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Multi-sensor system with Bluetooth connectivity for non-invasive measurements of human body physical parameters

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ABSTRACT

In the last few years, the availability of powerful personal computing devices, like smartphones, has opened new scenarios to the so called "Body Area Network" (BAN), i.e., sensor networks specifically designed to monitor physical conditions of the user. The traditional methods adopted to monitor physical parameters, like heart beat rate or exertion level, are not suitable for real-time measurements. However, a continuous monitoring of such kind of parameters would allow the athletes to constantly control their physical conditions, furnishing useful information to prevent overstrain and to improve their performance. In this work, a simple, portable and low-cost system for non-invasive and real-time measurement of physical parameters is proposed and experimentally characterized. It is composed of three units: the sensor apparatus, electronic interface circuit, and the data transmission unit. Two different sensors are combined in a unique structure to be placed in a clip-like fashion on the earlobe or other body part of a person. A photoplethysmographic sensor is used to optically measure the changes of blood volume in the arteries, thus to acquire information about heart beat, blood pressure, and arrhythmias. The second sensor is composed of two electrodes, hence an impedance measurement of the tissue is carried out. The impedance estimation can be used to monitor the dielectric properties of biological tissues and fluids, like blood flow. A commercial battery-operated Bluetooth earphone is used both to transmit sensor data and to provide the power supply for the sensors and the first conditioning electronics. Data transmission is operated by the standard Bluetooth Hands-Free profile; therefore, sensor data can be easily acquired, elaborated and visualized by a broad range of commercial devices. In fact, Hands-Free is the only Bluetooth data communication profile supported by any smartphone, from the low-cost ones to the high-end devices. The experimental characterization of the prototype, performed by using a specifically designed application for Android smartphone systems, has demonstrated the validity of the proposed approach.

1. Introduction

Monitoring physical data, particularly during sport activities, can provide athletes with useful information about the body response to fatigue. If the information was given in real-time, the athlete could immediately recognize potential serious hazards for his health, for example due to overstrain, thus reducing or interrupting the activity. Moreover, training programs tailored to the athlete characteristics may take advantage of the real-time information, by suggesting him how to adjust the activity in order to improve his performance. A system able to acquire such data from the human body must be compact, light and portable, non-invasive and low-power, in order to be battery-operated during outdoor use. Several devices are today available on the market for such purposes; for instance heart rate belts are used to collect information from athlete body and to transmit data to smartphones or dedicated devices. However, such systems are usually rather invasive and require a careful positioning of the sensitive elements, in order to provide meaningful results. In addition, the connection of these sensing devices to a smartphone for data visualization requires the use of external dongle, since typically their communication protocol is not natively supported. In [1], a new approach has been proposed to improve the comfort and the quality of the provided heart rate measurements. The sensor is placed on the user earlobe and the acquired data are transmitted with wireless technology to an end-device for data processing and visualization. Therefore, the complexity and the cost of the sensor apparatus can be maintained low, whereas the power consumption is comparable to the one of the wireless transmission unit. The purpose of the present work is to improve the system in [1], in order to collect additional physical information from the athlete's body; in particular, beside the photoplethysmographic (PPG) sensor of [1], the measurement of the earlobe tissue impedance has been considered [2]. Data from both sensors are transmitted by the same audio Bluetooth interface,

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without the need for additional processing unit. The aim is to use the audio signal to code, thanks to simple glue logic, two biological signals. Since data collected from the sensors have not particularly privacy issues, coding and protection of transmitted data (like for instance in [3]) have not been considered.

The PPG sensor is used to monitor modifications in blood volume in the arteries, measuring the variation of the light through the tissues [4]. The frequency of the signal provided by the sensor is used to estimate the heart beat rate and to gather additional information from the characteristics of the cardiac signal. For example, by analyzing the heart beat variability [5,6], it is possible to detect events that can seriously injure athletes, such as arrhythmias or arterial stenosis and occlusions. The use of a second sensor, operating with a different wavelength or, similarly, a single sensor employing two different wavelengths, would make possible the estimation of the oxygen saturation in blood as well [7,8]. On the other hand, the bio-impedance measurement is well-known in literature [9] to monitor the changes of biological tissue properties, like for example ions concentration due to physical effort. The monitoring of such properties may help the athlete to understand the body response to the current activity and, in accordance, to adjust his physical effort. In the present work, the measurement of the earlobe tissue impedance is achieved by encapsulating two electrodes in the clip support of the PPG sensor. By doing this, the size and weight of the sensor unit applied on the athlete earlobe are not substantially increased.

Data transmission takes advantage of the well-known and widespread Bluetooth wireless technology, which is already used in several applications for collecting sensor data [10,11]. In fact, Bluetooth is natively available in almost all portable devices, such as smartphones and tablets, which, in addition, are the best candidates for the data elaboration and visualization, thanks to the presence of relatively high computational resources and of a touch screen for the user interaction. Other communication technologies typically adopted to collect data from sensors, like Wi-Fi [12] and IEEE802.15.4 [13], present limitations regarding the power consumptions (Wi-Fi) and the support by smartphones (IEEE 802.15.4). Other interesting approaches, like the one proposed in [14], are not suitable for the proposed application, since the sensors are connected externally to the earlobe.

Lately, Bluetooth has been adopted for data transmission also in sensor systems for sport activities, thus making possible a direct communication link with the user smartphone. However, compatibility issues arise from this approach; in fact, Bluetooth standard defines a broad set of communication profiles, oriented for data as well as audio (streaming) transmission, differently supported by the most widespread devices on the market (Android, iOS, Windows Phone terminals). Currently, the only profile implemented by all the devices is the Hands-Free Profile (HFP), mainly used for communication with commercial headsets. The HFP solution has been chosen for data communication, to assure the full compatibility of the proposed sensor systems with the most available end-devices. This led to the need of implementing an effective first conditioning electronics for sensor data, which will be deeply described in the following.

For demonstrative purposes, a data acquisition and user interface programme has been implemented in Android environment. However, being the proposed solution independent of the used end-device, the development of applications for other terminals equipped with different operating systems is facilitated [1].

2. The proposed system

The proposed system is composed of three units, as illustrated in Fig. 1. The Sensor unit includes the sensors applied on the user earlobe for the physical data measurement. The analog front-end provides proper sensor excitation signals and implements the first conditioning electronics of sensor data. Moreover, as detailed in the following, it furnishes data to transmit to the Transmission unit in a suitable format. The latter is devoted to the Bluetooth transmission of data; to speed up the design process, a commercial Bluetooth earphone, able to transmit audio data, has been used for this purpose. The battery of the earphone is used to power also the other two units of the system.

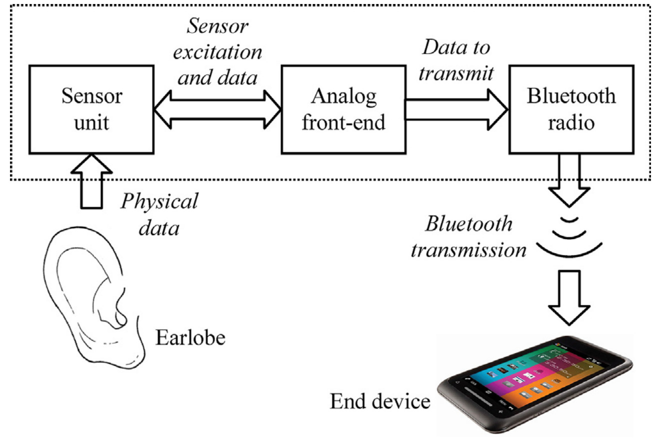

Fig. 1. Block scheme of the overall system; the circled part is the proposed solution for data measurement and transmission.

Transmitted data can be acquired by any device with Bluetooth capabilities. In order to demonstrate the validity of the proposed sensor system, a smartphone equipped with Android has been used as the end-device. A suitable software (App) has been developed to show the acquired data and to save them as an audio file for further off-line analysis. In the following, the three units of the sensor system will be detailed, whereas the smartphone App description will be included in Section 3.

2.1. Sensor unit

The sensor unit consists of an optical PPG sensor and two electrodes for the impedance measurement. The utilized PPG sensor adopts the transmissive technique and thus it is composed of a phototransistor and a photodiode to be placed face-to-face, with the target tissue in the middle. The photodiode emits an infrared beam which is detected by the phototransistor once the light has crossed the target tissue. An increase of blood volume in the tissue determines a decrease of the light received by the phototransistor; therefore, an electric signal following the behaviour of the blood volume can be acquired. Several details can be obtained by using the photoplethysmographic waveform. A single period is composed of two peaks separated by a small dip, called Dicrotic Notch; it represents the closure of the aorta with the end of systole, followed by the beginning of the diastole. The complete cardiac cycle can be used for the heart beat rate estimation. Moreover, recent works [5,6] illustrate that is possible to evaluate the occurrence of arrhythmias or arterial stenosis and occlusions from the heart rate variability. The two sensor components of the PPG, that is the phototransistor or photodiode, have been placed in the middle of two copper rings acting as electrodes for the impedance measurement. Each electrode has the form of a circular ring with 1 mm thickness. The diameters of the outer and inner circumferences of the rings are 10 mm and 5 mm, respectively. Electrical connections of the PPG sensor are assured by means of suitable hollows in the metallic rings. The attraction force of two magnets has been used to keep the rings in contact with the two sides of the earlobe and to