AC 2007-2420: A SMALL, HIGH-FIDELITY REFLECTANCE PULSE OXIMETER

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A Small, High-Fidelity Reflectance Pulse Oximeter

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Abstract

Pulse oximeters have become standard equipment in both biomedical education and clinical settings. Since the operational principles of a pulse oximeter are straightforward, and since the analysis of these sensor data require basic computational and mathematical toolsets, this type of device is well suited to hands-on experiences geared toward both undergraduate and graduate students. However, this seemingly simple type of biomedical device offers challenges in the areas of motion artifact reduction, light excitation/collection, signal fidelity, and parameter extraction that provide rich material for undergraduate and graduate education and research. This paper addresses a new design for a silver-dollar-sized reflectance pulse oximeter that is easy for students to use and incorporates multiple design enhancements that result in high-quality photo-plethysmograms. The pulse oximeter communicates with a LabVIEW virtual instrument via a serial USB interface. The double sided pulse oximeter board contains surface mount circuitry on one side and a reflectance sensor on the other side, where large area photodiodes are arranged radially around a central, dual red & near-infrared LED excitation source. The pulse oximeter is unique in that it is entirely digitally controlled and adjusts signal baselines depending on existing light levels. Additionally, it provides high fidelity red and near-infrared plethysmograms that demonstrate hundreds of analog-to-digital converter levels from peak to valley. Because the plethysmograms are unfiltered, they are good candidates for education and research projects that address signal filtering, blood oxygen saturation calculation algorithms, physiological parameter extraction from photo-plethysmographic signals, light/tissue interaction modeling, and the use of photo-plethysmograms in applications such as biometric authentication. These new devices have been employed in (a) a Fall 2006 lecture/laboratory pair within a biomedical instrumentation course sequence taken by undergraduate and graduate students, (b) undergraduate honors research experiences, and (c) graduate signal processing research.

I. Introduction

Blood oxygen saturation, often referred to as the sixth vital sign, can be obtained via a well known, empirically discovered technique referred to as pulse oximetry.[1, 2] In recent decades, pulse oximeters have become a staple in clinical environments and are therefore an expected element of any biomedical engineering curriculum. At a conceptual level, the operational principles of pulse oximetry are straightforward and easily conveyed in the classroom; pulse oximeters are therefore attractive for undergraduate hands-on laboratories. However, pulse oximeters intended for practical monitoring environments offer design challenges in the areas of motion artifact reduction, light excitation/collection geometries, wearability, power management, and physiological parameter extraction. This makes them ideal targets for educational design projects and independent research efforts at both the undergraduate and graduate levels.[3, 4]

This paper addresses the design and educational application of a small, surface-mount pulse oximeter that incorporates an optimized light excitation/collection geometry and employs a Universal Serial Bus (USB) connection to a LabVIEW virtual instrument running on a personal computer. Reflectance plethysmograms from this sensor are unfiltered and demonstrate high fidelity compared to previous designs. Section *II. Background* discusses the design requirements which motivated this work, and section *III. Methods* details the functional implementation of the design, the support software employed, and the initial use of these units in the context of a biomedical instrumentation laboratory designed for undergraduate and graduate students. Section *IV. Results & Discussion* includes hardware pictures, example reflectance signals, and text that demonstrate the increased effectiveness of the new design for educational applications when compared with prior experiences that employed a different pulse oximeter design.

II. Background

The pulse oximeter discussed here was designed for an array of applications in both biomedical education and research. The following design requirements support this diverse application set:

1. Full access to red and near-infrared plethysmograms
2. Unfiltered plethysmograms with hundreds of peak-to-peak quantization levels
3. Optimal excitation/collection geometry exhibited by the physical sensor
4. Feedback to allow subtraction of the baseline upon which the pulsatile red and near-infrared reflectance plethysmograms reside
5. Small sensor probe size
6. Low-cost sensor hardware
7. Universal Serial Bus (USB) connectivity to a host personal computer (PC)
8. Predominately digital sensor circuitry

The first two requirements speak to the need to obtain high-fidelity plethysmographic data that closely represent the underlying physiology. Data obtained from these sensors are used in undergraduate/graduate learning experiences and research investigations that address (a) the fundamental principles of pulse oximeter operation and data analysis, (b) extraction of hemodynamic parameters that map to user state of health, (c) the use of different digital filters to extract signal noise and motion artifact, (d) assessment of wearer identity based upon the time- and frequency-domain characteristics of plethysmographic signals, etc.[3-6] Most commercial pulse oximeters do not provide access to plethysmographic data, even if they display these data on their front panels. For units that provide these data, the filters applied to these pulsatile data are proprietary (and therefore unknown) and can have a significant bearing on the information contained in the resultant data, which equates to data loss and ultimately confusion regarding how to interpret these signals.

A reflectance-mode pulse oximeter sensor offers great flexibility with respect to the variety of body locations that can be targeted: finger, forehead, wrist, ankle, ear, etc. An optimized excitation/collection reflectance geometry (Requirement 3) can make a large difference in the quality of the plethysmographic data and the correctness of the resultant blood oxygen saturation calculations. Since tissue is highly forward scattering, reflectance sensors exhibit poor signal quality when compared to transmission-mode sensors. This can be addressed with a larger area sensor that incorporates photodiodes which are arranged radially around the excitation LEDs, where the photodiode/LED separations are spaced at 3 to 5 mm to optimize the acquisition of

reflectance photons that have had the opportunity to penetrate into deeper blood-perfused tissue regions.[7]

The need for plethysmogram baseline extraction (Requirement 4) is a consequence of three issues: (1) the inability to predict ambient light levels in the usage environment, (2) the location-dependent change in the amount of non-perfused tissue as well as tissue with residual but non-pulsatile blood, both of which contribute to constant ("DC") signal levels, and (3) DC signal levels that are orders of magnitude larger than the desired pulsatile, or "AC" plethysmographic signals. The system must be able to respond to large variations in DC level while maintaining the AC sensitivity needed for Requirements 1 and 2.

Requirement 5 (small probe size) can be viewed as a matter of convenience for storage and handling, but it also facilitates measurements from individuals with small fingers and promotes the adaptability of these sensors for wearable applications. This design requirement can be difficult to achieve with a radial reflectance arrangement addressed by Requirement 3.

Low-cost sensor hardware (Requirement 6) promotes broader use of pulse oximeter sensors in course demonstrations, laboratory courses, and research. At present, low-cost, easy to use pulse oximeters designed for educational laboratories are nearly nonexistent. While small commercial pulse oximeters can cost upwards of five hundred dollars, the design goal here was a total parts and labor cost of $150 for the entire sensor, circuitry, and support software collection.

Requirement 7 (USB connectivity) enables the device to be used in a plug-and-play manner with almost any personal computer, including laptops and notebooks. For applications that require small size, a mini-USB receptacle requires less real estate than a typical RS-232 connector.

The final requirement addresses the move to digital circuitry. While the sensor itself requires the limited use of analog elements, digital circuitry offers the potential to dramatically reduce the component count. In addition, a primarily digital design promotes greater flexibility with respect to follow-on sensor updates and the implementation of different data handling protocols.

III. Methods

The following sections address the technical rendering of the new pulse oximeter design and describe a Fall 2006 undergraduate/graduate laboratory experience within which the new design was employed.

A. Functional Comparison with Previous Pulse Oximeter Designs

Plug-and-play, reflectance pulse oximeters have been previously designed and utilized by this group for multiple education and research applications.[3-6, 8-10] The functional block diagram that forms the basis for the previous designs is illustrated in Figure 1. The light-feedback-based approach[7] in Figure 1 drives the LED excitation sources with ever changing currents with a goal of maintaining a constant level for the amount of light that actually reaches the photodiode detector. In this legacy arrangement, the sensor can be used in ambient light, and the drive currents provide the plethysmographic signals. A sample-and-hold-based differentiation circuit separates out the DC and AC components of the plethysmograms, which are then digitized and sent to a PC over an RS-232 serial interface. While this former design showed promise on paper,

in practice it exhibits limitations with respect to data quality. Constraints imposed by the red-to-near-infrared switching circuitry and the analog sample-and-hold circuitry used to obtain the signal derivative have resulted in poor signal-to-noise ratios for the pulsatile signal components. This legacy design was used in a biomedical instrumentation laboratory course[11] for four years prior to Fall 2006. In this scenario, it was not unusual for two-to-four students out of 10 to obtain photo-plethysmographic waveforms that were very low quality (i.e., tens of digitization levels from valley to peak in the pulsatile components). In an educational environment, this lessens student enthusiasm and affects the resulting learning experiences.

The new pulse oximeter design is described by the block diagram depicted in Figure 2. As in the previous design, the sensor microcontroller changes the LED drive currents to maintain a DC baseline that is placed appropriately within the range of the microcontroller analog-to-digital (A/D) converter. These drive currents, however, are constant over short periods of time (i.e., as long as the pulsatile signal excursion remains within the A/D converter range) and shared by both excitation sources, so the plethysmograms represent photodiode output currents. The digitized data are then uploaded to a PC via a uART-to-USB conversion chip.

Based on lessons learned from previous devices, five major design changes were made in addition to those discussed in the previous paragraph. One of the most important was the consolidation of the circuit: instead of building a separate optical probe and circuit module, the two sets of functionality were moved onto opposite sides of the same circuit board. The second, related change was a move to entirely surface mount technology, which made prototyping more difficult but promoted the use of more sophisticated circuitry and considerably simplified the manufacture of multiple probes. The third change was to arrange four collection photodiodes in a radial arrangement around the center set of red and near-infrared excitation LEDs, where physical separation was placed between the excitation and collection elements to maximize the relative contribution of the AC signal components, as noted in section II. *Background*. The fourth major change was a move to almost entirely digital circuitry, allowing for a drastic reduction in component count, cost, size, and complexity. Finally, USB was chosen as a serial, plug-and-play alternative to the previous RS-232 communication mechanism, since serial ports are being phased out of PCs (particularly laptops) and USB offers higher data throughput.

B. Implementation and Fabrication Technologies

The heart of the pulse oximeter circuitry is a Silicon Laboratories (SiLabs) C8051F411 microcontroller, a small-form-factor microcontroller with an integrated multi-channel, 12-bit A/D converter (ADC) and two 12-bit, current-mode D/A converters (DACs). These DACs, together with bipolar junction transistors, form the entirety of the drive circuit for the red and near-infrared light-emitting diodes. The integrated ADC and two operational amplifiers comprise the measurement circuit. The 411 microcontroller operates on an expanded 8051 architecture and was programmed using SiLabs' integrated development environment.

The sensor consists of a central red/near-infrared LED pair (Advanced Photonix PDI-E835) surrounded by four Advanced Photonix PDV-C173SM photodiodes. By design, a physical separation is maintained between the LED sources and the photodiodes to optimize the relative contribution of the AC portion of each plethysmogram: the design preferentially accepts reflectance photons with a higher probability of traveling through deeper, blood-perfused tissue.

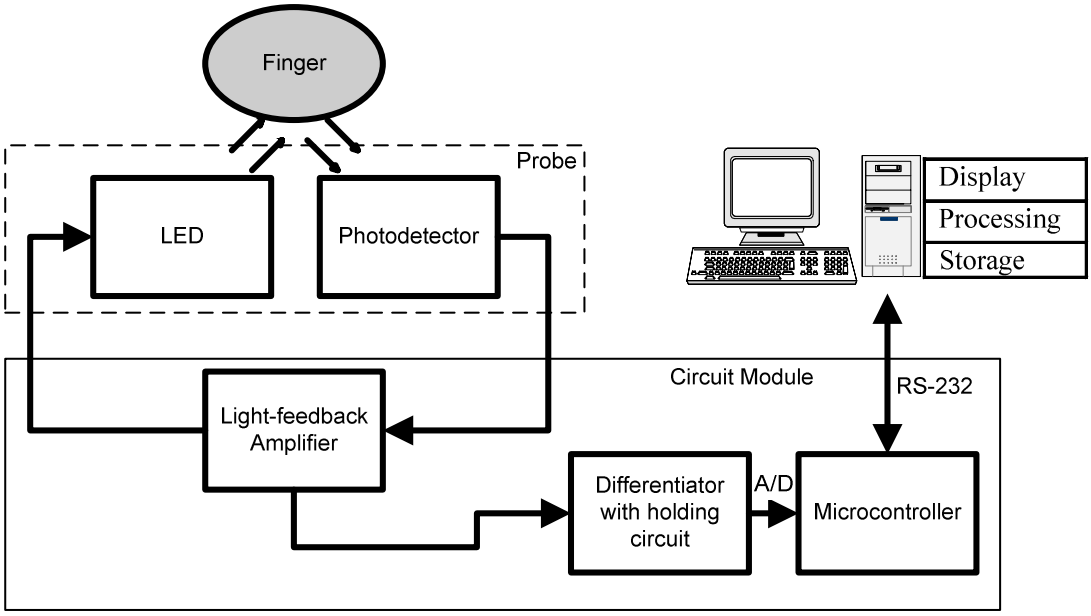


Figure 1. Functional block diagram for the previous pulse oximeter design.[3-5, 8, 9, 12]

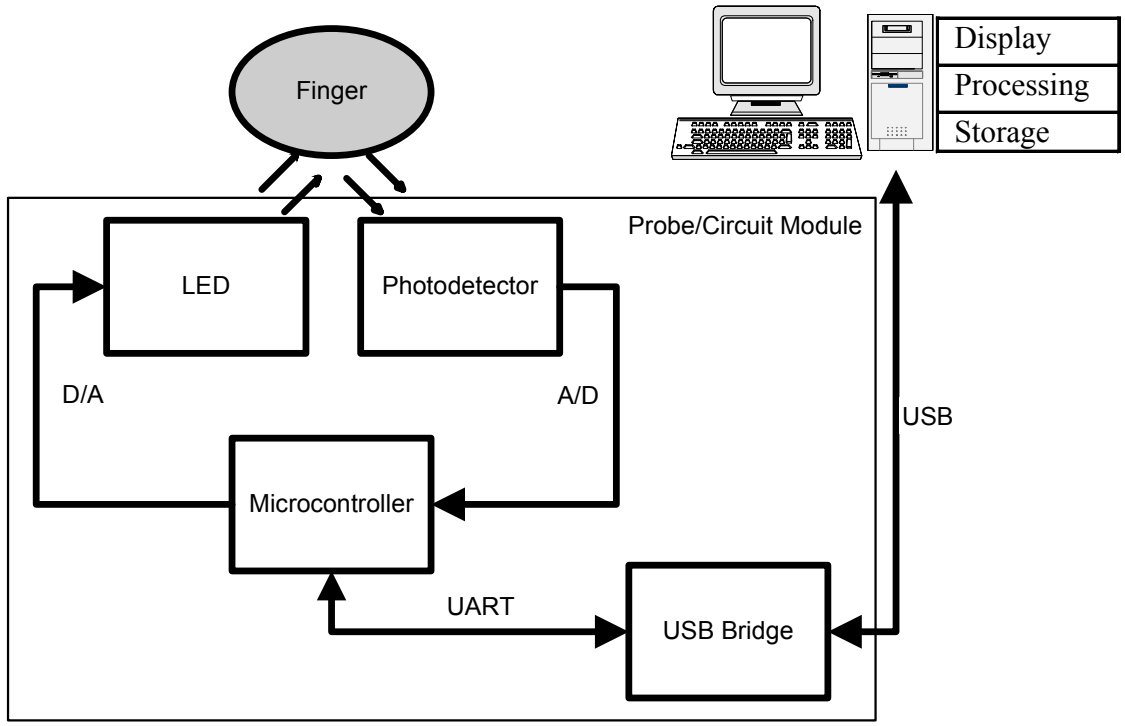


Figure 2. Functional block diagram for the current pulse oximeter design.

The circuit board was designed using CadSoft's EAGLE layout editor. It supports only two-layer layouts, which requires more care than four-layer layouts but saves on production and software costs. The board itself was fabricated by Advanced Circuits and populated with the

combined resources of the KSU Electronics Design Laboratory and the KSU Medical Component Design Laboratory.

Communication with a PC is accomplished through the use of another SiLabs chip: the CP2102 USB-uART bridge. In addition to translating between the two serial communication protocols, the CP2102 also performs the duty of a power supply by pulling power off of the USB bus and regulating it to 3.3V. On the computer side, communication is handled through a simple LabVIEW interface that displays real-time data while recording it for later analysis. The CP2102 evaluation kit includes a virtual serial port driver that allows the USB connection to appear as a serial port, simplifying LabVIEW development and allowing the use of commands from earlier LabVIEW interfaces.[3, 5] LabVIEW was chosen as the interface because

- LabVIEW has a broad educational user community in both engineering and non-engineering departments around the world,
- students can easily learn how to alter LabVIEW virtual instruments (VIs, i.e., interfaces) to make them better suited for a project, and
- the serial port sub-VIs hide the details of the implementations that accomplish the transfer of serial data across the USB interface.

C. Software Decision Flow

Figure 3 shows the decision flow diagram for the program implemented on the 411 microcontroller. The "low-resolution" (Low-Res) designator refers to the acquisition of the entire plethysmographic waveform, which incorporates both the DC and AC signal components. Since these components must be spread over a large portion of the ADC range and the signal's DC component can be hundreds of times greater than the signal's AC excursion, the AC portion must be sampled separately. To accomplish this, the circuit subtracts out the signal baseline and samples an amplified version of the pulsatile (AC) excursion, resulting in a "high-resolution" (High-Res) signal represented by hundreds of digitization levels from valley to peak. Note that this signal still contains minor amounts of drift present in the original DC signal; refer to Figure 6 later in the paper.

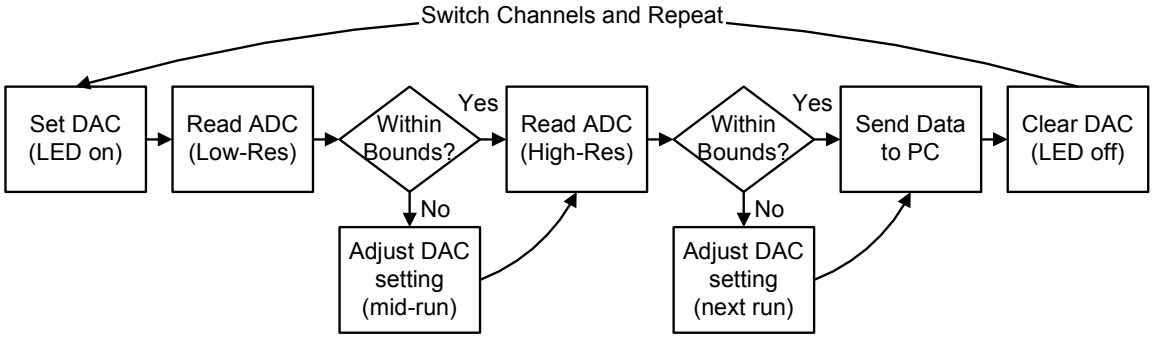


Figure 3. Program decision flow diagram.

In Figure 3, the 411 first adjusts the current through the LEDs until the photodiodes produce a response over the desired voltage range. The microcontroller then continually adjusts the drive current (and therefore the photo-plethysmogram DC baselines) throughout the data acquisition session, holding the low-resolution response at approximately one half of the ADC voltage reference level. This is indicated by the first decision in Figure 3.

Since light reflectance waveforms from tissue have such large non-pulsatile components, direct digitization of these waveforms with a 12-bit analog-to-digital converter often provides as few as 5 to 10 peak-to-peak quantization levels in the AC portion of a waveform. Therefore, a differential amplifier was implemented to separate out the pulsatile signal components from their non-pulsatile counterparts, achieving the desired high-resolution sampling in the red and near-infrared photo-plethysmograms. The differential amplifier, which consists of two high-quality operational amplifiers, first buffers the low-resolution signal from the photodiodes, then amplifies the signal using one half of the ADC voltage reference as a virtual ground, canceling out the majority of the DC signal component before amplification. The high-resolution waveform at the output of the differential amplifier is then digitized by the 411 ADC.

The second decision in Figure 3 indicates how the 411 prevents the amplifier from reaching saturation by automatically adjusting the current through the LEDs if a high-resolution output crosses preset thresholds. This ensures that data will not be lost but induces a secondary problem: whenever the LED current is adjusted, a jump discontinuity occurs in the high-resolution waveform, which is accompanied by a peak-to-peak amplitude difference in the high-resolution waveform. In other words, a change in the LED drive current will induce a change in the DC level of the plethysmograms, which also changes the peak-to-peak excursion of the AC signal components. Reconstructing these jumps proves to be challenging in real time but is easily done with post-processing routines.

D. Laboratory Exercise Utilizing the Pulse Oximeter Design

This new module design was utilized in a Fall 2006 offering of *AP 773 – Bioinstrumentation Laboratory*, a 1-hour laboratory section that is part of a 4-credit-hour Bioinstrumentation course sequence jointly taught by faculty from the KSU Department of Electrical & Computer Engineering and the KSU Department of Anatomy and Physiology. The course is offered to undergraduate and graduate students, and enrollment in the course is not limited to electrical engineering students; students from veterinary medicine, kinesiology, biological & agricultural engineering, etc. often enroll in this course sequence. Five devices were constructed for this laboratory session, which was designed to meet the following **learning objectives** (i.e., things a student should be able to do upon completion of the laboratory):

1. Explain the physiological origin of a transmittance/reflectance plethysmogram
2. Describe the hardware and software components required to determine blood oxygen saturation using light-based sensors
3. Calculate blood oxygen saturation given a set of red/infrared plethysmograms
4. Assess the character and spectral content of these time-varying signals
5. Extract physiological data from a photo-plethysmogram
6. Describe person-to-person variations in plethysmographic signal data
7. Calculate calibration coefficients using different approaches

For this laboratory session, the experimental protocol required three groups of three students each to address the following tasks:

- Acquire a 20-second segment of motion-free data from the fingertip of one group member. These data are saved to a file.
- Calculate a calibration coefficient for these data according to the expression $R = (I_{ac}/I_{dc})_{\text{red}}/(I_{ac}/I_{dc})_{\text{near-infrared}}$, where I_{ac} represents the AC (peak-to-peak) excursion of each

plethysmogram and I_{dc} represents the DC value, or baseline, of each plethysmograms. These coefficients are applied with two published calibration curves ($SpO_2\% \approx -25R + 110$[13] and $SpO_2\% \approx -25.6R + 118$[14]) to determine whether the calculated blood oxygen saturation values are within a sensible range. (Direct calibration of these devices is still needed; refer to the following section.)

- Determine the frequency-domain magnitude spectrum of the near-infrared plethysmogram via a Fast Fourier Transform call in MATLAB or Microsoft Excel.
- Calculate and compare heart rates obtained with the time- and frequency-domain signal representations.
- Calculate values for I_{ac} (and therefore R) using two approaches that are different from the peak/valley method used earlier.
- Address questions regarding relative signal strengths from the two excitation wavelengths, data smoothing, cyclic variations (in heart rate, signal shape, and R), and moving average approaches.
- Compare person-to-person variations in plethysmogram signal shape, signal-to-noise ratio, and calculated blood oxygen saturation.
- Acquire and compare signals from different body locations accessible to the probe.

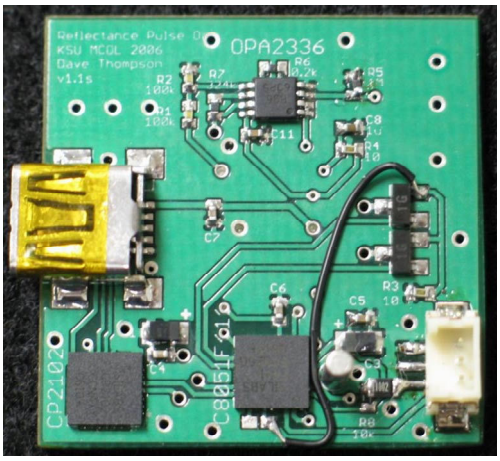
The learning assessment that resulted from these activities was accomplished through the evaluation of laboratory reports submitted by the three teams of students as well as anecdotal feedback obtained from these students in follow-on conversations.

IV. Results & Discussion

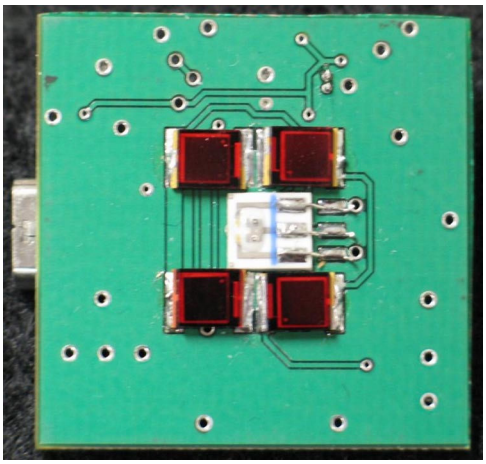
Pulse Oximeter Hardware, Student Usage, and Data Quality. Figure 4 contains images of the front and back of one of these pulse oximeter units. The form factor is square and 30 mm on a side. As noted earlier, the front of the printed circuit board contains the USB connector, the 411 microcontroller, a connector to program the 411, and the remaining surface mount components that constitute the digital circuitry. The back side of the unit hosts the reflectance sensor, which consists of the central excitation LED pair surrounded by four photodiodes.

Figure 5 contains images that illustrate the use of these modules in the Fall 2006 AP 773 laboratory. These pulse oximeter modules, being highly optimized relative to previous designs in terms of both sensor geometry and digitization fidelity, were able to acquire plethysmographic data from each of the nine students enrolled in the course, which is atypical when compared to past semesters, where students with low perfusion in their fingers would have difficulty obtaining anything other than low-quality pulsatile waveforms. In these previous offerings, it was not unusual if only 6 to 8 students out of 10 acquired reasonable plethysmographic data.

Typical data sets obtained from these units are illustrated in Figure 6, which depicts data from the fingertip and wrist of the same individual. The fingertip plethysmogram consists of ~600 digital levels from peak to valley and has a signal-to-noise ratio of ~30, both of which are substantial improvements over previous designs.[10] Additionally, obtaining high-quality wrist data from a subject can be difficult, often requiring the application of pressure to the sensor in order to reduce the physical distance between the sensor and the major arteries in the wrist.[7] As illustrated in Figure 5, students were also able to obtain viable plethysmographic data from the temple, forehead, nose, ear lobe, and palm.



Front Side – Microcontroller, digital drive circuitry, and Universal Serial Bus connector



Back Side – Sensor (red and near-infrared sources surrounded by 4 photodiodes))

Figure 4. Images of the front and back of the pulse oximeter.

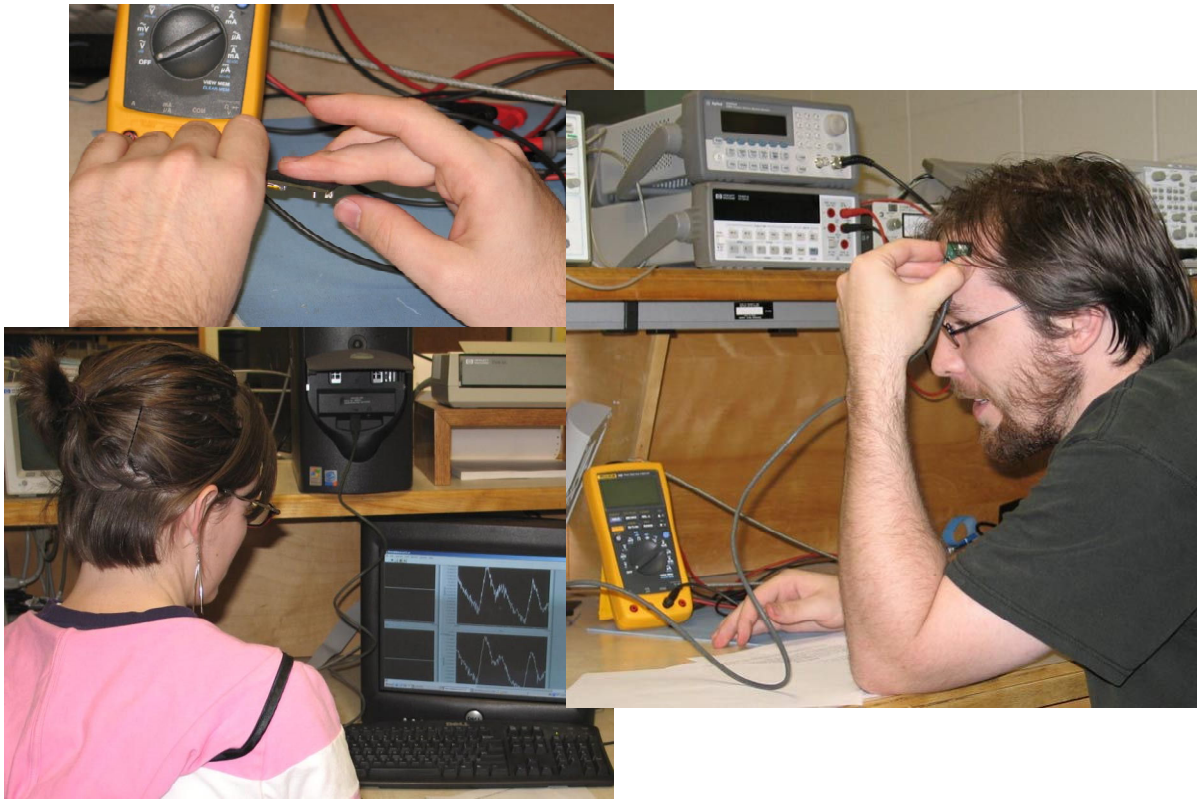
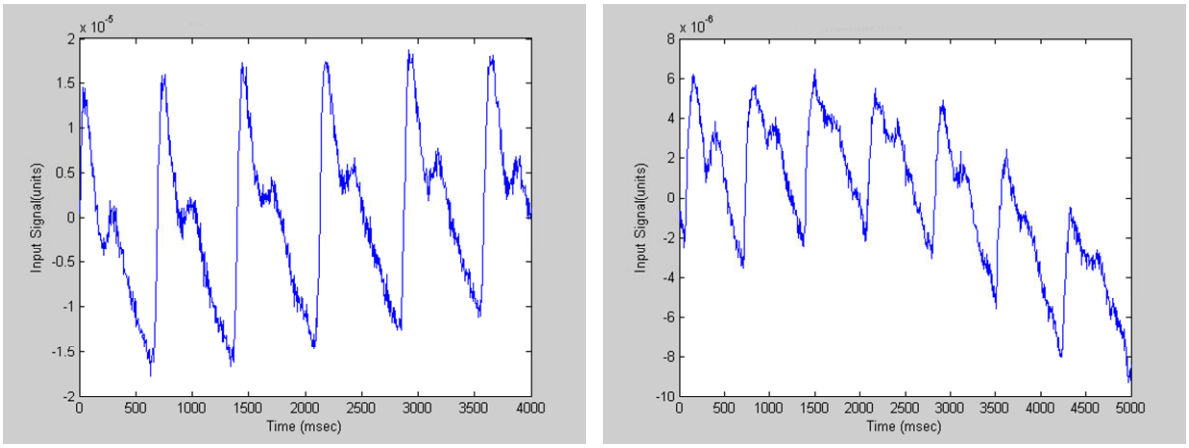


Figure 5. Pictures from a Fall 2006 bioinstrumentation laboratory illustrating finger placement on the pulse oximeter (upper left), typical red/near-infrared plethysmograms obtained with the unit (lower left), and data acquisition from the temple (right).



Fingertip Wrist

Figure 6. Typical photo-plethysmographic data acquired with the radial sensor design.

Assessment of the Initial Learning Experience. The structure of the Fall 2006 laboratory experience was unchanged relative to previous course offerings that utilized the former pulse oximeter design.[3, 4] In terms of assessment, the primary goals were therefore two-fold: (1) to ensure that the learning objectives were met given the insertion of a new device design into the learning experience and (2) to gauge the level of improvement in learning and/or interest incurred by the insertion of the technically improved device. The primary assessment addressed the seven learning objectives introduced in section *III. Methods*. These learning objectives were assessed based on typed laboratory reports submitted by each of the three student teams. Learning objectives 1 and 2, which speak to pulse oximetry theory and hardware implementation, were assessed based upon material in the *Introduction* and *Theory* sections of the three reports. Learning objectives 3 through 7 were assessed given the information presented in the *Results* sections of the three reports. These learning objectives were clearly met, as evidenced by the high scores that the students received on their laboratory writeups. A written exam was not used to supplement the assessment provided by the graded laboratory reports.

A quantitative assessment of the level of improvement in learning or interest that occurred as a result of this upgraded technology proved awkward, as the number of students (three groups of three for a total of nine students) was not large enough to warrant splitting the students into control and test groups that would use old and new module designs, respectively. However, indicators of improved learning could be identified if one is willing to assert that higher-quality equipment with improved reliability (and therefore lower student frustration) enhances learning:

- The increased fidelity of the sensor data is clear by way of visual comparison between data sets obtained with the former design versus those obtained with the current design.[10]
- Quality data sets were obtained from each of the nine students. In a previous course offering, two or three of those students would have had to rely on other students' data to perform their calculations.
- Calculated values for SpO_2% were more reasonable and more consistent over time than in previous semesters.
- In previous semesters, the serial data streams provided by the PIC microcontrollers on the pulse oximeters would periodically get out of synchronization with LabVIEW, resulting

in (a) inactive LabVIEW interfaces that had to be restarted or (b) spurious data due to improperly parsed data streams, which would require hardware resets on the pulse oximeter. These events would happen several times to each laboratory team during the course of the laboratory session. With the newer module design, the frustration generated on the part of the students was lessened because hardware resets were only needed a couple of times. It is unclear whether this improved performance was due primarily to the improved pulse oximeter design or whether the USB interface played a role, as it allows faster data rates than the previous RS-232 serial implementation. Note that the version of LabVIEW utilized in these new studies is the same as the version used in previous offerings of the laboratory course.

The instructors also gathered the following informal feedback from the students that participated in the laboratory:

- Students appreciate the visibility of the surface mount electronics (which are always hidden by packaging in commercial implementations) and feel they can relate to the in-house design because it was created by another student in their peer group.
- The students find the hands-on experience to be enjoyable.
- Students can realize the 'identity' experienced by having a photo-plethysmogram that is different in shape from the other members of their group.
- Students receive minor frustration from the fact that the LabVIEW display cannot always keep up with the data buffering process; the waveforms displayed on the screen are not always visually synchronized in real time with the data provided by the sensor.

Future Work. While the initial experience with this technology was highly positive, some minor changes can be made to the device and the accompanying software that will further improve it effectiveness. First, while the students find it interesting to have visual access to the hardware, the modules need physical packaging that will help them to withstand repeated use. Second, the physical cable between the device and the PC limits the ease with which the devices can be applied. A wireless link (e.g., Bluetooth or 801.11b at 2.4 GHz) would provide more flexibility in this regard and even allow the module to communicate with handheld computers and cell phones, but this type of upgrade will require (a) a battery to be added as a local power source (one of these USB pulse oximeter modules obtains its power from its host PC), (b) the creation of additional software to utilize the protocol stack of the corresponding wireless module, and (c) design creativity to add the wireless element without unduly enlarging the device. Third, the sensor needs its own blood oxygen saturation calibration so that it can be used in clinical studies, honors student investigations, and other studies that require reasonable fidelity in the reported saturation levels. Finally, upgrades need to be made to the LabVIEW interface to (a) synchronize the display in real-time with the data gathering process and (b) better present the data to the user.

As a side note, it is the intent of the authors to make this equipment more widely available to the biomedical education community. The optimal mechanism for this transfer is not yet clear, but at present the intent is to distribute collections of fabricated and tested modules at a reasonable price. While a mechanism can be put in place to publish documentation, a parts list, an EAGLE PCB layout, microcontroller code, driver software, and LabVIEW VIs, the construction of these modules requires access to surface mount equipment, 411 microcontroller development kits with

custom cable adapters, and software debugging expertise not always available in local engineering departments. The total parts cost is approximately $75 per unit, which can vary depending on part quantities and board fabrication costs. Additional cost factors include the time to populate the surface mount components, program the microcontroller, and debug the unit.

V. Conclusions

Biomedical engineering students must be taught the operational principles of pulse oximetry and the related design issues given its clinical importance as a health monitoring technique. This paper addressed the effectiveness of an inexpensive, small, plug-and-play pulse oximeter that gives students full access to unfiltered red and near-infrared reflectance plethysmograms whose characteristics map directly to underlying physiology. The plethysmographic data are very high fidelity, exhibiting high signal-to-noise ratios and hundreds of quantization levels from peak to valley in the pulsatile signal components. The radial sensor geometry optimizes the relative collection of pulsatile versus nonpulsatile signal components, and the preponderance of digital drive circuitry, coupled with a back-to-back, two-level board layout, minimizes the size of these units while providing feedback-constrained baseline extraction that allows the units to be employed in ambient room light. The inclusion of a plug-and-play USB serial bus allows the units to be used with most PCs and laptops, and the LabVIEW front end provides a reasonable interface that allows students to view and store the waveform data.

These modules performed well in an initial Fall 2006 laboratory experience. All participating students were able to acquire quality pulsatile signals from themselves, and an assessment of the laboratory learning objectives coupled with anecdotal student feedback indicate that the pulse oximeter platform effectively promotes student learning. In addition to enhancing biomedical learning laboratories, this new design will continue to yield high-fidelity data for multiple education and research applications, including (a) motion artifact reduction studies, (b) extraction of physiological parameters from reflectance plethysmograms (e.g., respiration rate and biometric indicators), (c) comparisons of filtering techniques applied to biomedical signals, (d) the assessment of different means for calculating blood oxygen saturation, and (e) trend analyses for health prediction.

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