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Experimental low cost reflective type oximeter for wearable health systems

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ABSTRACT

The advent of wearable technology is fundamental to the dissemination of wearable personal health monitoring devices. Recent developments of biomedical sensors have decreased the form factor and power consumption that can be worn on a permanent basis. This paper discusses a low cost reflective photoplethysmography (PPG) system using a dedicated integrated circuit (IC) solution as the core of a wearable health monitoring device. The measurement of two physiological indicators is performed, namely the pulse rate (HR) and the blood oxygen saturation (SpO_2). The paper analyses in depth the PPG signals sensing architecture, guaranteeing high resolution measurements due to a delta-sigma analog to digital conversion unit. Post-processing digital filter operations are implemented to enhance low noise PPGs acquisition for physiological signals extraction. A complete system design is presented and a detailed evaluation is made in a real-time processing scenario. The test platform is completed with a PC based graphics application for on-line and off-line data analysis. Minimizing power dissipation is the main challenge in a wearable design. However, it restrains PPG signal measurement sensitivity by lowering signal quality. Using the developed prototype power consumption, studies concerning the characterization of power consumption and signal quality over various working conditions are performed. Next, a performance merit figure is proposed as the main research contribution, which addresses the power consumption and signal quality trade-off subject. It aims to be used as an analysis for trade-offs between these two conflicting design criteria.

1. Introduction

Sensors for health monitoring have been used for decades in the conventional healthcare network. Whether being utilised for the diagnosis and prevention of the patient or being employed in cases where the patient is bedridden, these signal sensing tools play a crucial role in modern healthcare services. Until few years ago these sensing tools were exclusively part of the hospitals and major private clinics. Despite being portable to a certain extent they had a specific function of monitoring a bedridden patient or with limited mobility. From the functionality point of view, they were used and are still being used as static sensing devices.

With increasing reduction of the size of silicon manufactured electronics chips, the design of dedicated ICs for health monitoring is now feasible as more and more functions are integrated in a tiny silicon area providing advanced functionality at low cost [1].

Pulse oximetry is a non-invasive method that compares how much red (RED) and infrared (IR) light are absorbed by blood vessels and serves as the basis for measuring SpO_2 [2,3]. In addition, the detected IR signal variable component related to arterial part can be used to determine the subject HR [4]. Portable pulse oximeter systems are currently utilised in hospitals, which can be transported around by the patient under investigation. The measurements are typically made at the extremities of the body. Consequently, the sensor is applied to peripheral parts of the human body [5].

Several studies were performed in the literature regarding such type of devices. In [6] developed algorithms for automated quality assessment for pulse oximetry and blood pressure signals were tested retrospectively with data acquired from a trial that recorded signals in a home environment. The development of an Electronic Patch – a new health monitoring system incorporating biomedical sensors, microelectronics, radio frequency communication, and

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a battery embedded in a 3-dimensional hydrocolloid polymer is reported in [7] for wearable health monitoring. In [8] is presented through a prototype a power optimised PPG sensor interface to sense arterial oxygen saturation, a technique to dynamically trade off signal-to-noise ratio (SNR) for power during sensor operation, and a simple algorithm to choose when to acquire samples in PPG. In [9] a ring-shaped photodiode designed for use in a reflectance pulse oximetry sensor in wireless health monitoring applications is presented. A study which investigates the effects of local tissue and room temperature conditions on PPG signal quality as applied to pulse oximeters using transmittance sensors for 20 healthy adult volunteers is proposed in [5]. In [10] is presented a novel cross-coupled sigma delta modulator which ensures that measurement accuracy will be more robust in comparison with conventional fixed-frequency oximeter modulation technique especially in the presence of pulsed artificial ambient light. Moreover, this novel modulator gives an extra control over the pulse oximeter power consumption leading to improved power management. In [2] is given the results from a study showing the ability of the Gaussian basis representation to extract heart rate and respiratory rate from PPG signal where several simulation experiments have been used to demonstrate that the Gaussian decomposition results in a highly efficient method for the representation of PPG signals. An ultra-low-power pulse oximeter suited for portable medical applications implemented with an energy-efficient transimpedance amplifier is proposed in [11]. In [3] is presented a small, low-cost pulse oximeter design appropriate for wearable and surface-based applications that also produces quality, unfiltered PPGs ideal for emerging diagnostic algorithms while being distinct from conventional pulse oximeters that incorporate filters for signal extraction and noise reduction. In [12] is developed a unique on-board feature detection algorithm to assess the quality of PPGs acquired with a custom reflectance mode, wireless pulse oximeter. In [13] is proposed the implementation of the first fully integrated pulse oximeter front-end with power consumption lower than 1 mW enabled by system- and block-level noise optimisation. In [14] is designed a wearable pulse oximeter a novel algorithm is proposed where a minimum correlation discrete saturation transform has been developed for the estimation of arterial oxygen saturation, based on an optical model derived from photon diffusion analysis. In [15] is presented a new method that uses the pulse oximeter signal to estimate the respiratory rate and the method uses a recently developed time-frequency spectral estimation method, variable-frequency complex demodulation to identify frequency modulation (FM) of the PPG waveform. A novel approach using time–frequency analysis of pulse-oximeter data to detect progressive hypovolemia in spontaneously breathing healthy subjects is proposed in [16]. In [17] is presented a particle filtering algorithm for respiratory rate extraction from pulse oximeter, which combines both time-invariant and time-varying autoregressive models for accurate extraction of breathing frequencies that vary either slowly or suddenly. In [18] is proposed a novel method for estimating respiratory rate in real time from the PPG obtained from pulse oximetry where three respiratory-induced variations (frequency, intensity, and amplitude) are extracted from the PPG using the Incremental-Merge Segmentation algorithm. Finally, a novel approach for motion artefact reduction in PPG signals based on AS-LMS adaptive filter is presented in [19].

An increasingly number of handheld pulse oximeters currently exist for fitness segment and health domestic applications. The common type use is the transmittance of light through a finger [20]. The wrist-finger model is noticeably ordinary in the market as well. The appliance is in fact a finger model since the sensor is positioned on a finger which is consequently attached to a wrist display. However, the pulse oximeter on the finger is relatively visible and the finger might not be entirely comfortable for extended periods and nonstop monitoring [21]. There are some disadvantages such as the recurrent addition of movement artefacts intercede particularly with long term monitoring of a subject [22]. Another shortcoming is the low quality of the signal in the incident of centralisation in cases in which the subject suffers from sepsis, coldness, shock or cardio-pulmonary anomalies [23]. On the other hand, such occurrences are the highest application scenarios of portable SpO_2 monitors [24]. Reflectance principle operated pulse oximetry is other form of implementation. The reflection one appears to be more capable since is possible to measure any area on the skin surface [25]. Conversely, in the case of oximeters of reflection nature, the reasonably great background (BG) light incident on the light detector and the poor reflection signal acquired from the skin surface exclude precise measurements [26]. Nevertheless, wearable devices by reflectance pulse oximetry will gain more and more acceptance from the domestic market. Several semiconductor manufacturers are targeting this market by releasing sophisticated dedicated units for such purposes. The great level of miniaturisation signifies that a robust and reliable oximeter comprising a microcontroller unit (MCU), biomedical sensors and advanced wireless communication characteristics can be combined into a very small physical device [27].

In this paper a low-power reflective pulse oximeter prototype is presented and built with a dedicated analog front end (AFE) circuitry with post-processing digital techniques based signal extraction performed by a low power high performance MCU. Real time software routines ensure continuous processing of HR and SpO_2 and raw PPG data are delivered to a workstation. Full wearable pulse oximetry requires ultra-low power dissipation since energy is provided by a small size battery. To keep low the average power consumption high strength of the signal received at the photodetector circuit cannot be guaranteed since SNR is negatively affected with short LEDs on-time [28]. In this regard, two research lines were developed in this paper. First, the oximeter design is scrutinised in two areas: signal quality measurement considering LEDs current values full scale and power consumption characterization in the same LEDs current range. Since the SoC's analog digital converter (ADC) can be operated with different resolutions its impact on oximeter performance is measured for the same evaluation parameters mentioned above. For this purpose the highest and lowest ADC resolutions were chosen. Secondly, a novel technique aimed to perform power consumption to signal quality trade-off is described. On the basis of the information collected above, a ratio is created and mapped for the LEDs current full range. It quantifies how much power is required to code the PPG AC term per digitization level (bit).

The paper is organised as follows. The challenges regarding a fully wearable oximeter design are identified and discussed in Section 2. The pulse oximetry theory is described in Section 3. Section 4 details system design. Section 5 contains the tests performed on the prototype board and provides results discussion. Finally, the conclusions are summarised in Section 5.

2. Challenges on wearable oximeter design

A fully wearable photoplethysmographic HR and SpO_2 monitoring equipment can be challenging since several constraints should be fulfilled such as small design size, easy to incorporate in clothes or externally attached to the body, its use pass unnoticed from user view point and requiring a battery change after a long period of continuous use. High-end performance oximeter for professional usage presents high resilience to ambient light and or motion artefacts and excellent accuracy [29]. All this come at a price – energy consumption requirement is not necessary a priority target. However, for a wearable sensing device lowering the oximeter power