Implementation and Validation of a Power-Efficient, High-Speed Modulation Design for Wireless Oxygen Saturation Measurement Systems

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Abstract – **This paper describes the implementation and initial validation results of a novel power-efficient, high-speed modulation design for wearable oxygen saturation sensor systems. The research presented is in conjuction with the development of continuous photo plethysmographic health monitoring device known as the Ring Sensor. It is demonstrated that a high LED modulation rate coupled with a low duty cycle significantly reduce LED power consumption. Additionally, initial benchmarking results using a Nellcor N-395 pulse oximeter indicate good agreement with the new design for both heart rate and oxygen saturation measurements.**

I. Introduction

Recent work has led to the development of an ambulatory, telemetric, continuous health monitoring device known as the Ring Sensor [1]. The Ring Sensor utilizes a ring-shaped photo plethysmograph configuration to monitor arterial pulses at the base of the wearer's finger. Previous work has demonstrated improvements in motion artifact minimization and overall system power consumption. However, the LEDs used for signal acquisition have remained a significant limitation to extended battery life. The objective of this paper is to present initial benchmarking results related to a novel power-efficient, high-speed LED modulation design [2]. Heart rate and oxygen saturation measurements, acquired from healthy patients, are compared using an FDA-approved Nellcor N-395 pulse oximeter as a gold standard monitor.

II. High-speed LED modulation design

Signal stability is arguably the most important consideration in any noninvasive sensor design. Therefore, motion artifact minimization has been one of the fundamental focuses of the Ring Sensor. It has been found that a transmittance sensor configuration at the finger base, although requiring more power, is essential for motion artifact reduction. The increased power consumption, though, extremely limits the device's battery life and consequently its usefulness.

A solution to reducing the high power consumption required by the transmittance LED-photodetector configuration is LED modulation. Since previous ring sensor designs used relatively slow optoelectronic components, high-speed modulation was not possible.

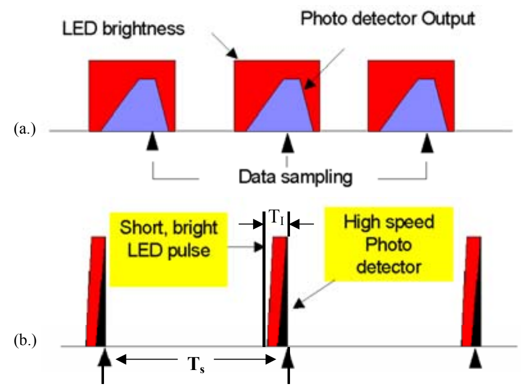

Fig. 1: (a) The slow response time of the photodetector meant that the LED had to be modulated at lower frequencies for data sampling. (b). Faster photodetector response times makes it possible to increase the modulation frequency of the LED.

Thus, the LED was 'turned on' for a long interval of time. While the LED was on, the photodetector, having a much slower response time, would increase gradually to a maximum value. Once the output was at a maximum value, the signal would be sampled (Fig. 1a). By using LEDs and photodetectors with extremely fast rise times it is possible to significantly reduce the average LED power. Consequently, high-speed optoelectronics make it possible to have the LED 'on' for a much short period of time and still sample a maximum intensity at the photodetector (Fig. 1b).

By definition, the sampling rate and duty ratio are as follows:

$$\text{Sampling Rate} = \frac{1}{T_s} = s \tag{1}$$

$$\text{Duty Ratio} = \frac{T_I}{T_s} = r \tag{2}$$

where T_s is the sampling period and T_I is the LED illumination time. The time for each LED illumination must therefore be,

$$T_I = \frac{r}{s} \tag{3}$$

This means that for a constant duty ratio, as the sampling rate increases the illumination time for the LED decreases.

Consequently, the average power consumed by the LEDs can be decreased by a factor corresponding to the LED duty cycle as follows:

$$P_{av} = \frac{1}{T_s - 0}\left[\int_0^{T_s}\left(P_{on} + P_{off}\right)dt\right] = \frac{1}{T_s}\left[\int_0^{T_1} P_{inst}\,dt + \int_{T_1}^{T_s} 0\,dt\right] = P_{inst}\left(\frac{T_1}{T_s}\right) = P_{inst} * r$$

III. Initial Benchmarking Results

Using the new high-speed LED modulation design, several experiments have been conducted to both validate the method and to benchmark the Ring Sensor's heart rate and oxygen saturation measurements. An FDA-approved Nellcor N-395 fingertip pulse oximeter was attached to the patient's index finger while the Ring Sensor was attached to the patient's ring finger (same hand). Data was sampled at a rate of 1 kHz using a 16-bit data acquisition card (PCI-6052E, National Instruments). Three sets of data, each approximately 400 seconds in length, were acquired for the patient.

Initial benchmarking comparisons included (1) the shapes of the captured plethysmograph waveforms, (2) the Fast Fourier Transform (FFT) power spectrums, (3) the calculated heart rates (based on values obtained during 10-second intervals), and (4) the measured oxygen saturation percentages.

A. Plethysmograph Waveforms and Power Spectrums -

In general, both the stability of the output plethysmograph waveform and the waveform's shape were quite comparable for monitoring situations with no patient motion (Fig. 2a). Although some differences were found while comparing the waveforms, it is believed that these differences are mostly due to variations in filtering used to obtain the waveform. It should be noted that all important features such as local maxima/minima and the dichrotic notch consistently occur concurrently. Additionally, the FFT power spectra for the waveforms were calculated and compared (Fig. 2b). Each power spectra calculation is based on data obtained during a 10-second sampling interval. The first, second and third peak frequencies of the spectra are exactly the same, 0.9 Hz, 1.8 Hz, and 2.7 Hz, respectively. Under static monitoring conditions, there is no significant difference between the fingertip PPG and the Ring Sensor power spectra.

B. Heart Rate Monitoring -

The consistent detection of the first peak of the FFT power spectra makes it possible to calculate and compare the heart rates measured using the two devices. We found excellent agreement between the two devices. The average calculated heart rate for the data obtained from each device was found to be 62.5 ± 3.8 bpm.

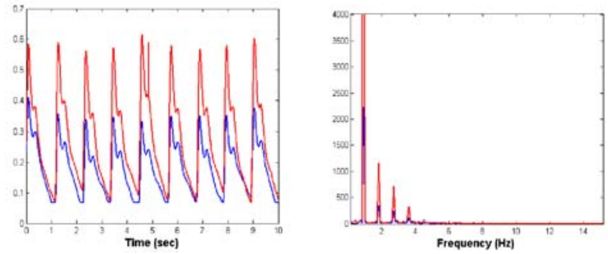

Fig. 2: (a) Plethysmograph waveforms. (b) Power Spectra of measured plethysmograph waveforms Ring Sensor (blue), Nellcor Sensor (red)

C. Oxygen Saturation Measurements -

Although the Nellcor Sensor produced a smoother overall signal, we found that the Ring Sensor was able to both estimate steady oxygen saturation values as well as accurately capture sudden desaturation states of the patient (Fig. 3). Additional processing (ie: comparison of previous oxygen saturation measurements) the ring sensor's monitoring of steady saturation states can be stabilized.

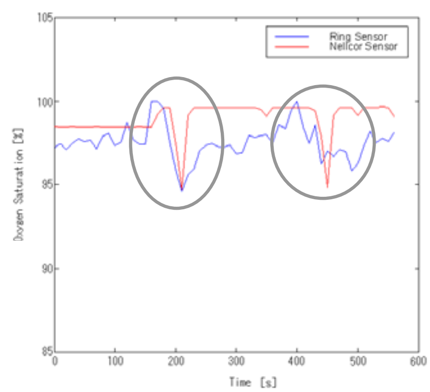

Fig. 3: A comparison of oxygen saturation measurements. It is important to note that the Ring Sensor correctly captured the patient's desaturation (highlighted regions).

IV. Conclusions

A novel high-speed modulation design for pulse oximeters has been presented and described. It has been shown through initial benchmarking that the method is capable of accurately measuring both the heart rate and oxygen saturation of a patient.

References

[1] Rhee, S., Yang, B-H., and Asada, H., "Artifact Resistant, Power-Efficient Design of Finger-Ring Plethysmographic Sensors, Part I : Design and Analysis," 22nd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Chicago IL USA, Jul 23-28, 2000.

[2] Shaltis, P., Rhee, S., Asada, H., "Artifact-Resistant, Power-Efficient, High-Speed Modulation Design for Photo Plethysomographic Ring Sensors," Annals of Biomedical Engineering Conference, Durham, NC USA, Oct 4-7, 2001.