Novel Methodology for Integrated Analog Front-End Signal Processing Blocks Based Portable Multifunctional Sensor for Biomedical Applications

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***Abstract*—Photoplethysmography (PPG) sensors are an inexpensive yet cost-effective way to track data correlated to the heart pulsation. The information is acquired with light signals generated by means of a photodiode and by detecting the amount of reflected or transmitted light through the tissue. In this paper, a novel methodology that enables a systematic approach for evaluating high compact signal processing designs, which are now a trend among several semiconductor manufacturers, is proposed and discussed. In this context, an integrated pulse oximeter sensor is embedded in a custom board and used to test the methodology concept proposed by the authors. Conclusions are duly drawn.**

Keywords—Biomedical electronics; Oximetry; Wearable health systems; Analog front-end block; Digital signal processing.

I. INTRODUCTION

Ever since the early 80s from the last century, wearable oximeters (WOs) appear as the established standard for non-invasive monitoring of arterial oxygen saturation (SpO_2) and heart activity.

Thus, oximetry is extensively utilized in medicine. WOs can monitor arterial SpO_2, which is the percentage of arterial hemoglobin that is fully saturated with oxygen, by transmitting red and infrared light through the finger, where it is sensed. When the SpO_2 is high, hemoglobin is saturated with oxygen, while a low SpO_2 has the opposite effect.

Oxygenation in the patient is a function of baseline oxygenation, metabolic requirement for oxygen, ability to utilize oxygen, and cardiac output [1].

The oximetry is an important instrument for the anesthetist as it supports rapid identification of decreased SpO_2 of a patient, and could reduce critical events in patients undergoing general anesthesia [2].

Commercial PPG sensors used in WOs typically work in transmission mode that needs the incident light sent by their emitters, red and infrared light-emitting diodes (LED), to penetrate the tissue at measuring areas to reach their detectors, photodiodes (PD) [3].

Based on the reflective technology, a number of WOs have been developed during the past decade. One challenge to WO design is how to balance comfortable wearing and reliable attachment. The simplicity of a basic WO coupled with increasing demand led to a large quantity of WOs being released into the market [4].

The current WOs are frequently designed as single modular devices, namely, the measurement and display modules are integrated on a single device, which are responsible for several problems. Such devices lack effective data management functions and by being limited by size, power consumption and cost, advanced operating systems cannot be embedded to such WOs, making difficult to store and manage data. Besides, such types of accessories process data and display results on a single device, leading to the design of controls and screen additionally increasing its size, power consumption and cost. Bearing in mind that the amount of data pulse wave signal collected is small, transmit it wirelessly is convenient and effective [5].

In this paper the authors discuss and propose a novel methodology that enables a systematic approach for evaluating high compact signal processing designs that are now a trend among several semiconductor manufacturers. These solutions are composed of dedicated analog Front-end circuits with internal red and infrared LEDs and a large set of configurable parameters. The following processing block is mostly based on sigma delta analogue digital conversion that offers variable data rate with different signal-to-noise ratios.

These types of integrated solutions preserve optical and electrical performance of the pulse oximeters with reduced energy consumption and considerable savings on board space. However, several designs options are still open which can create from designer view point, unexpected challenges to meet the balance between the desired accuracy, complexity level of signal processing algorithms which has an impact on microcontroller operation along with the adequate power management techniques. In this context, an integrated pulse oximeter sensor is embedded in a custom board and used to test the novel methodology concept proposed here.

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Common portable oximetry systems are usually designed utilizing excitation led units, a photodetector interface circuit and a precision analog digital converter (ADC) module operated by a microcontroller (MCU) that extract the DC and AC components of the plethysmography signals. Regardless of the small size of the components discrete circuitry a considerable print circuit board area is needed. With the purpose of facing the today trends towards smaller electronics devices without compromising the performance, efforts have been made to integrate as much as possible the various elements of the dedicated circuitry in miniature form into a single silicon unit. Such type of high integration and specialized circuitry is universally known as System on Chip (SOC) [6].

In order to become a wearable health application, the oximetry technology needs to be compact without causing discomfort with its use. Additionally, to be portable the oximeters weight need to be minimized and its energy consumption profile highly limited, something that can be considered challenging by reason of the LED sources [7]. As an alternative to transmission pulse oximetry the reflected PPG signals measurement devices could achieve the aforementioned qualifications while offering a singular advantage that enable them to be located in different body areas [8]. More than a few semiconductor manufacturers are targeting this market by releasing sophisticated SOC units for such purposes. The great level of miniaturization signifies that a robust and reliable WO comprising a MCU, biomedical sensors and advanced wireless communication characteristics can be combined into a very small physical device.

On the other hand, by facing growing levels of integration and a growing number of components connected to the bus, sentence such types of architectures as impractical [9].

To satisfy the power budget limitations is still a major obstacle for the engineers designing such type of systems. To tackle the issue of the increasing power consumption a trade-off has to be made. Thus, one has to reach to equilibrium between the power consumption and system precision.

The approach proposed in this paper has two main objectives. First, a more effective analysis on pulse oximeter design requirements taking as an example an integrated SOC MAX 30100 [10]. Typically, this type of dedicate circuits are characterized by including internal analog front end block, LED driver and dedicated analog to digital conversion system. Their function is to automatize basic tasks such as acquiring and filtering the PPG signals. At first glance, the task of the designer seems facilitated. However, from an oximetry project optimization view point less variables to trade-off implies less flexibility for the design engineer. It is true the engineering team can quickly design the product saving time and considerable resources following this approach. On the other hand, if the power consumption is critical to reduce as maximum as possible the wearable oximetry device or alternatively PPG signals accurate readings are required, extensive and time-consuming tests have to be made just only to get reliable information regarding the SOC device.

The paper is organised as follows. The challenges regarding a fully wearable oximeter design are identified and discussed in Section II. Section III presents an evaluation methodology. In Section IV is applied the methodology to a real case study. Finally, the conclusions are summarized in Section V.

II. 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, 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 [11].

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 consumption is critical. Several strategies are proposed in literature for handling energy consumption issue [4].

At core of an oximetry sensor the front-end design consists of a single photodiode at the detector end, a transimpedance amplifier (TIA) as photoreceptor and a signal conditioning stage to filter the noise outside the frequency band of interest and to match the PPG signal amplitude to the analog digital converter (ADC) input range. Furthermore, a LED driver circuit is part of the design, generating two modulate light output. The signal processing algorithms to estimate the quantities of interest, which are SpO_2 and HR are carried out by a microcontroller (MCU).

Fig. 1 depicts common composition for the signal conditioning chain.

The PPG signal quality depends on the resolution employed to measure the photocurrent. In other words, the level of sensitivity regarding the oximeter analog front-end is typically described in terms of signal-to-noise ratio (SNR). Therefore, PPG readings with adequate SNR imply low noise analog front-end design [12].

Oximetry devices have different noise sources that contribute to limit the SNR performance. Consequently, minimizing noise in the signal path is a primary concern as complex if an acceptable SNR is desirable using low LED duty cycles to save battery energy. Is sum, designing cheap wearable oximeters is a trade-off between accuracy and power. With this approach, LED current regulation is the main contributor for power consumption. At the other side of the spectrum, noise sources are related to the normal noise of the photodiode, the voltage source used to reverse-bias the photodiode, TIA feedback resistors thermal noise, the switched-integrator along the voltage-mode operational amplifier [4].

Fig. 2 highlights the pros and cons of the trade-off that has to be made given the initial goals when designing the oximeter.

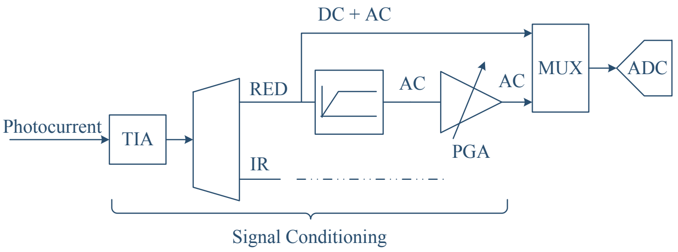


Fig. 1. Pulse oximeter signal conditioning typical block diagram.

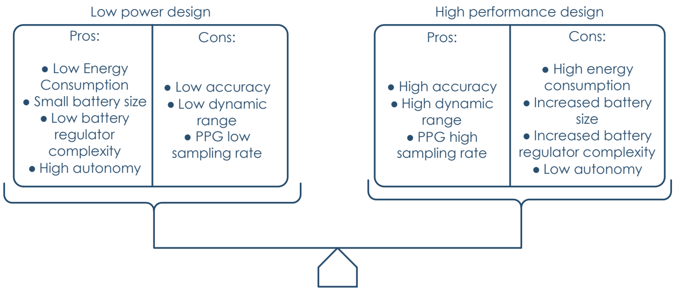


Fig. 2. Pulse oximeter signal conditioning typical block diagram.

III. EVALUATION METHODOLOGY

From a design perspective, the designer faces two contradictory goals. One is to maximize the PPG measurements with the best signal quality possible which means high resolution digital conversions. In particular, this is true since photocurrent AC component is lower in relation to the DC term. Extracting the AC portion of the PPG signal with high digital representation is affected by the LED current intensity that reaches the photodetector as photons. However, driving light sources at maximum rating requires a higher energy consumption that penalizes the portability target for wearable oximetry designs. In this sense, testing different configurations to find the best relation signal quality/energy consumption can be tedious and cumbersome. Instead, a procedure that identifies a set of steps to be followed could save testing time while data collected serve as inputs to specific merit figures.

Fig. 3 depicts the simple methodology for SOC power reduction versus AC term resolutions trade-off. In this sense a metrics was created. This matric provides effective number of bits that can be used for each mW required by the oximeter. Term ψ represents the IR related AC and ξ represents the RED. The ψ and ξ is as follows:

$$\psi = \frac{P_{SOC}^{AVG}}{AC_{IR}^{ENB}} \qquad (1)$$

$$\xi = \frac{P_{SOC}^{AVG}}{AC_{RED}^{ENB}} \qquad (2)$$

where AC_{IR}^{ENB} and AC_{RED}^{ENB} signify PPG signal peak to peak portion translated in terms of ADC bits used for representation. The P_{SOC}^{AVG} represents the average power which includes the consumption of internal modules of SOC and LED drive.

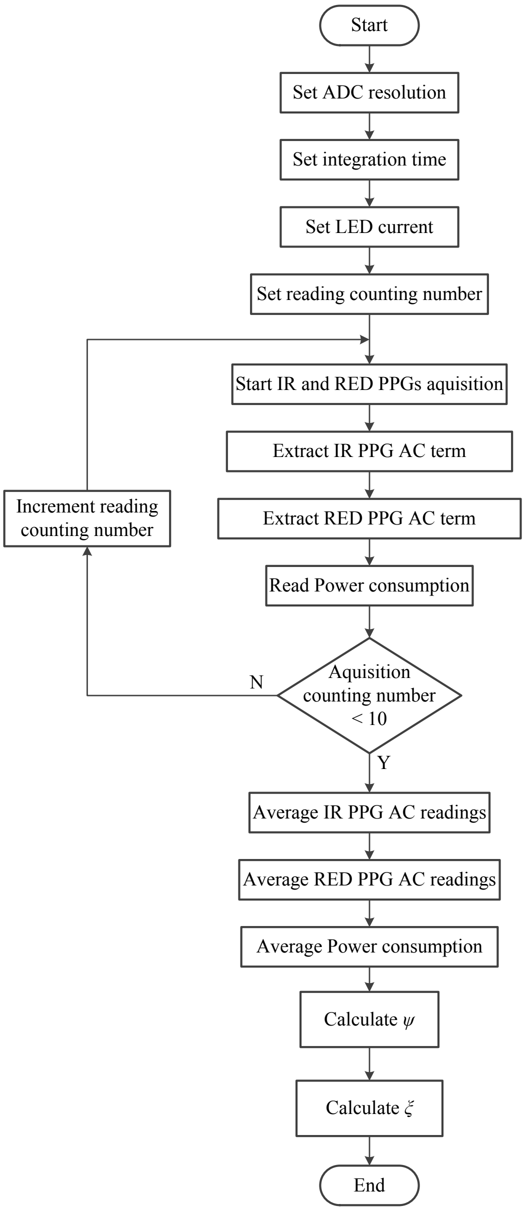


Fig. 3. Evaluation methodology.

IV. CASE STUDY

A reflectance pulse oximeter custom design based on a MAX30100 SOC unit manufactured by Maxim Integrated is used for the case study [10]. The SOC in question comprises IR e RED LEDs, a photodetector and a low-noise front end that reject ambient light effect on readings. In addition, the SOC device acquires digitally the PPG samples through a 16-bit sigma delta ADC. This integrated solution has high flexibility configuration allowing sampling rates from 50sps and 1000sps. In turn, the current driven to the LEDs is set from a significant range of values. The minimum is 4mA and a maximum is achieved at 50mA. Finally, depending on the pulse width chosen for LED operation PPGs can be digitalized with 16-bit resolution as a maximum. Instead, selecting a minimum pulse width it is not possible the get more than 13-bit. A preliminary custom design is shown in Fig. 4.

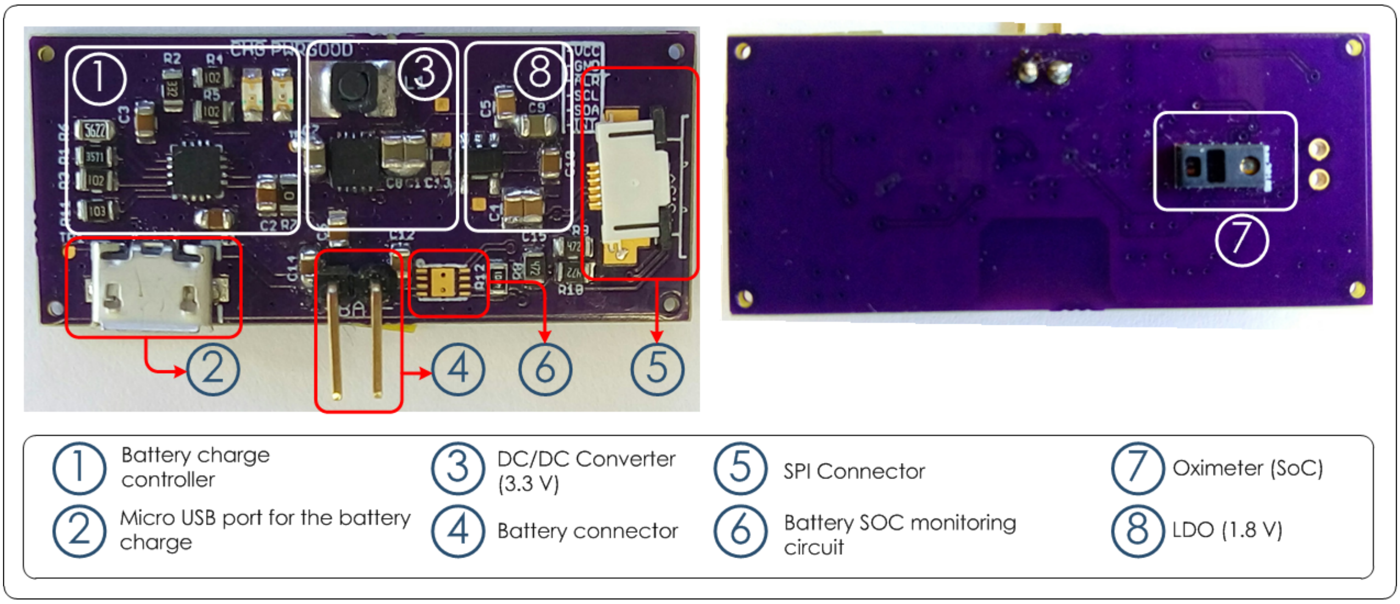


Fig. 4. SOC operated oximeter custom board.

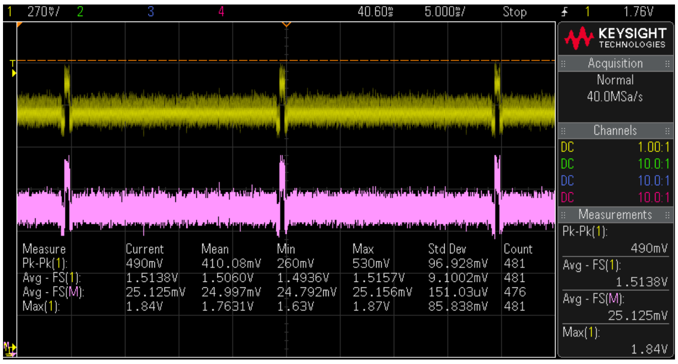
In the current version of the custom board, all post-signal processing activities are executed externally in another board equipped with a 32-bit MCU (TM4C123 reference from Texas Instruments).

The metrics were tested exploring two modes of ADC resolution, that is, the maximum and minimum available resolution was utilized, which are, respectively, 16 and 13 bits. Since the goals of the tests is to ascertain the quality of AC signal in function of excitation current applied to the IR and RED LEDs six LED regulation values were chosen. The LEDs are powered by modulated peak current that covers the values of 4.4, 7.6, 17.4, 27.1, 40.2 and 50 mA.

In Fig. 5 the MCU current profile can be observed that corresponds to the processing of the PPG signals acquired by the SOC. The observed peaks of the current consumption are correlated to the sapling rate programmed in the SOC. The duration of the signal during the peaks results from the digital signal processing operations necessary to obtain the quantity of SpO_2. The yellow signal represents current waveform measured through current shunt monitor. The pink signal represents current monitor output divided by the measurement circuit gain.

Tables I and II provide the results concerning the effective number of bits achieved by each modulated peak current. For the minimum conversion resolution available it is obtained approximately between 3.6 and almost six bits using a current from 7.6 to 50 mA. For the lowest current (4.4 mA) it wasn't possible to obtain consistent results.

With the maximum conversion resolution available is possible codify the AC term with almost eight bits utilizing the maximum allowed current by the SOC and minimum is 5 bits when setting the LED driver with 4.4 mA, as observed in Table II.



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Measure       Current    Mean       Min        Max        Std Dev    Count
Pk-Pk(1):     490mV      410.08mV   260mV      530mV      96.928mV   481
Avg - FS(1):  1.5138V    1.5060V    1.4936V    1.5157V    9.1002mV   481
Avg - FS(M):  25.125mV   24.997mV   24.792mV   25.156mV   151.03uV   476
Max(1):       1.84V      1.7631V    1.63V      1.87V      85.838mV   481
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Fig. 5. Current monitor raw output in yellow and current monitor output divided by the measurement circuit gain in pink.

TABLE I. 13-BIT ACQUISITION MODE

I_{LED} (mA)	IR AC term (Raw ADC count)	Bits	RED AC term (Raw ADC count)	Bits
50	51,1	5,7	37,2	5,2
40,2	51,5	5,7	44,1	5,5
27,1	33,0	5,0	25,0	4,6
17,4	25,7	4,7	16,9	4,1
7,6	12,4	3,6	11,9	3,6
4,4	-	-	-	-

TABLE II. 16-BIT ACQUISITION MODE

I_{LED} (mA)	IR AC term (Raw ADC count)	Bits	RED AC term (Raw ADC count)	Bits
50	241,8	7,9	179,1	7,5
40,2	251,5	8,0	171,8	7,4
27,1	194,7	7,6	139,4	7,1
17,4	147,9	7,2	100,0	6,6
7,6	73,5	6,2	49,6	5,6
4,4	31,2	5,0	23,2	4,5

Finally, the metric outputs are represented in the Figs. 6 and 7. Observing the aforementioned figures it can be noticed that the AC average power over effective number of bits is higher in the 16-bit acquisition mode. In the case of 13 bits and for each extracted bit for PPG AC representation only 16.6% of the energy is used when compared to the same bit in 16 bits conversion mode. By observing aforementioned figures, it can be noticed that a particular case of optimization can be identified where in the 16-bit mode by utilizing the minimum LED current (4.4 mA) it is obtained the identical number of bits in the 13-bit mode but utilizing the 27.1 mA.

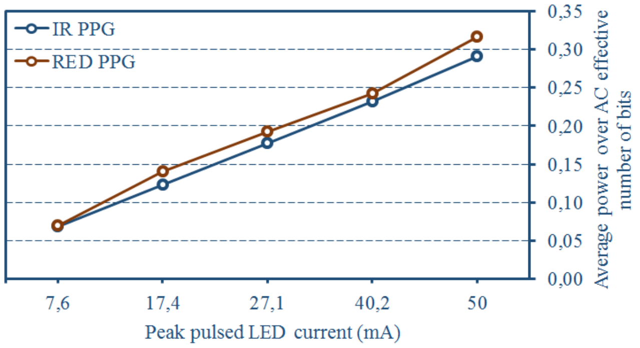

Fig. 6. 13-bit acquisition mode: ψ and ξ vs LED current.

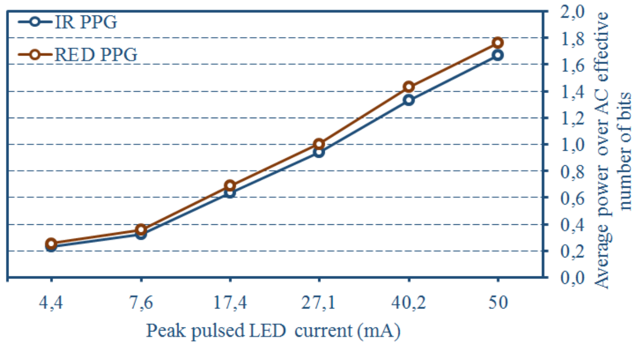

Fig. 7. 16-bit acquisition mode: ψ and ξ vs LED current.

V. CONCLUSIONS

The basis for an evaluation procedure considering high integrated reflectance pulse oximetry sensor has been discussed. The procedure in mind aimed to full characterize a design based on a dedicated SOC in terms of signal quality versus energy consumption. For that, the proposed methodology was tested making use of a custom board. PPG readings were conducted, AC component extracted and analyzed under different scenarios of LED current using maximum and the lowest ADC resolution available.

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