34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Plug-and-Play, Single-Chip Photoplethysmography

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Abstract — Remote patient monitoring (RPM) relies on low-cost, low-power, wearable sensors for continuous physiological assessment. Photoplethysmographic (PPG) sensors generally require >10 components, occupy an area >300 mm^2, consume >10 mW power, and cost >$20 USD. Although the principle of PPG sensing is straightforward, in practice, a robust implementation requires a careful design including optical alignment, analog circuits, ambient light cancellation, and power management. This paper reports the first use of digital optical proximity sensors (OPS) for "plug-and-play" PPG. OPS have traditionally been used for distance sensing in smartphones and factory automation. Here we show that a digital OPS can perform PPG functions in a single 4x4 mm package which also provides a direct digital interface to a microcontroller. By exploiting its key features, a digital OPS can provide substantial performance advantages over existing state-of-the-art PPGs, including: i) 10X lower power consumption (200 µW) due to pulse operation; ii) high signal to noise ratio (>90), as a result of built-in optical barriers, filters, and ambient light cancellation; iii) 10X lower cost ($2 USD); and iv) 12X smaller area. We show single wavelength PPG measurements in multiple anatomical locations, including fingertips and earlobes. The results suggest that a digital OPS can provide an elegant solution for battery-powered, wearable physiological monitors. To the authors' knowledge, this is the smallest and lowest power PPG sensor reported to date.

I. Introduction

The physician-centric health care model, where patient assessment occurs intermittently during clinic visits, is often an inefficient approach for managing chronic illness. Remote patient monitoring (RPM), a rapidly emerging paradigm in chronic disease management [1], relies on ambulatory biosensors to assess patients' physiological indicators on a continual basis. RPM can provide early diagnosis, encourage preventative health and treatment compliance, increase connectedness between patient and doctor, promote evidenced-based decision making, and improve overall patient satisfaction [2].

Manuscript received March 29th, 2012.

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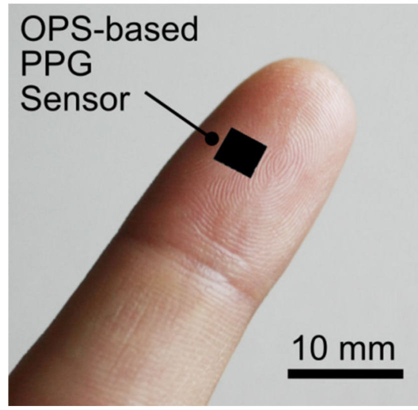

Figure 1: Picture of a digital optical proximity sensor (OPS) used for photoplethysmography (PPG). The sensor offers out-of-the-box high performance PPG sensing with order of magnitude improvements in power consumption, size, and cost compared to existing PPG sensors.

Photoplethsymography (PPG) is a ubiquitous monitoring technique for measuring heart rate and oxygen saturation. PPG sensors detect blood volume pulsations by time-resolved analysis of optical radiation either absorbed or scattered by a capillary bed [3]. In principle, PPGs are considered simple devices; however, in practice, implementation requires a careful design involving optics (multiple paths, alignments, leakage barriers) and mixed signal electronics (transimpedance amplifiers, analog digital conversion, drivers, modulators, filters). A robust PPG sensor must also consider power consumption, ambient light rejection, sensitivity, dynamic range, signal to noise ratio, motion artifacts, calibration, size, and cost [4]. As a result, designing a robust PPG sensor requires a engineering effort and investment. A complete sensor typically requires 10-20 components, 1.5-10mW power, and costs >$20 USD.

History has shown that with sensor technologies, the key to widespread acceptance is to make the sensor "plug-and-play". In other words, the ideal sensor should function out of the box without additional components, provide a digital interface to a microcontroller for configuration and data transfer. It should also be small and low cost. The most successful recent example is the microaccelerometer, which has seen rapid, pervasive growth in the smartphone, automotive safety, and home entertainment markets.

This paper reports the use of digital optical proximity sensors (OPS) for PPG. OPS provide a plug-and-play, single chip solution for high performance single-wavelength PPG. To our knowledge, it is the smallest reported PPG sensor, with a size of 4x4 mm (Figure 1). Moreover, it provides substantial improvements in power consumption

(5X), signal to noise ratio (2-5X), and cost (10X) compared to existing reflectance-mode PPG sensors. Section II describes the features of OPS sensors which make them well suited for PPG. Section III describes experimental setup. Section IV discusses experimental results, and compares sensor performance with the state of the art.

II. Concept

A. *Optical Proximity Sensors*

Optical proximity sensors, also called light beam sensors, detect distance by measuring the magnitude of light reflected from an object. They are widely used for non-contact distance measurement in a variety of applications, including smartphones (touch screen dimming), factory robotics (motion control), lavatories (touchless switches), vending machines, and home entertainment. Recent studies have also used OPS for the recognition of hand and tongue gestures [5-7].

An OPS consists of an infrared light emitting diode (IR LED), a photodiode (PD), a visible light blocking filter, an optical barrier for reducing lateral light leakage, and an integrated circuit for amplification, signal conditioning, and digitization. Some OPS systems also include a 2nd photodiode for visible light detection and ambient noise cancellation. Digital OPS, which have recently become available, are highly integrated devices which include all the above components in a surface mount package typically a few mm in size. They also provide a bidirectional digital interface to a microcontroller for data transmission and device configuration.

B. *Using a Digital OPS for PPG*

In this paper, we show how a digital OPS can be used as a high-performance, reflectance-mode PPG sensor (Figure 2). The OPS is placed in direct contact with the skin near a capillary bed, such as the fingertip, earlobe, or forehead. A transparent protective overlay can be added if desired. The IR LED emits light into the tissue, where it experiences diffuse reflection from the tissue and capillary bed. This establishes a baseline reflectance signal which is detected at the PD. When a pulse wave propagates through the capillary bed, the reflectance signal falls slightly (0.5-5%) due to light scattering. The change is detected by the PD and processed by embedded amplification and signal processing circuitry.

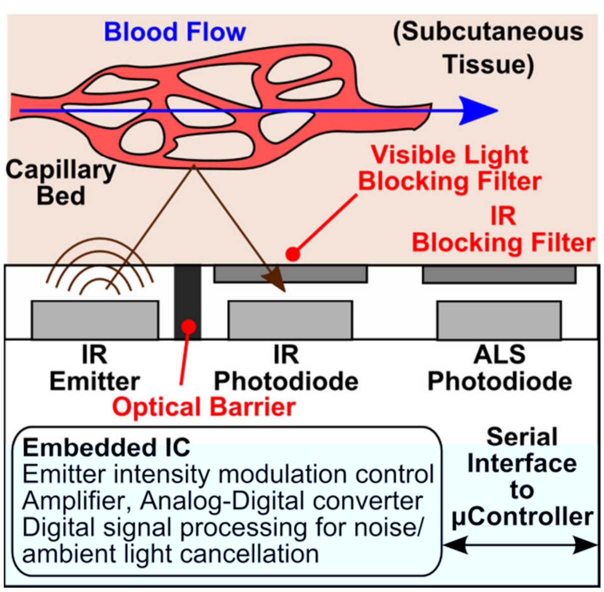

Figure 2: Structural features of digital optical proximity sensors, and they can be used for PPG.

Interestingly, many of the performance requirements for PPG are similar to those in proximity sensing. As a result, several features of the digital OPS can be exploited for high performance PPG sensing:

Integrated IR LED and visible light blocking filter. OPS LEDs typically emit at near infrared wavelengths (850-950 nm), which is ideal for PPG [3]. The integrated visible light filter reduces the impact of ambient light.

Improved sensitivity due to small PD-LED spacing. One of the challenges in reflectance mode PPG is that <5% of the light is backscattered to the detector. The intensity of the backscattered light, which forms a concentric ring around the excitation LED [4,8], falls off as the square of the distance (Figure 3). Therefore, it is critical to maintain a small distance between the LED and PD. In a digital OPS, the distance is <1-2 mm, compared to >5mm in a typical PPG [9-10]. This increases the reflected light (and therefore, signal to noise ratio) by a factor of 5-25x.

Reduced background due to optical barrier. A drawback of a small LED-PD spacing is light leakage, which increases the baseline PPG signal. Digital OPS include an optical barrier between the LED and PD which substantially reduces light leakage [9] and thereby improves SNR. This is particularly important in "zero-distance detection" where the skin is in direct contact with the sensor [10].

High sensitivity and dynamic range due to high-resolution ADC. PPG sensors must be able to detect a small pulsation (AC) superimposed on a large baseline (DC) signal. The perfusion index (PI) is defined as the ratio of the AC to DC component. Conventional PPGs extract the AC component using a 0.5-5Hz bandpass filter and multiple amplifiers. Modern digital OPS include a high resolution analog to digital converter (ADC) which can resolve PIs without filters. For example, a 16 bit ADC can resolve a PI as little as $1/2^{16}$, or 15 ppm. The advantage of this approach

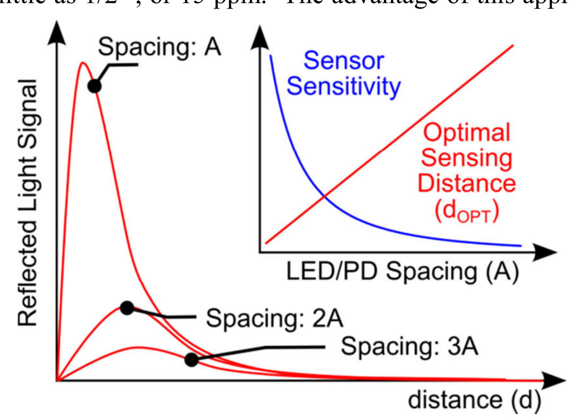

Figure 3: Effect of LED-PD spacing on sensitivity. The graph shows the reflected light signal as a function of distance between the sensing object and the OPS. A small LED-PD spacing offers the largest sensitivity.

is that both DC and AC components of the PPG signal can be simultaneously measured. This is useful for calculating the PI, and for detecting saturation of the light detector.

Electronic noise and offset cancellation. Conventional PPGs require a bandpass filter to avoid 60/120 Hz noise from ambient light. This can limits the bandwidth of the sensor, making it difficult to resolve high frequency features of the pressure pulse. In a digital OPS, the LED emitter is pulsed at a high frequency (>1 MHz) which is an integer multiple of 60 Hz. The signal processing circuitry utilizes a demodulation scheme, similar to lock-in-detection [11], which eliminates ambient light artifacts and 1/f noise. This enables fast measurement rates while maintaining low noise.

Reduced power consumption via burst operation. In a digital OPS, the IR emitter, typically the most power hungry component in a PPG, is operated in short pulses, followed by long periods of idle time. This reduces power consumption by 1-3 orders of magnitude depending on the data rate.

Digital Interface. Many digital OPS include an industry standard I^2C serial bus, which provides a bidirectional link to a microcontroller for data transmission and configuration. The digital output is inherently more noise immune than an analog interface, and allows multiple sensors on a single bus.

Intensity control. To maximize the signal to noise ratio in PPG, the LED intensity should be made as large as possible without saturating the detector. In a digital OPS, the LED intensity is programmable through the serial interface, allowing closed loop control to prevent detector saturation.

III. Experimental Setup

We used the VCNL4000 (Vishay Semiconductor), a fully integrated digital proximity and ambient light sensor with 16-bit resolution in a 4x4 mm leadless surface mount package (Figure 1). It includes an 895 nm IR LED and a PD with an integrated visible light blocking filter. The LED-PD spacing is ~2 mm, and the LED is embedded in a recessed region which serves as an optical barrier. The integrated signal processing IC handles LED modulation, current control (10-200 mA in 10 mA steps), photodetector amplification and signal conditioning, ambient light cancellation, 16-bit ADC, and I^2C bus communication. The LED can be modulated at frequencies up to 3.125 MHz (user selectable) for electronic noise cancellation. Each measurement is completed in 75 μs, and the LED remains off until the next measurement cycle. This allows one to use a large current (100 mA) while consuming <200 uW power at a 100 Hz measurement rate. The 3V supply voltage is well suited for operation from a coin cell battery. The LED is placed on a separate supply to reduce digital switching noise. The sensor includes an I^2C serial interface, and the cost is <$2 USD. The sensor data is recorded using a Silicon Labs microcontroller connected to a laptop via USB.

PPGs are obtained by placing the sensor at a fixed pressure with the skin at multiple locations, including the index finger, earlobe, and upper ring finger. In the earlobe measurements, a metal backing is placed on the opposite side to improve the reflectance signal. Before performing the measurement, the current for the IR emitter is manually set to a value approximately 75% of the dynamic range of the sensor. This maintains a large reflected light signal while minimizing the likelihood of detector saturation. The SNR is found to scale proportionally with the reflected light. The ideal current setting is found to be between 80-130 mA, depending on the anatomical location and the individual being tested.

IV. Results and Discussion

Experiments show that the OPS sensor can produce high quality PPGs in multiple anatomical locations (Figure 4). The signal amplitude ranges from 130-560 counts within a full scale range of 2^{16}. Pulsation indices (PIs) vary from 0.26-1.25%, which is typical for reflectance pulse oximetry, and is well within the resolution of the 16 bit ADC. The SNR varies between 20-90 depending on the location and the applied pressure. This is comparable or better than existing PPG sensors, which typically have SNR between 30-50. The index fingertip provides the largest overall signal amplitude and SNR, while the earlobe with metal backing gives the largest PI. Heart rate can be easily

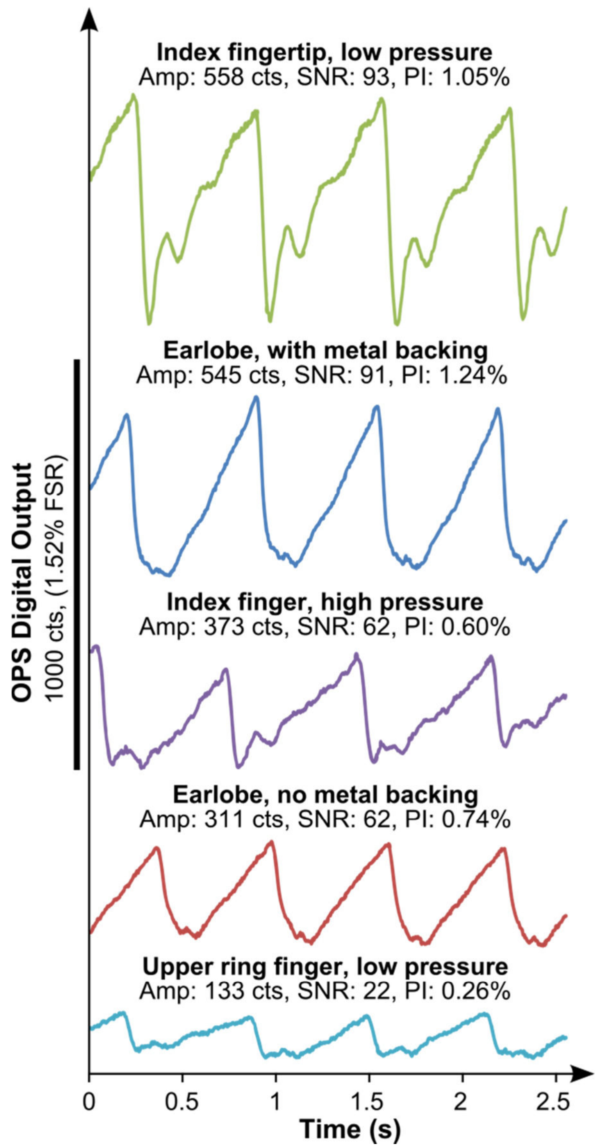

Figure 4: PPG waveforms obtained using a digital OPS.

calculated from the PPG waveforms using computationally inexpensive signal processing algorithms such as time derivatives, averaging windows, or infinite impulse response (IIR) filters implemented on the microcontroller [3]. The power consumption of the device is <200μW at a 100 Hz data rate, which is 7X smaller than the state of the art, and more than 10X smaller than commercial devices.

Table 1 further compares the performance of the digital OPS reported in this paper with state-of-the art PPG sensors reported in both the research and commercial sectors. It is notable that the OPS-based device provides better performance in most categories, particularly those of interest in wearable sensors. These include substantial improvements in power (10X), size (12X), cost (5-10X), and signal to noise ratio (2-3X). To the authors' knowledge, this is the smallest and lowest power single-wavelength PPG sensor currently available. Another advantage is that the sensor provides an industry standard I^2C digital interface to a microcontroller. This link allows for device configuration and data transfer, thus making it simple to integrate a high performance, single-chip PPG sensor into a microcontroller-based embedded system. These features, along with the low cost ($2 USD), make the sensor well-suited for wearable and mobile health monitoring.

TABLE I. COMPARISON OF DIGITAL OPTICAL PROXIMITY SENSOR-BASED PPG SENSOR WITH CONVENTIONAL PPG TECHNOLOGY

Performance Parameter	**Existing PPGs (best case)** [3–4],[8], [12-13]	**OPS-based PPG**
# of Components	>10	1
PCB Area	200 mm^2	16 mm^2
Power Consumption	1.5-10 mW	200 μW (100mA, 10 Hz)
Cost:	$15-20 USD	$2 USD
Supply Voltage	3V/5V	3V
Sensor Output	Analog	Digital (I^2C serial)
Max. Data Rate	200 Hz	1000 Hz
LED, PD spacing	4-6 mm	1-2 mm
Noise rejection features	Bandpass filter: 0.5-5 Hz	Electronic noise cancellation @3.125 MHz
IR filter	Not included	Integrated
SNR	20-30	Up to 95
Wavelength	650-950 nm	895 nm (can be changed)

V. CONCLUSIONS

Digital OPS provide a high performance, single chip, plug-and-play solution for PPG. We have demonstrated a single wavelength device which (to our knowledge) is the smallest, cheapest, and lowest power PPG sensor reported. The technology shows promise for applications in wearable sensors and remote patient monitoring.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge funding from the Cardiovascular Research Institute (CVRI) at Wayne State University. This technology is patent pending.

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