Stimulating Student Learning with a Novel "In-House" Pulse Oximeter Design

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Abstract

This paper addresses the design of a plug-and-play pulse oximeter and its application to a biomedical instrumentation laboratory and other core Electrical Engineering courses. The low-cost, microcontroller-based unit utilizes two light-emitting diodes as excitation sources, acquires reflectance data with a photodiode, and sends these raw photo-plethysmographic data to a personal computer via an RS-232 serial link. A LabVIEW interface running on the personal computer processes these raw data and stores the results to a file. The design of this pulse oximeter is unique in two ways: the excitation sources are driven just hard enough to always keep the photodiode active (meaning the sensor can be used in ambient light), and the hardware separates out the derivatives of the red and infrared photo-plethysmograms so that it can amplify the pulsatile component of each signal to fill the range of the analog-to-digital converter. Unlike commercial pulse oximeters whose packaging hides the hardware configuration from the students, the open, unpackaged design stimulates student interest and encourages dialogue with the developer; the in-house nature of the design appeals to students. Moreover, most pulse oximeters on the market are expensive and provide users with a front panel that displays only percent oxygen saturation and heart rate. This low-cost unit provides unfiltered pulsatile data, allowing students to investigate tradeoffs between different oxygen saturation calculation methods, test different filtering approaches (e.g., for motion artifact reduction), and extract other biomedical parameters (e.g., respiration rate and biometric indicators). Time-domain data from these units have been used in linear systems and scientific computing courses to teach filtering techniques, illustrate discrete Fourier transform applications, introduce time-frequency principles, and test data fitting algorithms.

I. Introduction

An optical pulse oximeter measures the intensity of light passing through heterogeneous tissue and uses variations in this light intensity (primarily resulting from the fractional volume variation of arterial blood) to calculate blood oxygen saturation. Due to its non-invasive nature, high precision in its operational range, and reasonable cost, optical pulse oximetry is widely adopted as a standard patient monitoring technique. Although its foundations date back more than fifty years,[1] many facets of this technology still attract researchers. Current interest areas include motion artifact reduction,[2, 3] power consumption optimization,[4] low-perfusion measurements,[5, 6] and issues germane to various application environments (e.g., wearability for battlefield and home care monitors).[7-9] It is important for biomedical engineering students to understand the principles of pulse oximetry, hardware/software design issues, and signal processing approaches.

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Pulse oximeter design addresses engineering areas such as optical component selection, mechanical layout, circuit design, microprocessor control, digital communication, and signal processing. Therefore, a pulse oximeter not only serves as an excellent study vehicle that allows students to learn techniques such as photoplethysmographic signal processing; it also provides a platform where students can acquire hands-on experience in practical device design. In addition, the real-time data that a pulse oximeter offers gives instructors flexibility when assigning projects and homework to students of various educational levels (graduate and undergraduate) and backgrounds (e.g., electrical engineering or biology).

Many commercial pulse oximeters display calculated parameters (i.e., percent oxygen saturation and heart rate) on their front panels, hiding the original unfiltered data from which these calculations were made. In this paper, we present an "in-house" pulse oximeter that provides raw sensor data for use in the classroom. The device is utilized in bioinstrumentation laboratory sessions, and its data provide real-world signals to other core Electrical Engineering courses.

This paper first briefly describes the theory behind photoplethysmographic (PPG) pulse oximetry. It then presents the development of a pulse oximeter, emphasizing design features that enable its application to education. These features include (a) a stand-alone pulse oximeter module with a novel circuit design, an open form-factor, and multiple signal outputs, (b) a personal computer station with a flexible, user friendly LabVIEW interface and a variety of signal processing options, and (c) the production of raw data that can be used for parameter extraction exercises. The paper describes how this device and it features have been applied in classroom environments to stimulate student learning. Several examples are introduced in detail, including (a) a pulse oximetry laboratory/lecture pair for a bioinstrumentation course sequence, (b) data sources for course projects in Linear Systems (EECE 512) and Scientific Computing (EECE 840), and (c) a platform upon which undergraduate honors research students can build. This approach can be extended to other devices and classes.

II. Theory – Principles of Pulse Oximetry

PPG pulse oximetry relies on the fractional change in light absorption due to arterial pulsations. In a typical configuration, light at two different wavelengths illuminating one side of tissue (e.g., a finger) will be detected on the same side (reflectance mode) or the opposing side (transmission mode) after traversing the vascular tissues between the source and the detector.[10] When a fingertip is simplified as a hemispherical volume that is a homogenous mixture of blood (arterial and venous) and tissue, the detected light intensity is described by the Beer-Lambert law: [11]

$$I_t = I_0 \left(e^{-\mu_{at}T}\right)\left(e^{-\mu_{av}V}\right)\left(e^{-\mu_{aa}A}\right) \quad (1)$$

where I_0 is the incident light intensity, I_t is the light intensity detected by the photodetector, and μ_{at}, μ_{av}, and μ_{aa} are the absorption coefficients of the bloodless tissue layer, the venous blood layer, and the arterial blood layer, respectively, in units of cm^{-1}.

The heart's pumping action generates arterial pulsations that result in relative changes in arterial blood volume, represented by dA, which adds an "ac" component to the detected intensity:

$$dI_t = -I_0 \mu_{aa} \left(e^{-\mu_{at}T}\right)\left(e^{-\mu_{av}V}\right)\left(e^{-\mu_{aa}A}\right) dA \quad (2)$$

Multiple elements contribute to the attenuation of light traveling through tissue, and arterial pulsation has only a small relative effect on the amount of light detected (on the order of one percent or less; see Figure 1).

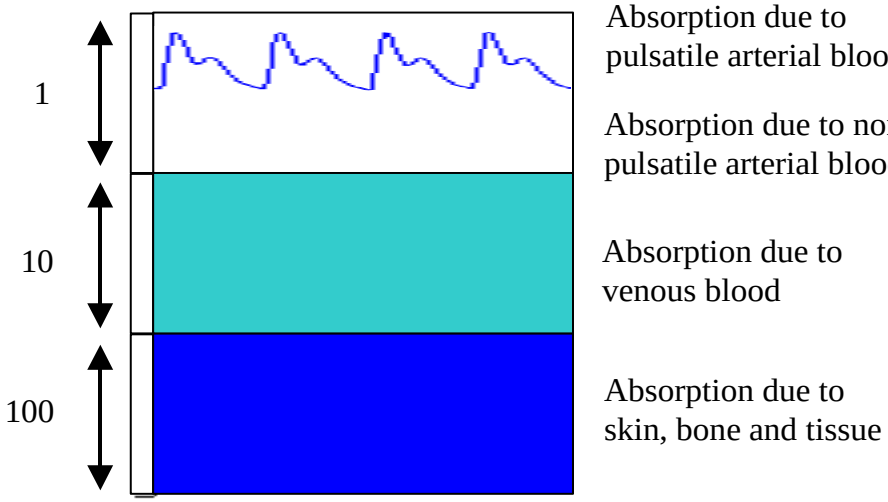

Figure 1. Breakdown of the components in the detected photo-plethysmographic signal.[12]

Dividing this change by the dc value normalizes this variation:

$$\frac{I_{ac}}{I_{dc}} = \frac{dI_t}{I_t} = -\mu_{aa}\,dA \tag{3}$$

The ratio of the above ratio for two wavelengths ('r' for red, 'IR' for infrared) is given by

$$R = \frac{(dI_t / I_t)_r}{(dI_t / I_t)_{IR}} = \frac{\mu_{a,r}}{\mu_{a,IR}}, \tag{4}$$

where $\mu_{a,i}$ can be expressed as a function of S_aO_2,[13] arterial oxygen saturation:

$$\mu_{a,i} = \frac{H}{v_i}\left[S_aO_2\sigma_a^{100\%} + (1 - S_aO_2)\sigma_a^{0\%}\right] \tag{5}$$

Here, $i = r, IR$, while $\sigma_a^{100\%}$ and $\sigma_a^{0\%}$ are the wavelength-dependent optical absorption cross sections of the red blood cells containing totally oxygenated and totally deoxygenated hemoglobin, respectively. One can therefore calculate arterial oxygen saturation using

$$S_aO_2 = \frac{R\sigma_{a,IR}^{0\%} - \sigma_{a,r}^{0\%}}{\left(\sigma_{a,r}^{100\%} - \sigma_{a,r}^{0\%}\right) + R\left(\sigma_{a,IR}^{0\%} - \sigma_{a,IR}^{100\%}\right)} \tag{6}$$

Equation (6) provides the desired relationship between the experimentally-determined ratio *R* and the arterial oxygen saturation S_aO_2. Researchers assume this relationship applies to monochromatic light sources. In reality, commonly available LEDs are used as light sources and typically have spectral widths of 20 to 50 nm. Therefore, the standard molar absorption coefficient for hemoglobin cannot be used directly in (6). Furthermore, the simplified mathematical description above only approximates a real system that incorporates

inhomogeneities and mechanical movement. Consequently, (6) is often represented empirically by fitting clinical data to the following generalized function:

$$S_a O_2 = k_1 R + k_2 \tag{7}$$

where, e.g., k_1= -25.6, k_2= 118.8[14] or k_1= -25, k_2= 110.[15]

III. Methods

A. Pulse Oximeter Development

As shown in the functional block diagram in Figure 2, a pulse oximeter consists of three main units: (1) an optical probe, (2) a circuit module that hosts an analog amplifier, signal conditioning element, and microcontroller, and (c) a personal computer that receives data from the circuit module and processes, displays, and stores these data.

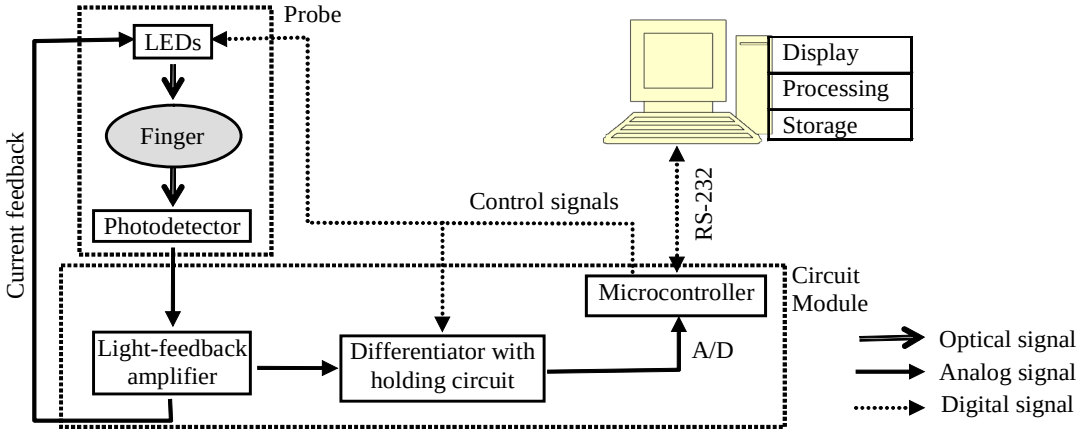

Figure 2. Functional block diagram of the pulse oximeter.

The analog portion of the pulse oximeter consists of a light-feedback amplifier and an analog differentiator with a specialized sample and hold circuit. The current feedback design adjusts the light level at the excitation LEDs such that the detected light intensity is constant, keeping the photodiode centered in its active region. To improve the stability of this feedback loop, a photodiode with smaller gain, rather than a phototransistor, is used as a photodetector. Two LEDs with wavelengths of 660 nm and 940 nm were selected as excitation sources.

As discussed earlier, the “ac” component resulting from arterial blood volume variation is very small. If A/D conversion is performed on the overall signal, this tiny “ac” component will be buried in the “huge” “dc” component after conversion. A differentiator addresses this issue. It removes the “dc” component by subtracting the previous signal voltage-level from the present signal voltage-level and amplifies this difference, yielding the “ac” component. A hold circuit is added to store voltage-levels from the previous sample cycle. The differentiator improves signal resolution by allowing one to take advantage of the full range of the A/D converter.

This circuitry is coordinated by a PIC microcontroller. Three output lines control the operation of the circuitry, and two A/D inputs sample the desired signal. Two outputs modulate the two light sources and switch the charging and discharging of their corresponding hold capacitors. The

other output operates the differentiator. The two A/D inputs acquire and digitize two signals: the "dc" signal when the differentiator is turned off (it is actually the original signal that includes both "dc" and "ac" components) and the amplified difference of the present and previous voltage level when the differentiator is turned on.

The PIC microcontroller also operates an RS-232 port to a personal computer running a LabVIEW interface. Digitized data are sent to the PC over this RS-232 interface. Because the sensor module and personal computer communicate asynchronously, and 8 bytes (two bytes for each signal) are sent in each RS-232 packet, a handshaking protocol is used to synchronize the two devices. The PC generates an acknowledgement after successfully receiving each data packet so that the pulse oximeter module can transmit the next data packet.

On the PC, LabVIEW virtual instruments (a) reconstruct the differentiated data, (b) filter the pulsatile signal with motion artifact reduction algorithms, (c) display the differentiated and reconstructed waveforms, (d) compute and display values for heart rate and blood oxygen saturation (see Figure 4), and (e) store the original and processed data to a text file for follow-up analysis. The data in the file are in columnar format:

Column 1 – Time in milliseconds,
Column 2 – $d(I_{ac})_{ir}/dt$ (derivative of the near-infrared signal)
Column 3 – $(I_{dc})_{ir}$
Column 4 – $d(I_{ac})_{red}/dt$ (derivative of the red signal)
Column 5 – $(I_{dc})_{red}$
Column 6 – $(I_{ac})_{ir}/dt$ (reconstructed near-infrared signal)
Column 7 – $(I_{dc})_{red}$ (reconstructed red signal)

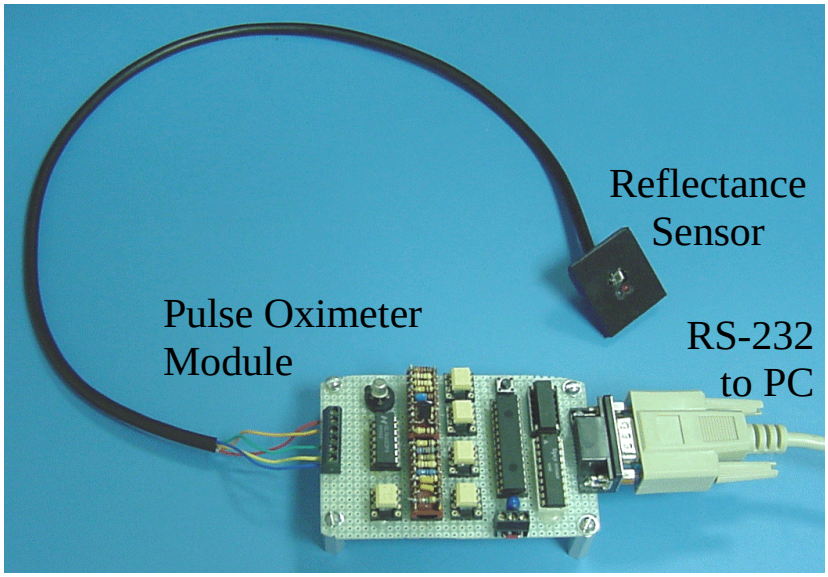

Figure 3. Pulse oximeter module and reflectance probe.

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