Wearable wireless photoplethysmography sensors

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ABSTRACT

Wearable health monitoring sensors may support early detection of abnormal conditions and prevention of their consequences. Recent designs of three wireless photoplethysmography monitoring devices embedded in hat, glove and sock, and connected to PC or mobile phone by means of the Bluetooth technology, are described. First results of distant monitoring of heart rate and pulse wave transit time using the newly developed devices are presented.
Keywords: photoplethysmography, distant cardiovascular monitoring, wireless bio-sensing, vascular response.

1. INTRODUCTION

Wearable optical health monitoring sensors integrated into telemedicine and/or mobile systems represent a novel biophotonic technology for early detection of abnormal conditions and prevention of their serious consequences. Recent advances in integrated circuits, wireless communications and physiological sensing open the way to miniature, lightweight, low power and intelligent cardio-vascular monitoring devices. Biomedical monitoring systems can greatly benefit from the integration of electronics in textile materials [1]. Synergy of textiles and electronics mainly originates from the fact that clothing is our most natural interface to the surrounding world. The higher is the level of integration of the sensors and circuits in the clothing, the more unnoticeable the monitoring system becomes to its user and thus the higher is comfort of the user.

Photoplethysmography (PPG) ensures detection of blood volume pulsations by time-resolved analysis of the tissue back-scattered or absorbed optical radiation [2]. PPG technique has good potential for express diagnostics and early screening of cardio-vascular pathologies, as well as for self-monitoring of the vascular condition [3, 4].

It is very important for a patient suffering from the cardiac disease to perform accurate and quick assessment of his/her cardiovascular condition, so development of new techniques for continuous monitoring of the PPG signals seem to be clinically significant. Studies on wireless PPG systems based on Bluetooth technology have been initiated recently [5]. Tests of the first experimental prototypes confirmed viability of this approach, and PPG distant sensing at distances up to 10 m has been demonstrated using PC or specially designed detecting unit as the bio-signal receiver.

Contemporary mobile phones are suitable as the PPG monitoring terminals, providing immediate interaction between the patients and caregivers. This technique seems to be especially promising for future telemedicine since mobile phones are always with doctors, nurses and other clinical personnel. Besides, the mobile nets nowadays cover all the most developed areas on the Globe, so the PPG signal data from the detector-phone can be transmitted practically to any country for consulting or joint decision taking. The most challenging part still is design of the embedded optical contact sensors and development of appropriate methods to enter the measured data into the communication system.

Our recent designs of wireless PPG monitoring devices embedded in wearable items - hat, glove and sock, with real-time transmission of output bio-signals to mobile phones or other Bluetooth-friendly devices are reported here. Some design solutions and the first results of distant monitoring of heart rate and pulse wave transit time using the newly developed devices are presented. Possibilities and challenges associated with wireless bio-data transmission will be discussed, as well.

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2. METHODS AND TECHNIQUES

The developed wireless PPG sensor incorporates GaAs emitting diode (peak wavelength 940 nm) and Si photodiode, both mounted side-by-side (PPG reflection mode), as well as a microprocessor that controls a 10-bit amplitude-to digital converter of signals at programmable sampling frequencies (e.g. 100 Hz) and drives a Bluetooth module capable to transmit real-time signals within 10 m surrounding area. Besides, filters, amplifiers and a compact 2-axes accelerometer were also integrated in the device. All circuitry was powered by a standard Li-Ion 3.6V mobile phone battery that can sustain more than seven day continuous functioning. Utilizing the Bluetooth Sniff mode to reduce transmission power, the whole electronic circuit has been designed for minimum power consumption in order to operate it for a long time without changing or recharging the battery. Since LED is one of the most power-consuming parts involved in the sensor, the emission intensity of the LED was lowered along with reduction of the duty cycle. This, however, incurred a poor signal-to-noise ratio problem - the signals had to be amplified several thousand times.

Block-diagram of the sensor device is presented at Fig. 1; Fig. 2 shows its outlook (dimensions 45x30x7mm).

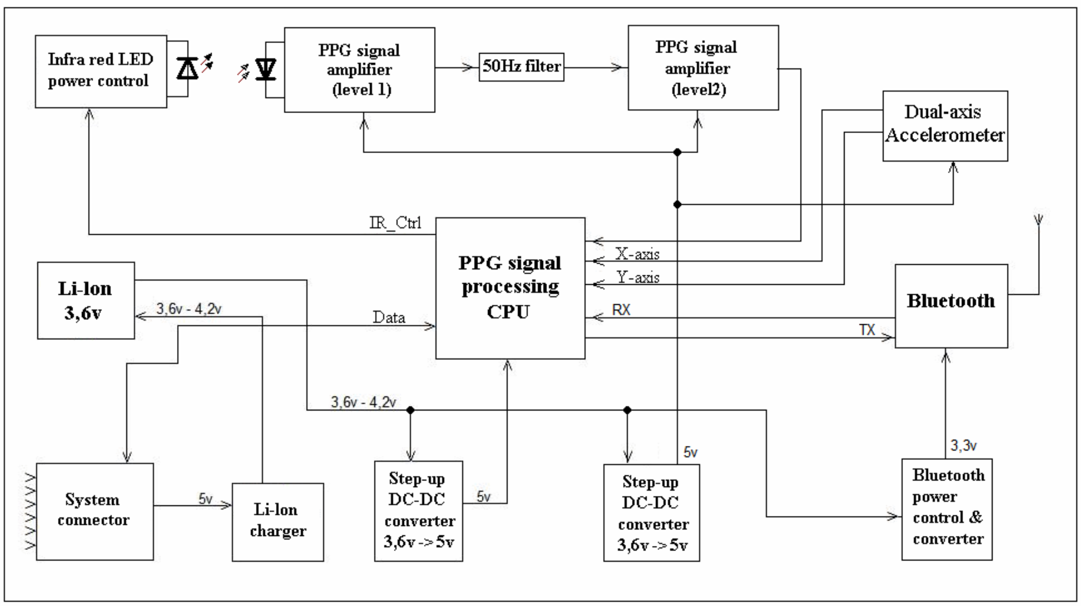


Fig. 1. Block-diagram of the wireless PPG sensor device.

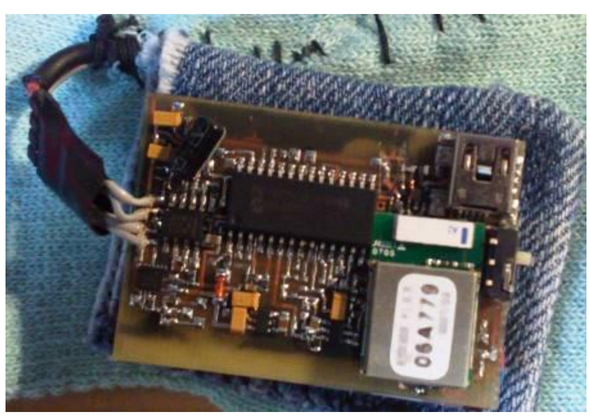


Fig. 2. Outlook of the wireless PPG sensor device (dimensions 45x30x7mm).

The device is powered by a rechargeable Li-Ion accumulator with voltage stabilizers, connected to central processor, Bluetooth module and analogue circuit. The feeding of infrared LED is performed by a special circuit that stabilizes the voltage over the whole discharge process to ensure constant intensity of the emission (four fixed intensity levels are available).

The analogue bio-signal after passing two amplifying cascades and a 50 Hz filter enters the central processor and becomes digitized by means of a 10-bit ADC. Another 10-bit ADC is used for digitizing of the analogue signals from the X-Y accelerometer (see below). The wireless transmission is ensured by a Class II Bluetooth module that receives the digital PPG signals from the central processor by means of the USART (*Universal Synchronous Asynchronous Receiver/Transmitter)* protocol.

The PPG contact sensor is inevitably susceptive to a variety of disturbances such as a patient's motion. When the patient moves, the inertia force created at sensor causes movement relative to the skin surface, and the measurement data may be distorted or even ruined completely. There are several existing techniques for rejection of the PPG signal artifact and disturbances; the most common is signal processing, as reviewed by Hayes and co-authors[6]. Another standard method is to identify and reject corrupt signals by comparing pulse features with a predetermined template. Implementing this concept, the motion disturbances in the present work were detected by the 2-dimmensional accelerometer, Mod. ADXL311 (Analog Devices, Inc.). The artifact detection by this methodology proved to be highly sensitive – see Fig. 3 where the disturbed PPG signal is compared with the X-Y acceleration sensor outputs during shaking the hand with PPG-glove.

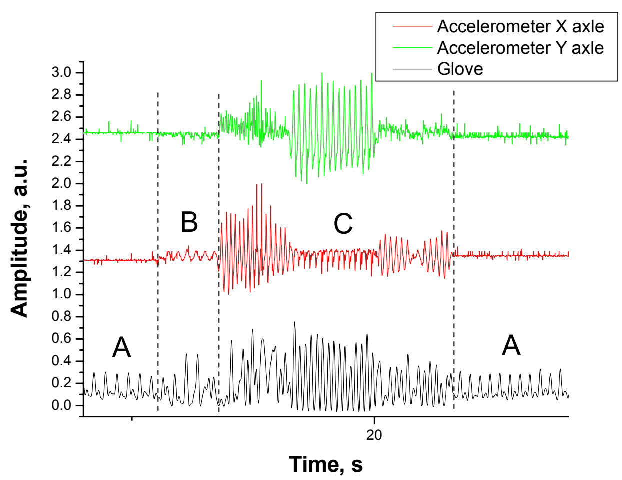


Fig. 3. Use of the X-Y-accelerometer to identify the glove PPG signal artifacts: **A** – stable PPG signal; **B** – X-axis movements, **C** – X- and Y-axis movements.

Wireless transmission of the bio-monitoring signals was performed by means of the Bluetooth technology, developed for cable replacement when connecting devices still maintain a high level of security. The key features of Bluetooth technology are low power, low cost and durability. Bluetooth technology operates at 2.4 to 2.485 GHz (ISM, industrial, scientific and medical band), available and licensed in most countries. Acquisition and processing of the bio-signals was performed using Java Wireless Toolkit [7]. It can run on any Java compatible mobile phone. The acquired data were transferred to another mobile phone or computer in real-time using GPRS. The data sampling rate 50 s^{-1} was usually chosen. As example, the mobile phone screenshot during PPG measurements is presented on Fig. 4.

The above-described PPG contact sensors were integrated in three wearable items – glove (against the left index fingertip), golf-hat (against the forehead) and sock (against the toe). All three PPG-garments are shown on Fig. 5.

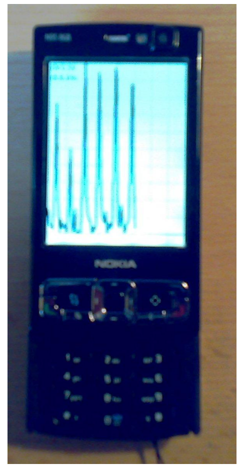
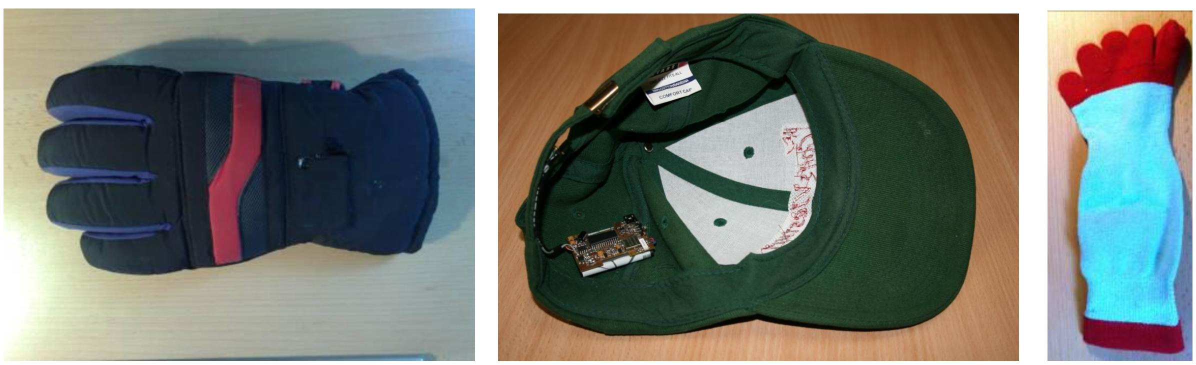


Fig. 4. Wireless transmission of the PPG signals: the mobile phone screenshot.



a b c

Fig. 5. Three garments with integrated wireless PPG sensors: a) glove, b) golf-hat, c) sock.

3. RESULTS OF THE TEST MEASUREMENTS

8 volunteers of age between 24 and 50 have tested the integrated wireless PPG sensing devices. In order to cause changes in the cardio-vascular system, a sit-stand-sit test was performed. Pulse rate variations as detected by the "smart glove" for a single volunteer are presented on Fig. 6. One can notice increase of the pulse rate while standing; it was typical for all volunteers. However, the individual heart rate variations were quite different – see Table 1 for comparison.

PPG technology has an advantage to assess easily the pulse wave transit time (correlated with blood pressure [8]) by measuring the time delay between two PPG pulses originated from the same heartbeat but detected at different locations on the body [2-4]. Simultaneous wireless PPG sensing by two "smart garments" can provide additional clinical information on the pulse wave propagation features. For instance, the PPG signals recorded from a volunteer wearing both "smart hat" and "smart glove" are presented on Fig. 7. The well-measurable time delay δt between the forehead and finger PPG signals confirms the potential of above-described wireless PPG technology for distant assessment of pulse wave transit time and eventually also blood pressure in future.

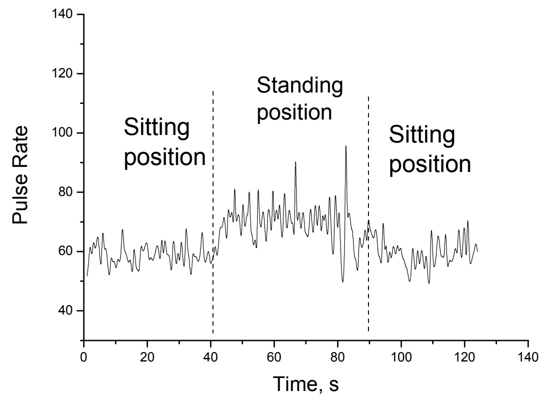


Fig. 6. Pulse rate variations during the sit-stand-sit test, as detected by the wireless "smart glove" PPG sensor.

Table 1. The mean heart rate (HR) values for 8 volunteers during the sit-stand-sit test: wireless PPG measurements by means of the "smart hat".

Volunteer No.	Sitting position, $\pm$ 1	Standing position, $\pm$ 1	Sitting position, $\pm$ 1	Stand-up increase of the HR, $\pm$ 2
1	65	78	69	13
2	60	75	61	15
3	65	77	68	12
4	63	73	60	10
5	66	75	63	9
6	86	98	85	12
7	89	97	88	8
8	78	90	85	12

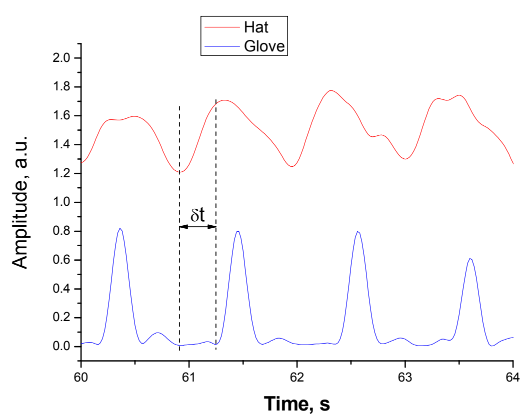


Fig. 7. The PPG signal delay time δt as recorded by simultaneous use of "smart hat" and "smart glove".

4. DISCUSSION

A low cost system for PPG data acquisition and visualization in mobile devices has been developed. Its design allows easy technological updates and further improvements. Incorporating technologies such as Bluetooth and GSM/GPRS, and further development of software tools for computers and mobile devices open possibilities for a wide range of application scenarios.

The presented results prove feasibility of the concept on patient-friendly distant health monitoring by means of compact garment-integrated PPG sensors and associated electronics, combined with wireless powering and data communication. On-line continuous monitoring allows to follow important cardiovascular parameters (heart rate, arrhythmia, pulse wave transit time), as well as to detect emergencies and abrupt changes in the patient conditions. It may provide critical information for long-term assessment and preventive diagnosis for which signal patterns and trends are of special importance.

Besides, application of advanced telecommunication technologies to long-term home care of the elderly is a rapidly growing segment of the health care industry. The current trend is home and community-based care, so the proposed solutions may be successfully used in this clinical area. This type of technology could be used round-the-clock with patients having various long-term medical needs and diseases, including patients with congestive heart failure, chronic cyanotic pulmonary diseases, chronic wound care, permanent disability, terminal illnesses, etc.

With the adoption of 2G and 3G cellular network technologies, mobile phones now have the bandwidth capability to stream data back to monitoring stations in real-time. Advantages of using mobile phones for health services are quite obvious:

- Most people carry, use and know how to operate mobile phone.
- No need to learn how to use a new device.
- Mobile phones have memory to store vast amount of information.
- Can be used as a personal health recorder.
- Information sharing with patient and doctor can be done anywhere.
- Wearing comfort, unlimited movements.
- Immediate expert's feedback available.
- GPS location possible in emergency cases.

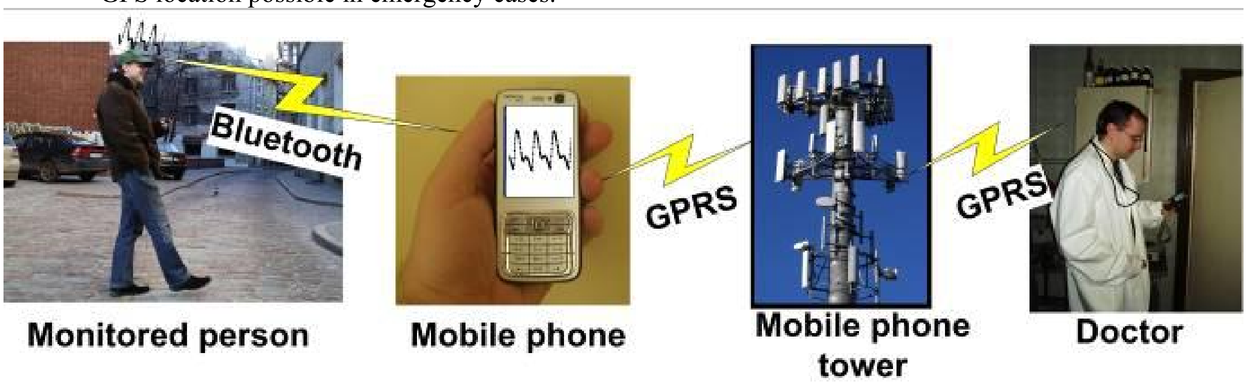


Fig. 8. Transmission of the Bluetooth-monitored PPG signals: via the mobile phone network from patient to doctor.

As a future vision, Fig. 8 illustrates the way of bio-signals detected by the proposed PPG “smart hat” to the doctor. The developed systems may provide a good solution for ambulatory continuous monitoring, as well as for daily life self-monitoring, with storage of the cardiovascular data in the mobile phone memory. It could enable doctors/hospitals to respond immediately when something happens to patients while they are at home, at work or on travel. Future research is needed, including connection of the PC application to a database, and hardware processing of the PPG signals for automatic detection of specific cardiovascular pathologies.

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