DESIGN AND PROTOTYPING OF A MINIATURIZED SENSOR FOR NON-INVASIVE MONITORING OF OXYGEN SATURATION IN BLOOD

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ABSTRACT
In this paper a new sensor for the non-invasive monitoring of the oxygen saturation in blood has been designed, realized and tested to obtain an ultra-small device having very high noise immunity. This goal has been reached by using a particular integrated circuit, the PsoC (Programmable System on Chip), which integrates two programmable arrays, one analogue and one digital, to obtain a device with very large capabilities. We have configured the PsoC and developed the electronic interfaces. The proposed design allows the acquisition of the continuous component of the signal and the data elaboration has been done in place using a local CPU, without requiring to pass data to an external computer.

KEYWORDS: *Oxyhaemoglobin Saturation, Spectrophotometric Method, Pulse Oximeters, Electronic Interfaces and Data Processing, Sensor Prototyping and Testing.*

I. INTRODUCTION

Non-invasive health monitoring is the main goal of modern electronic applications to medicine. In particular, among the most critical vital parameters, one can find the oxygen saturation of oxyhaemoglobin HbO_2. Currently the standard procedure for monitoring gases in blood is to take arterial blood samples. This is time consuming for the nurses and stressful particularly for those patients with cardiac respiratory or renal insufficiency, i.e. requiring a continuous monitoring.
Several invasive methods for continuous monitoring have been proposed, based on the use of catheter or optical fibre sensors, but they have many problems such as inevitable pain for the patient, possible infections, long term drift caused by blood's substances deposition on the catheter, need for hospitalization, and last but not least, the high cost.
In order to overcome these problems, there is an effort to develop other devices with better characteristics, which allow mainly the non-invasive, continuous monitoring with good accuracy. Among these devices, the pulse oximeter, which senses the oxygen saturation in blood using non-invasive optical sensors, seems to be the best [1]. Although this device is typically used in hospitals, it still has some drawbacks that should be solved in order to make this device available even for home proposes without the assistance of registered nurses. Moreover, among the required enhancements, it has to be cheap, small, user-friendly, accurate and noise immune.
In this paper we present a new pulse oximeter, which has been realized and tested at the Electronic Devices Laboratory (Electrical and Electronic Department) of Polytechnic of Bari.
The proposed sensor, designed in order to obtain a cheap device with reduced size and very high noise immunity, uses a single chip, such as the PSoC (Programmable System on Chip) [2], produced by Cypress MicroSystems, which, through its programmability, i.e. its capability within hardware and software to change, allows the signal acquisition and conditioning of the whole system on a single chip.

In Section 2 we have described the front end of the proposed pulse oximeter, while in Section 3 the obtained results are analyzed and discussed. The conclusions and future scope are illustrated in Section 4.

II. FRONT END OF THE PROPOSED PULSE OXIMETER

The pulse oximetry is a spectrophotometric method for non-invasive measurement of the arterial oxygen saturation, SpO_2, and pulse [3]. It is based on the different light-absorbing characteristics of oxyhaemoglobin (HbO_2) and deoxyhemoglobin (Hb) at two different wavelengths, typically 660 nm (RED) and 940 nm (IR), and on the pulsatile nature of arterial blood flow [4]. Of course, the optical sensor measurements of HbO_2 and Hb are dependent on the concentration of these molecules in blood. With pulse oximeters, a finger or earlobe probe is used. A red light-emitting diode (LED) and an infrared LED is located, as sources, on one side of the probe, and a couple of photodiodes, as receivers, are located on the other side.

The method relies on difference in the absorption spectra of oxygenated and de-oxygenated hemoglobin. The ratio between these, as shown in [3], has a peak at approximately 660 nm and at higher wavelengths the ratio is lower than one.

Conventionally the previous two wavelengths are used since the absorption ratio is large and small at those wavelengths, respectively. This minimizes the uncertainty of the SpO_2 measurement. The measured absorption is then displayed as an estimate of the arterial oxygen saturation, SpO_2. The sensor, applied to a finger or to earlobe, can work on the transmitted light, realizing in this way a transmission pulse oximeter, or on the reflected light, as a reflectance pulse oximeter [5-9]. The equipment is electrically the same in both cases.

Fig. 1 shows the block scheme of the proposed pulse oximeter.

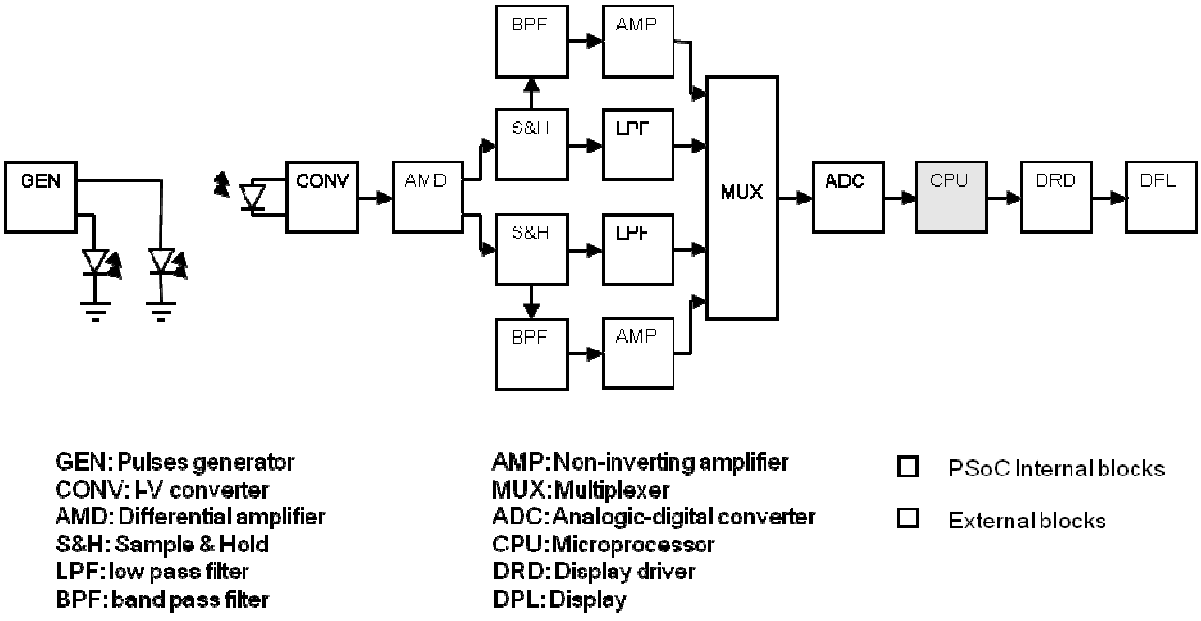

Figure 1. Block scheme of the proposed pulse oximeter.

We have used the PSoC CY8C27443 produced by Cypress MicroSystems [2], a family of devices which allows the implementation of systems on a single chip that contains both analogue and digital programmable blocks, thus allowing the synergic management of analogue and digital signals in a single programmable device, reducing in this way the number of integrated circuits on board.

LEDs are powered by a sequence of square pulses, as shown in Fig. 2, 0.2 ms long at a frequency of 500 Hz and with a phase difference of 1 ms, obtained by an internal PSoC oscillator.

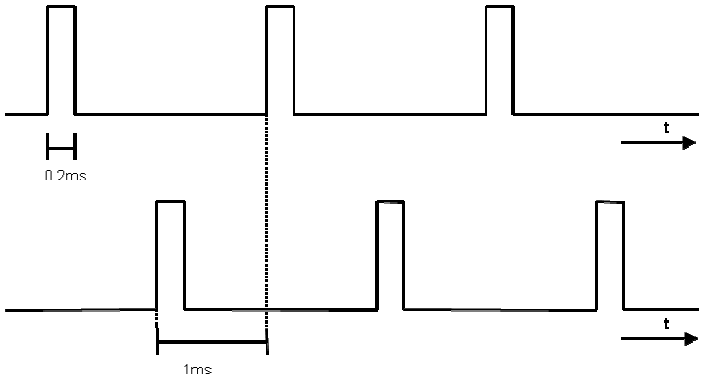

Figure 2. Control signal of the power on the LED.

For each LED we have placed a photodiode on the other side of the finger to collect the transmitted light (Fig. 3). This layout allows us to have a larger collection efficiency.

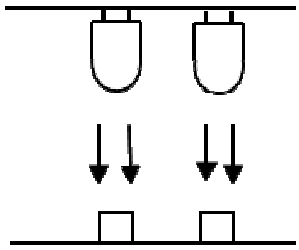

Figure 3. Sensor's scheme.

The light signal measured by the photodiode can be divided in two components: A and B [3]. Component A is the light signal during a systole and is a function of the pulsations of oxygenated arterial blood, while component B is the light signal (during a diastole) that has a constant intensity and is a function of various tissues (i.e. skin pigment, muscle, fat, bone, and venous blood). The pulse oximeter divides the pulsatile absorption of component A by the background light absorption of component B, at the two different wavelengths (RED and IR), to obtain an absorption ratio, R:

$$R = (A_R/B_R) / (A_{IR}/B_{IR}) \quad (1)$$

The photodiode transforms the light signal into an electrical signal that is amplified and converted into digital information.
The current generated by the photodiode is the input of a current-voltage converter working in differential mode, followed by INA105 amplifier (Fig. 4), used to obtain the signal in single ended mode.
The resulting amplifier topology is then that of an instrumental amplifier but with inputs placed in at different nodes, allowing in this way an high noise immunity at the input since most of the noise is a common mode noise.
After the amplifier, the acquisition system splits in two just alike channels, each of them obtained using a Sample & Hold, synchronized with the pulse generator that feeds the LEDs. In this way, it is possible to distinguish between the signal corresponding to red wavelength and the one corresponding to infrared wavelength.

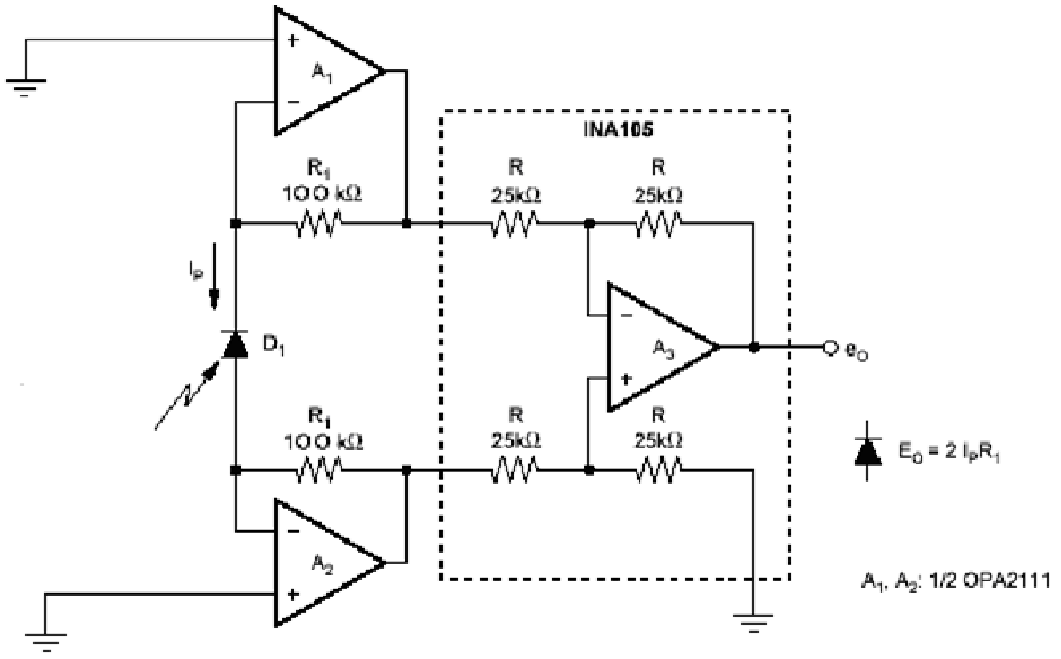

Figure 4. Converter and amplifier circuital configuration.

The oxygen partial pressure in blood has a power spectra concentrated around 1 Hz, while our signal has also high frequency noise, coming from our sampling, and a low frequency noise, down to the continuum, coming from light background, photodiode and from amplifier (1/f noise). For this reason we have applied a band pass (BP) filter realized with two second order stages, both in Sallen-Key configuration [10]. First stage is a low pass filter, the second a high pass filter.
Subsequently the signal goes to a non-inverting amplifier, which insulates the filter from the Analog-Digital Converter (ADC) load, and drives the ADC input.
Based on the red/infrared absorption ratio, defined by the Eqn. (1), an algorithm within the pulse oximeter allows to measure SpO_2, as a function of the measured magnitude at the systolic and diastolic states on the two photoplethysmograms:

$$SpO_2 = (S_R/B_R) / (S_{IR}/B_{IR}) \quad (2)$$

where S_R is the peak-to-peak red photodiode signal and B_R is the red photodiode continuous component, measured at the systolic and diastolic states respectively, and likewise for S_{IR} and B_{IR}.
Since we need also the continuous components, we have used PSoC's internals component to create a low pass filter with a cut frequency at 200 mHz.
To digitalize the signal, we used a 12 bit ADC available inside the PSoC, and, since we had only one ADC, we had to multiplex the signals to the ADC input under software control.
The digitized signal is then passed to the PSoC's CPU where both signals are normalized and from these data the partial pressure of SpO_2 is computed and shown on a 3-digit display.
With regard to the LEDs, they have a tight band emission spectra with peaks concentrated at 660 nm (R) and 940 nm (IR), as shown in Fig. 5.

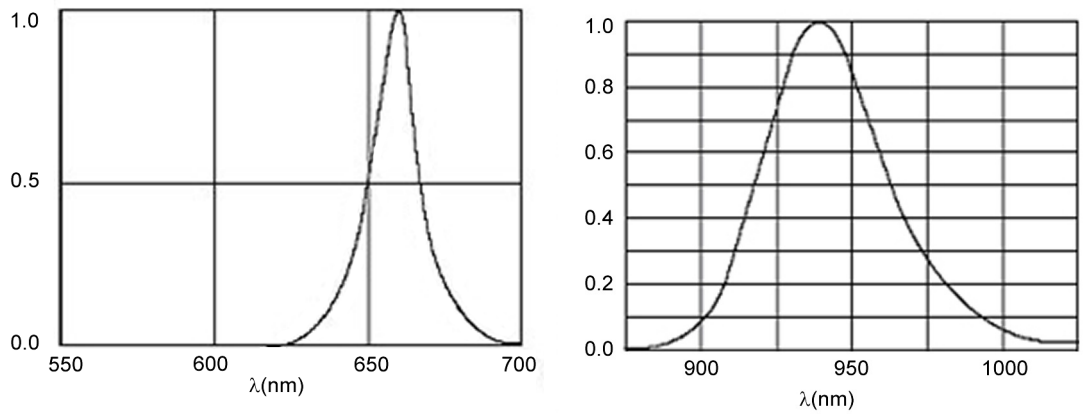

Figure 5. Emission spectra of the two LEDs normalized at their maximum value.

Furthermore their emission is concentrated in a narrow cone in the forward direction.
LEDs are driven with a 50 mA current for the red light and 60 mA for the infrared light.
The photodiode has a wide acceptance angle to maximize the light collection so that it could efficiently collect all the light diffused inside the finger. Its spectral sensibility has a peak at 850 nm, as shown in Fig. 6, and it is at least 60% (compared to the peak) in the bands between 600 nm and 1000 nm, with a good covering of the emission bands of LEDs.

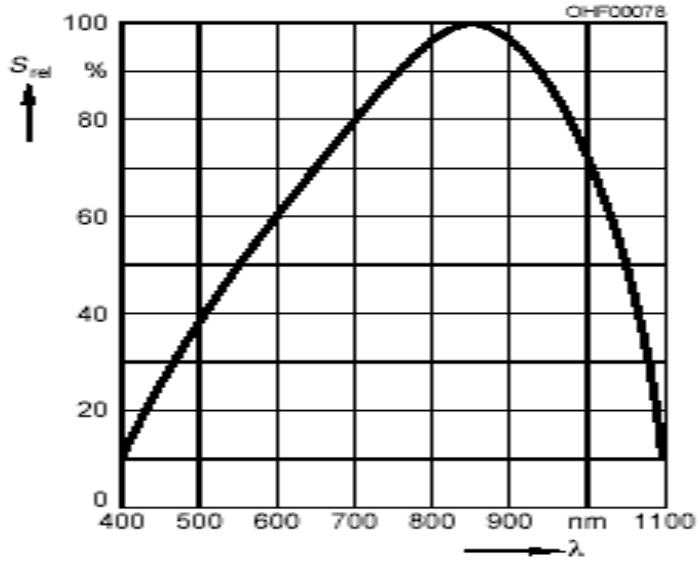

Figure 6. Relative spectral sensibility.

III. ANALYSIS OF RESULTS AND DISCUSSION

With the proposed design, it has been possible to obtain a gain, whose value is about unitary between 0.66 Hz and 3.2 Hz, as shown in Fig. 7.

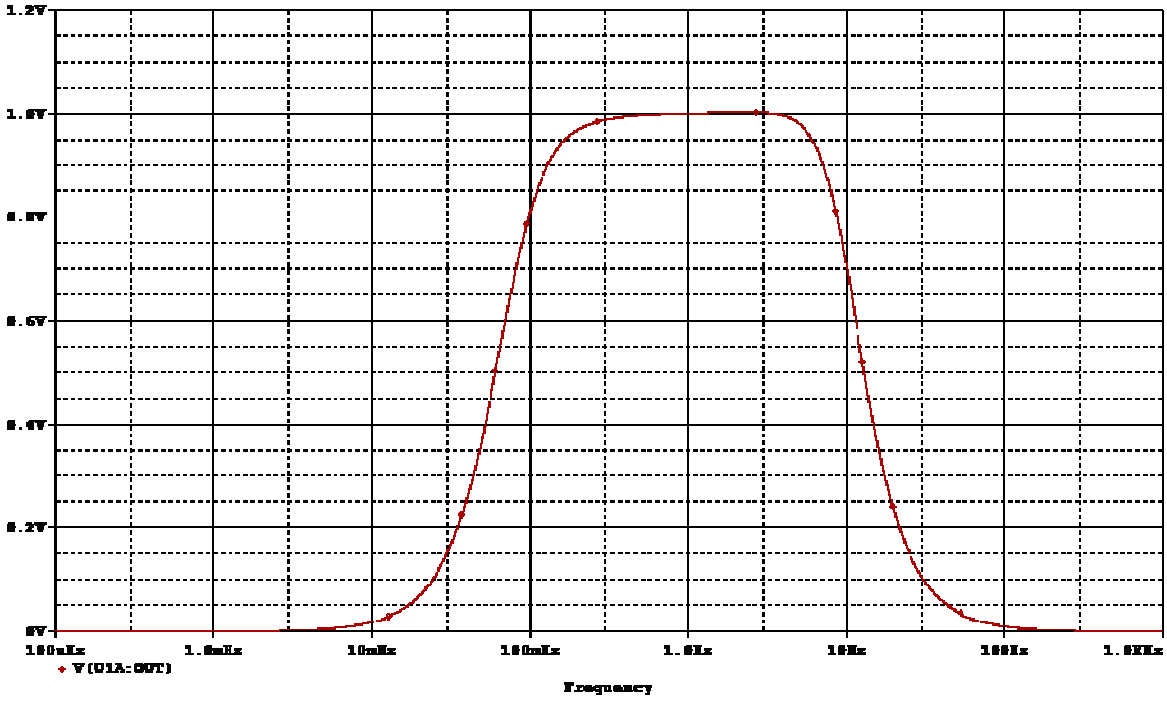

Figure 7. Output voltage of the band pass filter versus frequency.

Fig. 8 shows the amplified signals coming from the sensors for the red and infrared light respectively, after the continuous component removal.

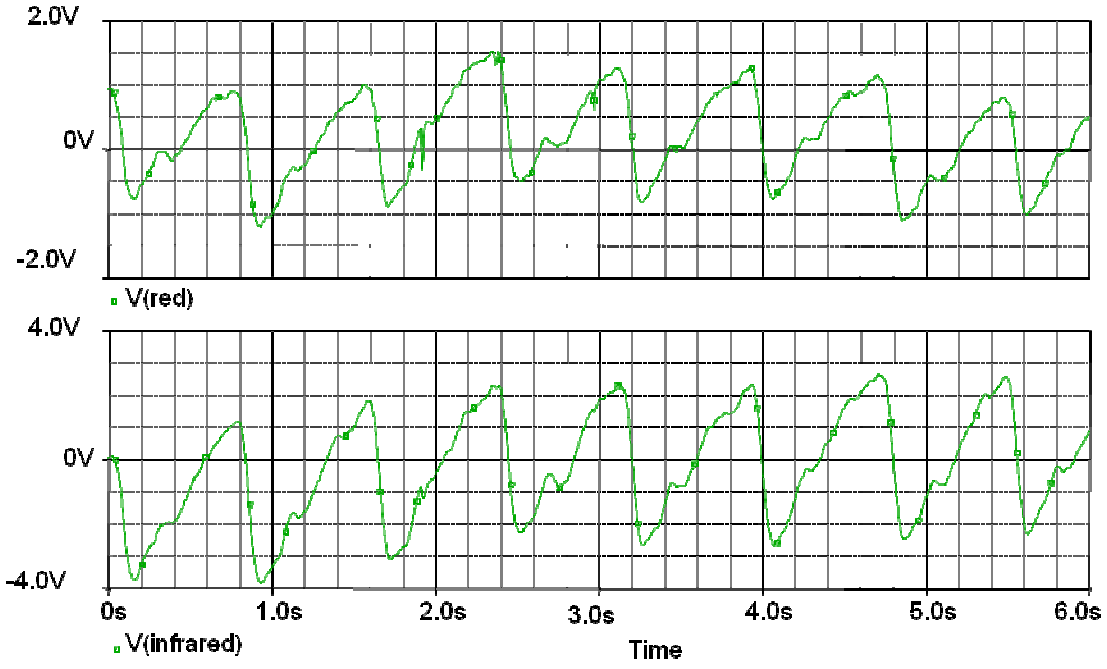

Figure 8. Amplified photoplethysmogram of signal after the continuous component removal.

The measurement of SpO_2, as a function of the measured magnitude at the systolic and diastolic states on the two photoplethysmograms allows us to delete the dependence on the LED emissivity and on the photodiode sensibility. However, the relation (2) has to be empirically calibrated for the specific device [11].

Moreover, as our sensor has been shielded on three sides, we have been obtained a low probability that the ambient light may reach the photodiode and, therefore, may influence the measurement.
Finally Fig. 9 shows the prototype realized and tested at the Electronic Devices Laboratory (Electrical and Electronic Department) of Polytechnic of Bari.

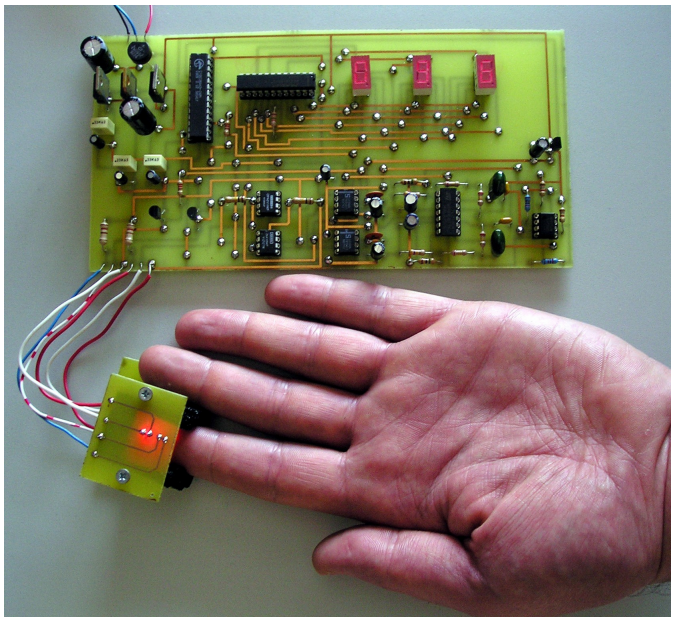

Figure 9. The realized prototype: a double-sided printed circuit board.

From this image it is clear that, even if the prototype is already small, but it will hugely squeezed using SMD (Surface Mount Device) technology. The image also shows the display with the measured values, there is no action to be taken to have the measurement since the device is continuously working.

IV. CONCLUSIONS AND FUTURE SCOPE

We have presented the design and realization of an electronic device for non invasive monitoring of the oxygen saturation in blood (transmission pulse oximeter). The main goals of our design have been the miniaturization, the cheapness and a good noise rejection. The key element to achieve these goals has been the PSoC, a system on chip family for mixed analogue and digital applications, programmable in both analogue and digital parts, allowing the implementation of a whole acquisition chain, from signal generator to the display driver, passing through sensor's amplifier, ADC and CPU. Having a single programmable device for both analogue and digital part, it has been easy to reach our goals. Furthermore this implementation of the pulse oximeter, using PSoC, has required some innovation in the circuit compared to previous schemes. The whole acquisition chain has a new plan that allows the collection of the continuous component of the signal. Moreover the whole data elaboration has been done in place using a local CPU, without requiring to pass data to an external computer.
For further development of this system, we are planning to include a miniaturized electrocardiograph.

REFERENCES

[1] Mengelkoc L. J., Martln D. & Lawler J., (1994) "A review of the Principles of Pulse Oximetry and Accuracy of Pulse Oximeter Estimates during Exercise", *Physical Therapy*, Vol. 74, No 1, pp. 40-49.

[2] Datasheet PSoC CY8C27443, http://www.cypress.com/?mpn=CY8C27443-24PXI

[3] Duun S., Haahr R. G., Birkelund K., Raahauge P., Petersen P., Dam H., Noergaard L. & Thomsen E. V., (2007) " A Novel Ring Shaped Photodiode for Reflectance Pulse Oximetry in Wireless Applications", *Proceedings of IEEE SENSORS Conference*, Atlanta, Georgia, USA, pp. 596-599.

[4] Mannheimer P. D.,. Casciani J. R, Fein M. E. & Nierlich S. L., (1997) "Wavelength selection for low-saturation pulse oximetry", *IEEE Transactions on Biomedical Engineering*, Vol. 44, No 3, pp.148-158.

[5] Konig V., Huch R. & Huch A., (1998) "Reflectance Pulse Oximetry – Principles and Obstetric Application in the Zurich System", *Journal of Clinical Monitoring and Computing*, Vol. 14, No 6, pp. 403-412.

[6] Goldman J. M., Petterson M. T., Kopotic R. J. & Barker S. J., (2000) "Masimo Signal Extraction Pulse Oximetry", *Journal of Clinical Monitoring and Computing*, Vol. 16, No 7, pp. 475-483.

[7] Gisiger P. A., Palma J. P. & Eberhard P., (2001) "Oxicarbo, a single sensor for the non-invasive measurement of arterial oxygen saturation and CO_2 partial pressure at the ear lobe", *Sensors and Actuators B: Chemical*, Vol. 76, No 1, pp.527 -530.

[8] Mendelson Y. & Kent J. C., (1989) "Variations in optical absorption spectra of adult and fetal haemoglobins and its effect on pulse oximetry", *IEEE Transactions on Biomedical Engineering*, Vol. 36, No 8, pp. 844-849.

[9] Fine I. & Weinreb A., (1995) "Multiple scattering effect in transmission pulse oximetry", *Medical & Biological Engineering & Computing*, Vol. 33, No 5, pp.709-712.

[10] Sallen R. P. & Key E. L., (1955) "A Practical Method of Designing RC Active Filters", *IRE Transactions on Circuit Theory*, Vol. 2, No 1, pp.74–85.

[11] Webster J. G., (1997) *Design of Pulse Oximeters*, IOP Publishing, Bristol, UK.

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