PPG/ECG Multisite Combo System Based on SiPM Technology

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Abstract.

Two versions of a PPG/ECG combined system have been realized and tested. In a first version a multisite system has been equipped by integrating 3 PPG optodes and 3 ECG leads, whereas in another setup a portable version has been carried out. Both versions have been realized by equipping the optical probes with SiPM detectors. SiPM technology is expected to bring relevant advantages in PPG systems and overcome the limitations of physiological information extracted by state of the art PPG, such as poor sensitivity of detectors used for backscattered light detection and motion artifacts seriously affecting the measurements repeatability and pulse waveform stability. This contribution presents the intermediate results of development in the frame of the European H2020-ECSEL Project ASTONISH (n.692470), including SiPM based PPG optodes, and the acquisition electronic components used for simultaneous recording of both PPG/ECG signals. The accurate monitoring of dynamic changes of physiological data through a non-invasive integrated system, including hemodynamic parameters (e.g. heart rate, tissue perfusion etc.) and heart electrical activity can play an important role in a wide variety of applications (e.g. healthcare, fitness and cardiovascular disease). In this work we describe also a method to process PPG waveform according to a PPG process pipeline for pattern recognition. Some examples of PPG waveform signal analysis and the preliminary results of acquisitions obtained through the intermediate demonstrator systems have been reported.

Keywords: PPG, SiPMs, Pattern Recognition.

1 Introduction

PhotoPlethysmoGraphy (PPG) is a noninvasive optical technique that measures blood volume changes during the heart pulsation. PPG is widely used in commercial and clinical devices to evaluate cardiovascular indicators such as oxygen saturation, beat to beat pressure and arterial compliance [1]. In a typical PPG system, visible or infrared wavelength photons coming from a light emitting diode (LED) go through the skin layers up to the underlying tissues and are revealed by a photodetector either for the case of backscattered or transmitted beams. PPG signal and its physiological relation have been widely studied [2]. Recorded pulse has a direct relationship with perfusion and the greater the blood volume the more the light source is attenuated. Since the arterial volume changes during each cardiac cycle, because of the propagating pulse pressure wave, the upcoming light is modulated accordingly. The pulsatile (AC) component of the signal, related to the heart beat, is superimposed to a much larger slow oscillating (DC) component related to tissue and baseline blood volume absorption. Although PPG measurements, because of light diffusion, generally integrate the signal coming from blood vessels of different caliber, different experimental setups can be more sensitive to one vessel type with respect to the others [2]. PPG measurements can be performed in backscattering and/or transmission mode. Most of the commercial devices work in transmission mode on the fingertip or earlobe. In these devices, the tissue is irradiated by a LED and the light is measured by a photodiode on the other side of the tissue. These measurements are limited to microvascular assessment on specific body sites. In fact, larger arteries lie deeper in the tissue and are difficult to be inspected. The depth sensitivity, affecting the capability of exploring the larger arteries, depends on both the wavelength [3] and the sensitivity of the detector employed.

In this perspective the use of Silicon Photomultipliers (SiPMs) operating with intrinsic avalanche gain (up to 10^6) and single photon sensitivity (down to 5-10 detected photons) is expected to bring relevant advantages in PPG systems in terms of higher AC-to-DC ratio in PPG pulse waveform, high repeatability and immunity to motion artifacts and reduced power consumption [4]. The enhanced sensitivity of the SiPMs can add new measurements capabilities to existing PPG solo systems (e.g. blood pressure) or in multisite PPG systems (e.g. pulse wave velocity (PWV)), opening new interesting markets for these devices. Besides the expected innovation in PPG systems, the accurate monitoring of dynamic changes of physiological data through a non-invasive integrated system, including hemodynamic parameters (e.g. heart rate, pulse wave velocity etc.) and heart electrical activity, can play an important role in a wide variety of applications (e.g. healthcare, fitness and cardiovascular disease). To this purpose, there is also a great interest to develop integrated, low-power consumption and portable photoplethysmography-electrocardiography (PPG/ECG) combo systems for assessing the above-mentioned physiological parameters and their ubiquitous monitoring over time. The EU H2020-ECSEL ASTONISH project (grant agreement 692470) [5] will deliver an advanced multisite PPG-ECG combo system for the assessment and monitoring of relevant cardiovascular diseases occurring as result of ageing, hypertension, and atherosclerosis, providing also information on arterial stiffness. This will be done through a proper combination of advanced technology blocks including high sensitivity SiPM based PPG probes, innovative electronic hardware for fully synchronized multisite measurements, advanced algorithms for data filtering, analysis and pattern recognition and suitable software interface for measurements calibration, data recording and analysis. In this contribution, we present the intermediate results of this development including SiPM based PPG optodes, the acquisition electronics components used for simultaneous PPG/ECG measurements (Fig.1) and a PPG pattern recognition pipeline [6]. In particular, the preliminary acquisitions obtained through an intermediate demonstrator system composed by 3 PPG optodes and 3 ECG leads along with some examples of PPG waveform signal analysis are reported (Fig.2).

2 Experimental Setup

The PPG probes used for the development of the PPG/ECG combo systems introduced in the previous section were equipped with large area n-on-p SiPM [7-10] detectors manufactured at STMicroelectronics in Catania [10].

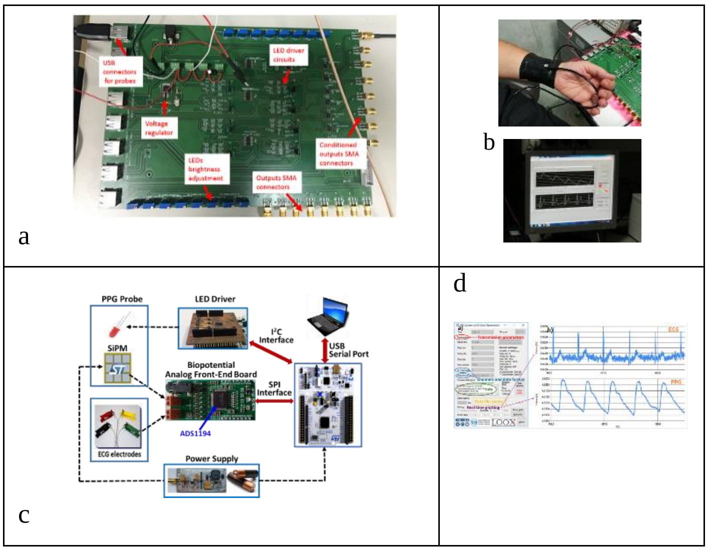

Fig. 1. SiPM based PPG/ECG combo systems demonstrators. a) Interface board containing suitable circuits for LED and SiPMs operation b) IR PPG transmission wristband with USB communication data transfer and comparison of the PPG/ECG signals of the multisite system of ST. c) Schematic of the portable PPG/ECG demonstrator with two channels realized at UNIPA, d) Example of synchronized PPG and ECG signals. PPG pulsatile component is characterized by a larger peak of absorption (local minima) during the diastolic phase in which the blood volume change is maximum. A secondary small peak or a bump, due to wave reflection, is also visible. The latency between the ECG R-peak (the largest one) and the PPG onset reflects the propagation of the shock wave in the vascular system.

The devices were fabricated on p-type silicon epitaxial wafers and formed of n^+-p microcells. N-on-p SiPMs were chosen for this application considering their higher photon detection efficiency (PDE) in the visible and near infrared wavelength ranges with respect to the p-on-n version of the technology. The probe consisted of two LEDs 1 cm distant from the SiPM, which was at the center of the probe. Used SiPMs have a geometrical fill factor of 67.4%. Fig. 1b shows an IR PPG transmission wristband with USB communication data transfer. The SiPMs array is packaged in a surface mount housing (SMD) with 5.1x5.1 mm^2 total area. Light source was a LED emitting at 940 nm wavelength. The SiPMs were equipped with an optical "longpass" plastic filter having a cut-off wavelength at λ=700 nm in the near infrared [11]. The SiPM was mounted on a small PCB, about 3x2 cm^2, containing only the detector and passive components. To have a probe with a smooth front surface, a sheet of black rubber was applied, with suitable holes in correspondence of sources and detectors and in such a way to assure optical isolation between sources and detectors. This very simple probe was highly flexible and comfortable. Given the average travel speed of the pulse pressure-wave, a time resolution in the range of milliseconds is needed. This has been achieved using a high resolution (24 bit) National Instruments NI-PXIe-4303 ADC for both PPG and ECG. This device has also a very high synchronization time between two different channels which is significantly lower than 1 µs. An interface board (Fig. 1a) has been internally developed including the power supply, the amplification stages and conditioning circuits for output SiPMs signals, the LED driver circuits and suitable connectors for PPG optodes and ECG probes. This system will allow multisite PPG and ECG measurements up to a total of 32 channels. Measurements have been conducted in backscattering mode on the radial and tibial arteries. Simultaneously, the subject ECG was acquired to monitor the heart activity and to assess the PPG Pulse Transit Time. In a typical measurement session, the subject was lying in supine position and instructed to avoid any unnecessary movement. Three probes were placed in correspondence of the right and left wrist radial artery and left ankle as shown in figure 2. Following the ECG standard procedure, three electrodes have been placed to acquire LEAD I, LEAD II and LEAD III derivations.

Fig. 2. Experimental setup and first measurements obtained on an intermediate PPG/ECG combo system composed by 3 synchronized PPG probes and 3 ECG leads.

3 Data Analysis

The assessment of quality of PPG waves was conducted by using a fully automatic processing pipeline. A toolkit based on Matlab scripts and functions has been implemented according to the following four main steps:

- QC: overall **quality check** assessment
- AI: **artifact identification**
- PRW: **pattern recognition** of PPG **waveforms**
- FDA: **First derivative analysis** for the assessment of the main PPG parameters.

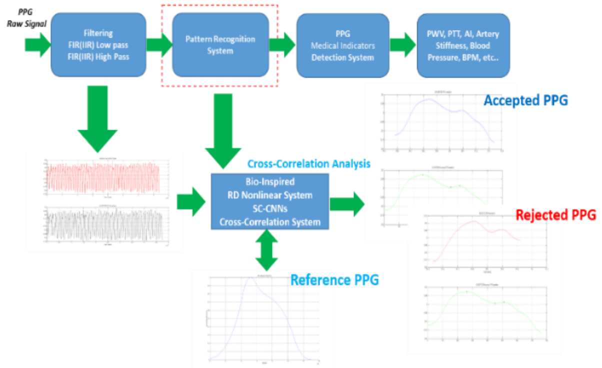

Fig. 3. PPG pattern recognition pipeline.

In the first step (QC), the overall quality of the PPG raw data was considered. The pulsatile (AC) and the slow varying (DC) contents of the signal were considered and compared. Pulsatile component was obtained by filtering the raw data with a band pass zero-lag Butterworth filter in the 1-10 Hz frequency range. Parameters used were the AC/DC ratio and the variation of the AC and DC amplitudes with respect to their initial values. The second parameter can be slightly varying with the pressure of the probe over the skin [2]. Thus, the stability of the AC/DC ratio was used to check for possible decoupling of the probe from the subject skin. Without any external pressure of the probe, the AC/DC ratio is generally larger than 1% and smaller than 10%. The second step (AI) was an automated artifact detection algorithm based on the evaluation of the variance of the signal over time. Artefact affected signal epochs were identified by means of a statistical threshold and discarded. An iterative procedure allowed the identification of all the contaminated periods.

The Pattern Recognition Algorithm (Figure 3) allowed to identify good PPG waveforms with an accuracy above 90%.

The proposed pattern recognition system supposes to find compliant PPG waveforms between two minimum local points so that firstly performs a simple segmentation of the pre-filtered PPG signals through the detected local minimum.

Afterwards, the bio-inspired core of the proposed pipeline performs ad-hoc nonlinear dynamic evolution.

Pattern recognition of PPG waveforms relies on a theoretical waveform derived from a reaction diffusion nonlinear mathematical model properly configured [12]-[13]. The nonlinear mathematical model was implemented by means of Cellular Neural Networks (CNNs) as reported in [13]. Due to its analogic implementation, the CNNs are able to perform such operations with high-speed computational capability i.e. near real-time.

Ad-hoc normalized sample cross-correlation analysis was performed in order to have a compliance measure for the analyzed PPG waveform. Only the PPG patterns showing high normalized sample cross-correlation (≥ 0.90) were considered as compliant whereas the other ones were discarded [6]. The results of the proposed pipeline applied for PPG signal processing confirmed the robustness and effectiveness of the approach herein described showing very promising sensitivity and specificity. The developed algorithm showed encouraging results in discriminating good PPG signals and artifacts. This novel approach may be extended to the classification of PPG waveforms of different physiological and pathological conditions. Some pulse parameters were obtained by searching for local maxima and minima of the pulse in the proper order [14]. A sample of PPG waveforms together with the related features is reported in Fig. 4. In the last step, a further standard PPG first derivative analysis was performed on the selected waveforms [14]. Good epochs were divided in trials corresponding to single heart beats. The ECG was used to define the trial onset based on the ECG R-peak. In this way, all the parameters found were time-locked to the heart cycle. Waveform foot (foot), primary peak (P1), dicrotic notch (DN) and the secondary peak (P2) were the main pipeline output. Fig. 5 shows the first derivative analysis on the average PPG waveform of the radial site as an example.

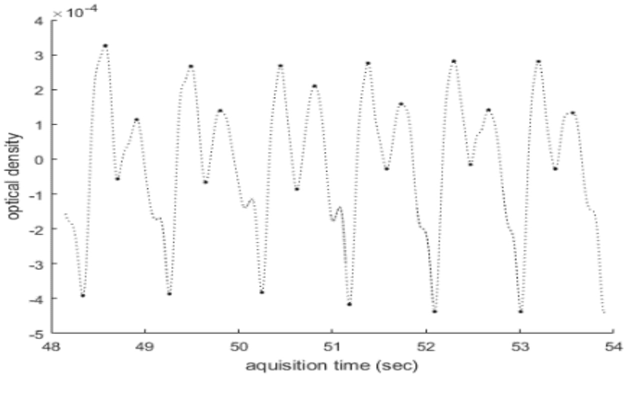

Fig. 4. Examples of features identification of a collection of PPG waveforms.

The parameters were obtained by searching for local maxima and minima of the pulse in the proper order [14]. A sample of PPG waveforms together with the related features is reported in Fig. 5.

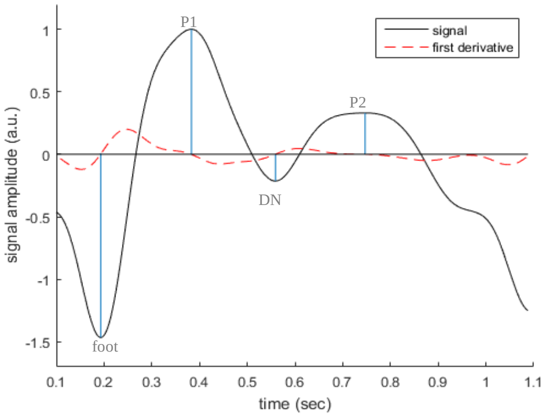

Fig. 5. First derivative analysis of the waveform obtained by averaging over the selected recorded PPG trials.

4 Conclusions

The results presented in this work demonstrate the capabilities of the SiPM photodetectors technology in combination with ECG electrodes in order to build a multisite and a portable PPG/ECG system to be employed for PPG measurements in a backscattering mode. Measurements were performed by using infrared light of an LED used as optical light source and a suitable optical longpass filter on SiPM detector for environmental light rejection. For both the systems, to analyze data, we have implemented also an automatic process pipeline able to perform data cleaning, selection of good PPG trials and carry on a first derivative analysis. A novel approach based on pattern recognition was also presented. The analysis showed the feasibility of the pipeline on the acquired data. Future directions may exploit SiPMs high sensitivity and large dynamic range by employing them in the PPG evaluation of deep arteries for which a small pulsatile signal is expected. These measurements could be conducted both in backscattering and transmission mode and in different body sites than just fingers and ear lobes.

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References

1. Allen, J.: Photoplethysmography and its application in clinical physiological measurement, Physiological measurement 28(3), R1-R39 (2007).
2. Reisner, A., et al.: Utility of the photoplethysmogram in circulatory monitoring. The Journal of the American Society of Anesthesiologists 108 (5), 950-958, (2008).
3. Liu J, Yan BP-Y, Dai W-X, Ding X-R, Zhang Y-T, Zhao N,.: Multi-wavelength photoplethysmography method for skin arterial pulse extraction, Biomedical Optics Express, 7(10), 4313-4326, (2016).
4. Mazzillo, M. et al., Silicon photomultiplier technology at STMicroelectronics, IEEE Trans. Nucl. Sci.: 56 (4), 2434–2442 (2009).
5. ASTONISH project homepage, http://astonish-project.eu, last accessed 2018/03/20.
6. Vinciguerra, V. et al.: Progresses towards a processing pipeline in photoplethysmogram (PPG) based on SiPMs. 2017 European Conference on Circuit Theory and Design (ECCTD), 1-5, (2017).
7. Agrò, D. et al.: PPG embedded system for blood pressure monitoring, Proc. AEIT Int. Annu. Conf. (AEIT), pp.1-6, (2014).
8. Pagano, R.et al., Improvement of sensitivity in continuous wave near infra-red spectroscopy systems by using silicon photomultipliers, Biomed. Opt. Express, 7(3), 249662, (2016).
9. Chiarelli, A. et al.: Wearable Continuous Wave functional Near Infrared Spectroscopy system based on Silicon Photomultipliers detectors: In-Vivo assessment of primary sensorimotor response, Neurophotonics, 4(3), 035002, (2017).
10. Buzhan, P. et al., Silicon photomultiplier and its possible applications, Nucl. Instrum. Methods Phys. Res. A, (504), no. 1–3, 48–52, (2003). Bland, J. M. and Altman, D. G., Measuring agreement in method comparison studies, Stat. Methods Med. Res. 8(2), 135–160 (1999).
11. Mazzillo, M., et al. Noise Reduction in Silicon Photomultipliers for Use in Functional Near-Infrared Spectroscopy, IEEE Transactions on Radiation and Medical Plasma Sciences, 1(3) 212-220, (2017).
12. Rundo, F., Battiato,S., Giuffrida, E.U., A Cellular Neural Network for Zooming Digital Colour Images, International Conference on Consumer Electronics (2008) 1-2.
13. Arena. P., *et al.* A CNN-based chip for robot locomotion control, IEEE Transactions on Circuits and Systems, 2005, 52(9).
14. Elgendi, M., On the analysis of fingertip photoplethysmogram signals, Current cardiology reviews 8.1: 14-25, (2012).