-1/12/$26.00 ©2012 IEEE

with passband of 0.2Hz to 70Hz. After conditioning, the ECG in Lead-I configuration was input to the 10-bit ADC of the MCU, which sampled it at 200 samples / sec. Figure 4 shows a trace of the ECG captured from a standing subject with the shirt prototype.

Fig. 2. Outlook of the wearable system in the form of a shirt. Left: electrodes and circuits knitted inside the shirt. Right: Flexible finger-ring sensor as an extension of the shirt.

Fig. 3. Textile ECG electrodes

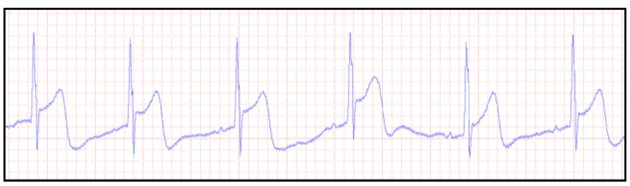

Fig. 4. Trace of Lead-I ECG acquired with the textile electrodes of the wearable system.

C. *PPG-Monitoring Subsystem*

The finger-ring PPG sensor was first developed by Asada's group [5]. PPG measured at the proximal phalanx is vulnerable to motion artifact, but its quality can be enhanced with mechanical design [6] and adaptive filter [7]. However a remaining challenge is sub-optimal sensor location on the finger, as illustrated in Figure 5. In ambulatory application, the sensor may easily shift away from the digital arteries, thus resulting in PPG with low PI (perfusion index).

To solve this problem, an intelligent ring sensor consisting of arrays of LEDs and photodiodes has been developed [8]. A PID (proportional–integral–derivative) control algorithm in the MCU coordinated the simultaneous 200 samples / sec 10-bit ADC of the PPG, as well as the control of the LEDs and photodiodes. As shown in Figure 6, the algorithm could continuously and automatically derive the average PI, and switch on individual LEDs on the finger surface with a sequential pattern until the optimal location with the best PI was found. In experiments with 12 subjects, the subsystem could locate a digital artery within five seconds. PPG sensed at this location had at least 20% improvement in PI compared to the worse case in the same subject. Figure 7 is a sample trace of the PPG measured with the "smart shirt".

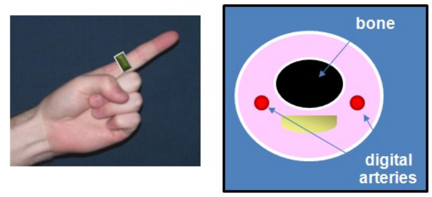

Fig. 5. Left: PPG sensing at the proximal phalanx. Right: locations of the digital arteries at the proximal phalanx.

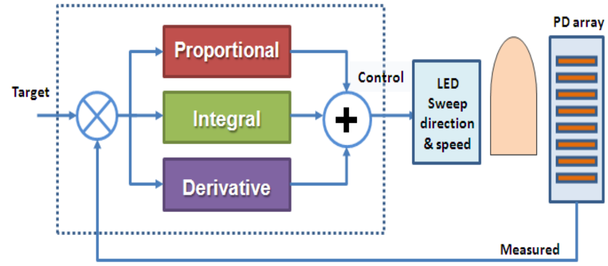

Fig. 6. Block diagram of the PPG-monitoring subsystem

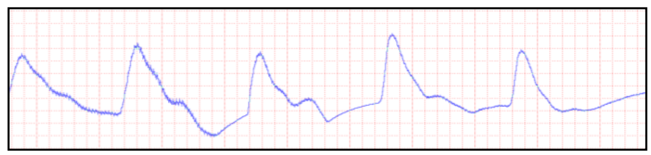

Fig. 7. Trace of PPG measured from the intelligent finger-ring sensor.

D. *Temperature-Monitoring Subsystem*

Compared to semiconductor sensors, optical fiber-based sensors are less vulnerable to electromagnetic interference (EMI); and among these the FBG sensor has the advantage of easy implementation in terms of size and stability [9][10]. Although FBG sensor has been used in some medical applications, the conventional setup was not wearable due to large sizes of the light source and photodetector [11]. For this reason, a wearable FBG temperature sensor setup was employed, as shown in Figure 8. The MCU controlled switching of the laser diode, and upon change in the temperature / strain of sensor, light intensity sensed by the photodiode would change accordingly. The output voltage was sampled by the MCU at 10 samples / second. Experimental results showed that the sensor's sensitivity was 0.010 ± 0.001nm/°C in the body temperature range.

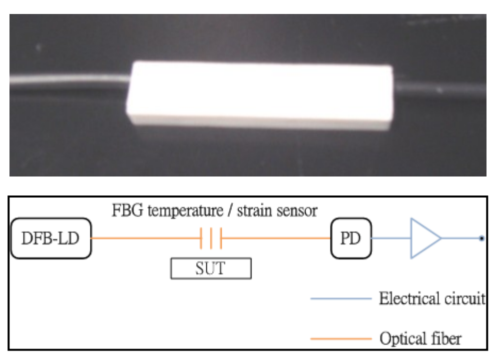

Fig. 8. Top: FBG temperature sensor of the wearable system. Bottom: Schematic diagram of the FBG temperature sensor.

E. Eye-Monitoring Subsystem

Pupil size variability (PSV) refers to the continuous fluctuation of pupil size without visual accommodation or light stimulation. Recent findings such as in [12-16] have shown that PSV actually contains respiratory rhythm and heart rate variability (HRV) frequency components, thus implying potential applications in health monitoring. The eye-monitoring subsystem is an extension of the "smart shirt". It consisted of a CMOS camera mounted on a pair of glasses, infrared LED for illumination, and a 2.4Hz wireless video transmitter module. As shown in Figure 9, PSV could be captured by a wearable camera at 25 fps.

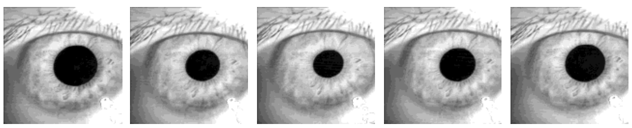

Fig. 9. PSV captured by wearable camera.

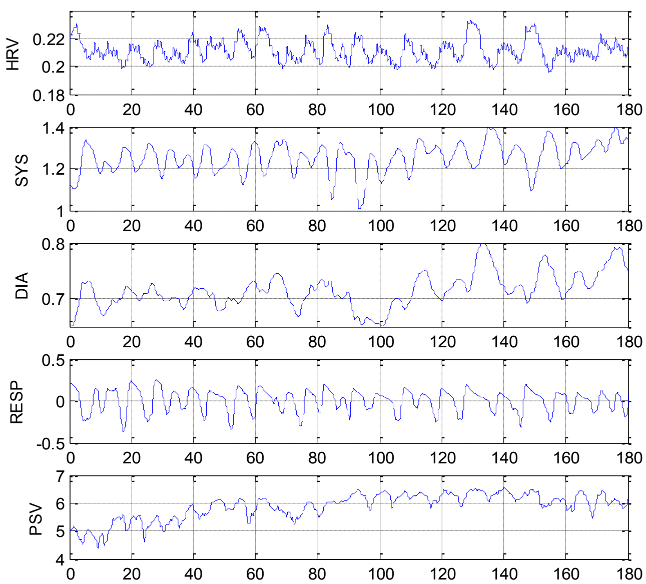

Fig. 10. Biosignals measured from a subject. Top to bottom traces: HRV, SBP (100mmHg), DBP (100mmHg), RespA, and PSV (mm). x-axis is in seconds.

PSV, respiration activity, and HRV from 22 human subjects were studied. Figure 10 shows signals measured from a subject at sitting position. Inspiratory mydriasis and expiratory miosis were observed. PSV amplitude was found to be maximal for mid-range pupil size, and minimal when pupil size was at its extremities. This suggests that PSV exhibits the range-nonlinearity (RNL) relationship, which was originally thought to describe only the noise in pupil size measurement. Findings from our work suggest that the PSV LF/HF ratio is not a reliable indicator of autonomic balance, since the frequency components are influenced by the RNL characteristic. The pupillary plant acts as a lowpass filter, which cutoff frequency increases as the pupil size approaches either extremity. PSV can be considered for health monitoring applications only if subject-centered calibration is performed.

E. Global Positioning Subsystem

To provide tracking service, a GPS module (Linx Technologies RXM-GPS-SR-B) with an update rate of 1Hz was included in the wearable system. A PC-based software was developed for checking the accuracy of the system. Error was found to range from 10 to 20 meters. Figure 11 shows a PC software which was used to display location, ECG and HR simultaneously.

F. Wireless Subsystem

Small-sized module, low power consumption, frequency hopping spread spectrum, and widespread use makes Bluetooth an attractive option for short-range communication in m-health. A Class 1 Bluetooth module (RF Solutions LinkMatik2) has been incorporated into the wearable system for wireless transmission of the aforementioned monitored signals and GPS readings to a nearby computer. The module was configured to operate in Serial Port Profile (SPP), automatically sending to the PC the data which were received from the MCU via its UART port (9600 baud). The PC then stored the information in a cloud.

III. Conclusion

Alternative techniques for physiological monitoring in ubiquitous healthcare have been demonstrated with a wearable system developed in our laboratory. The system was capable of monitoring PPG, ECG, eye dynamics, location, and body temperature. On-going work includes comparison of the system's sensing performance with certified sensors, further tests on more subjects, reduction of power consumption, real-time preprocessing at the PC, eye biometrics for user authentication, respiration activity monitoring with FBG sensors, and biosignal analysis based on cloud computing.

Fig. 11. Software for real-time display of ECG, heart rate and patient location.

References

[1] United Nations, Department of Economic and Social Affairs, Population Division, *World Population Ageing: 1950-2050*. New York: United Nations Publications, 2007.

[2] R.S.H. Istepanian, E. Jovanov and Y.T. Zhang, “Guest Editorial Introduction to the Special Section on M-Health: Beyond Seamless Mobility and Global Wireless Health-Care Connectivity,” *IEEE Trans. Inf. Technol. Biomed.*, vol. 8, no. 4, pp. 405-414, 2004.

[3] S. Park and S. Jayaraman, “Smart Textile-Based Wearable Biomedical Systems: A Transition Plan for Research to Reality,” *IEEE Trans. Inf. Technol. Biomed.*, vol 14, no. 1, pp. 86-92, 2010.

[4] T.-H. Kang, C.R. Merritt, E. Grant, B. Pourdeyhimi and H.T. Nagle, “Nonwoven Fabric Active Electrodes for Biopotential Measurement During Normal Daily Activity,” *IEEE. Trans. Biomed. Eng.*, vol. 55, no. 1, pp. 188-195, 2008.

[5] H. Asada, P. Shaltis, A. Reisner, S. Rhee, and R.C. Hutchinson, “Mobile Monitoring with Wearable Photoplethysmographic Biosensors,” *IEEE EMBS Magazine*, vol. 22, no.3, pp. 28-40, 2003.

[6] S. Rhee, B.-H. Yang, H.H. Asada, “Artifact-Resistant Power-Efficient Design of Finger-Ring Plethysmographic Sensors,” *IEEE Trans. Biomed. Eng.*, vol. 48, no. 7, 2001.

[7] H. Han, M.-J. Kim, and J. Kim, Development of real-time motion artifact reduction algorithm for a wearable phototplethysmogrphy,” *Proc. 29th Annual Intern. Conf. IEEE EMBS*, Lyon, 2007, pp. 1538-1541.

[8] K. Hung, W.M. Chan, C.C. Lee, Sheung-On Choy and Paul Kwok, “Preliminary Design of an Intelligent Finger-Ring Sensor for Physiologic Monitoring in Mobile Health,” presented in *AMA-IEEE Medical Technology Conference*, Boston, 16-18 October, 2011.

[9] K. O. Hill, Y. Fujii, D. C. Johnson, and B. S. Kawasaki, “Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication,” *Appl. Phys. Lett.*, Vol. 32, pp. 647–649, 1978.

[10] K. O. Hill and G. Meltz, "Fiber Bragg Grating Technology - Fundamentals and Overview," *J. Lightwave Technol.*, Vol. 15, pp. 1263–1276, 1997.

[11] L.T. D’Angelo, et al., “A system for respiratory motion detection using optical fibers embedded into textiles,” in *Proc. 30th Annual International IEEE-EMBS Conference*, Vancouver, pp. 3694-3697, 20-24 August, 2008.

[12] K. Ohtsuka, K. Asakura, H. Kawasaki and M. Sawa, “Respiratory fluctuations of the human pupil,” *Exp. Brain Res.*, vol.. 71, no. 1, pp. 215-217, 1988.

[13] P. Borgdorff, “Respiratory fluctuations in pupil size,” *Am. J. Physiol.* vol. 228, no. 4, pp. 1094-1102, 1975.

[14] G. Calcagnini, P. Giovannelli, F. Censi, P. Bartolini and V. Barbaro, “Baroreceptor-sensitive fluctuations of heart rate and pupil diameter,” in *Proc. 23rd Annu. IEEE EMBS Int. Conf.*, vol. 1, pp. 600-603, 2001.

[15] G. Calcagnini, F. Censi, S. Lino and S. Cerutti, “Pupil Diameter Variability in Humans,” in *Proc. 22nd Annu. IEEE EMBS Int. Conf.*, vol. 3, pp. 2298-2301, 2000.

[16] K. Hung and Y.T. Zhang, “Preliminary investigation of pupil size variability: toward non-contact assessment of cardiovascular variability,” in *Proc. 3rd. IEEE EMBS Int. Summer School in Medical Devices & Biosensors*, Cambridge, pp. 137-140, 2006.