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Pulse Oximeter Improvement with an ADC-DAC Feedback Loop and a Radial Reflectance Sensor

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Abstract—**Pulse oximeter circuitry must meet several design constraints, including the ability to separate a small pulsatile signal component from a large signal baseline. This paper describes pulse oximeter design changes that produced order-of-magnitude improvements in signal quality. The primary changes were (a) the replacement of an analog sample-and-hold-based differentiator circuit with an ADC-DAC feedback loop and (b) the replacement of a side-by-side reflectance sensor design with a radial sensor arrangement that maximizes the pulsatile-to-baseline signal ratio.**

Keywords—**Light-based sensor circuitry, photoplethysmogram, pulse oximeter, reflectance**

I. Introduction

Pulse oximeter signal circuitry must accommodate multiple light sources, signal drift, and photoplethysmograms that consist of small pulsatile ("AC") signals riding on large "DC" offsets. In a pulse oximeter with a reflectance sensor, the peak-to-peak AC amplitude of a photoplethysmogram can be on the order of 0.1% of the DC amplitude, while the DC value can vary by as much as 50% depending on sensor placement, ambient light levels, respiration, and motion. Attempting to filter out a DC component with such a large drift while maintaining sensitivity to signal components of 0.3 Hz and greater can be difficult. Multiple-pole filters with these low corner frequencies are hard to construct and control. Additionally, these filters must be able to switch between inputs with different DC values at a rate of 50-200 Hz in order to accommodate multiple excitation sources.

Unfortunately, such a small AC signal (sometimes as small as one to four least significant bits on a 10-bit system) is also difficult to accurately measure directly with an analog-to-digital converter (ADC). 16-bit ADC chips may be able to sufficiently resolve the signal for most applications but may still be insufficient for obtaining a high-quality representation of the waveform shape.

One possible solution to this problem is the use of sample-and-hold circuitry and differential amplifiers to take a discrete derivative of the signal, which cancels the baseline and requires a subsequent signal reconstruction [1]. That method was used in the previous design of the pulse oximeter discussed here [2,3]. This paper discusses the changes made to produce the most recent design, namely the inclusion of an ADC-DAC feedback loop (to control the vertical placement of the DC baseline) and an improved sensor design that maximizes the quality of the pulsatile signal.

II. Methodology

A. High-Level Circuit Functionality

Fig. 1 shows the functional block diagram for the new circuit, which replaces the functionality performed by the previous sample-and-hold based differentiator circuit. The input signal is a photoplethysmogram obtained from either the red or near-infrared excitation light emitting diode (LED). This signal is sent into a 12-bit ADC whose output (a low-resolution version of the signal) goes to a PIC microcontroller. The PIC microcontroller also sets the output of a 12-bit digital-to-analog converter (DAC) by sending it a control signal via a 3-wire serial interface. The DAC output essentially provides for an adjustable baseline against which the input signal can be compared. The output from the DAC and the original signal both enter a differential amplifier, and the resulting difference (an amplified version of the pulsatile component minus a shift) is read by a second channel of the ADC, essentially creating a high-resolution version of the input signal. The microcontroller currently sends the original (low-resolution) reading, the DAC setting, and the second (amplified) reading through an RS-232 serial cable to a computer for processing.

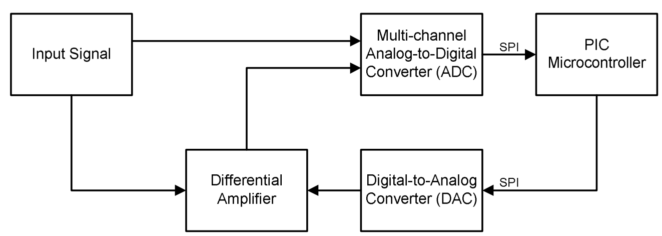

Fig. 1. Block diagram for the ADC-DAC feedback loop.

B. Circuit Specifics

The measurement circuit incorporates a MAX188 12-bit serial ADC, an LTC1451 12-bit serial DAC, a PIC16F73 microcontroller, and a differential amplifier. The ADC, DAC, and PIC communicate through a three-wire Serial Peripheral Interface (SPI), with the PIC's Master Synchronous Serial Port (MSSP) Module acting as the master. Some supporting circuitry is present as well, including an oscillator and a 2.5 V virtual ground.

The differential amplifier used for this proof-of-concept demonstration consists of four operational amplifiers. The first acts as a unity-gain inverting amplifier, the second acts as an inverting summing amplifier, and the last two act as

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gain stages. In principle, any form of differential amplifier should work, from standard (though difficult to adjust) single op-amp configurations to instrumentation amplifiers. The primary concern for battery-operated or single-supply systems is op-amp selection, paying particular attention to rail-to-rail output performance, power supply ranges, and supply current. Texas Instruments' OPA336 family seems to do an adequate job for 5V single-supply applications and is specified to work in 2.7 V environments as well.

C. *Circuit Operation*

The microcontroller is in charge of timing and DAC settings. Four instruction cycles (<1 µs) prior to switching between LED sources, the PIC also outputs the previous DAC reading. This is critical to avoid driving the amplifier into saturation and thus causing a very slow response time. Once this occurs, the ADC checks the input signal directly. If this low-resolution result is too far from the previous offset value, the microcontroller will immediately change the DAC offset to a more reasonable setting without requiring the offset to be adjusted in small incremental steps. This allows the system to cope with fast changes in the DC value of the input signal. The microcontroller then instructs the ADC to take a reading from the output of the differential amplifier. If the output of the amplifier is above or below the software thresholds for the 12-bit ADC, the PIC will adjust the next DAC setting slightly so that the output of the differential amplifier remains in the ADC conversion range.

D. *Sensor Design*

The creation of a new sensor design was driven by the need to increase both the amplitude and the signal-to-noise ratios (SNRs) of the red and near-infrared photoplethysmogram. Previous sensors [2,3] used a single photodiode to acquire the reflectance signals from individual red and infrared LED's. More functional designs [1,4,5] can utilize an array of photodiodes wired in parallel that encircle the LED's. These new designs benefit from the increased detector area provided by multiple photodiodes whose signals are summed. Additionally, the distance between the excitation sources and the photodiode detectors has been increased. This promotes the selective detection of reflectance photons that have more likely penetrated deep into perfused tissue, yielding an improved AC/DC ratio. The two sensor designs are shown in Fig. 2.

Fig. 2. Previous (left) and new (right) reflectance sensor designs.

III. Results

A. *Circuit Results*

Two trial runs were performed using the old sensor design with both the old and new circuitry. The data was taken from a subject's middle finger in sequential measurements without any change in physical condition. The plots in Fig. 3 display representative sections of these data for a red LED. Note that red waveforms will typically demonstrate a poorer signal-to-noise ratio, since red light does not penetrate tissue as well as near-infrared light; the data in Fig. 3 present a worst case scenario.

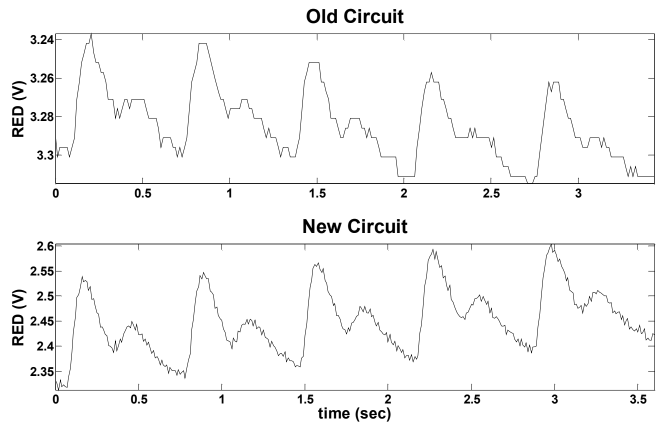

Fig. 3. Comparison of red photoplethysmograms for the two circuit designs when using the old sensor (subject A).

As can be seen in Fig. 3, the improvement was dramatic. While the signal from this test subject is typically very low amplitude, the approximately doubled sampling rate, the accuracy of the ADC-DAC approach compared to the previous sample-and-hold circuit, and the increased number of quantization levels have yielded a high-quality signal. The old circuit yielded a signal with a peak-to-peak amplitude of ~60 mV after amplification and reconstruction, where ~15 quantization levels could be observed. The new circuit's signal is ~ 200 mV peak-to-peak after amplification, where ~200 quantization levels can be resolved.

B. *A Complication – Offset Movement*

One minor complication with the new circuit is that for subjects that produce large signals, baseline drift can cause the offset to change too frequently, often in consecutive cycles of the waveform. While the frequency of this occurrence can be minimized by (1) allowing a large vertical signal window over which the signal can migrate and (2) making large offsets when the upper/lower thresholds are exceeded, this type of behavior can be expected during a typical measurement session (e.g., refer to the upper waveform in Fig. 4). An important aspect of this event is that the PIC outputs the offset for each sample, so offsets and offset changes are known and can be saved for later use. For maximum accuracy, only values between offset adjustments would normally be considered valid. However, as Fig. 4

shows, a reconstruction can be accomplished using an equation of the form

$$v_{rec}(n) = v_{offset}(n) + \frac{\left(v_{high-res}(n) - v_{ground}\right)}{A},$$ where all the terms on the right refer to the differential amplifier: $v_{high-res}(n)$ is the high-resolution output, v_{ground} is the virtual ground (if used), and A is the amplifier gain. While some accuracy may be lost during the reconstruction, Fig. 4 illustrates that the resultant waveform can represent a complete, high-resolution version of the original signal.

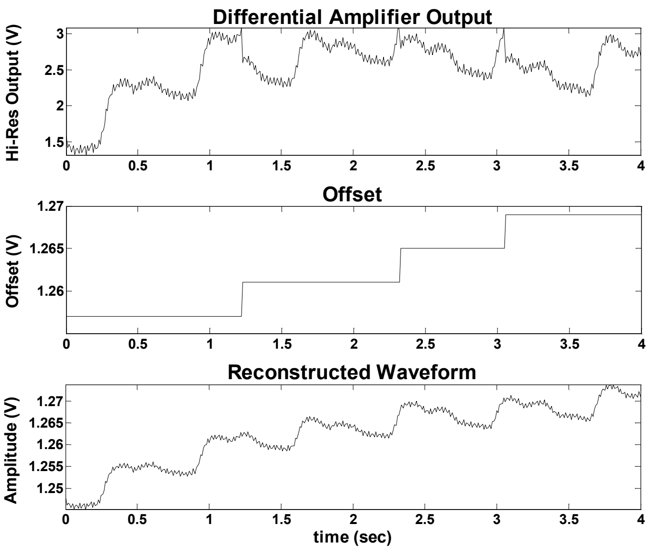

Fig. 4. Reconstruction after offset movement (subject B).

C. Sensor Results

Test data were acquired using both the new and old sensors connected to the improved sampling circuitry. The test data was taken from a subject's middle finger in sequential measurements without any change in physical condition. The plots in Fig. 5 show representative waveforms for the old and new sensors. Comparing the waveforms, it is evident that the new sensor produces a much cleaner signal. *Without any added filtering*, the new sensor produces signals with larger amplitudes and less noise; the SNR has obviously improved. SNRs for the data presented in Fig. 5 are shown in Table 1, where

$$SNR = 20\log(\text{Signal}_{\text{peak-to-peak}}/\text{Noise}_{\text{peak-to-peak}}).$$

IV. Discussion

One advantage of the change in circuit topology is that the new circuit avoids all types of analog filtering, so it has a very flat response versus frequency that is limited only by the gain-bandwidth product of the amplifiers and the circuit gain. For biometric applications, hemodynamic assessments, or other applications where retention of the signal shape is critical, this lack of filtering can be a significant advantage. Also, component tolerances become less important (except for variations in gain), so results from different units should be more comparable. Even gain differences are of relatively little importance for blood oxygen saturation calculation: since the same circuitry is used for both red and near-infrared LEDs, the ratiometric nature of the calibration coefficient calculation should entirely cancel that effect. Note that the lack of analog filters does require digital filtering (i.e., smoothing) if a clean output is desired. This is balanced somewhat by the fact that the output no longer has to be digitally integrated as it did in the previous design.

This new approach is valuable for three important reasons. First, this pulse oximeter design outputs raw data with very few filtering effects. This will allow further study of the reflectance plethysmograms and also investigation of the effects from different types of filters. Second, the approach is scalable. Immediate benefit could be gained from upgrading to a higher-resolution ADC and DAC, which would require some hardware changes but only minor software changes. Linear has several 14-bit ADCs that are pin compatible with 12-bit chips, allowing an easy upgrade path. Linear also has 14- and 16-bit DACs that are pin compatible with the LTC1451. Third, the sampling rate is quite variable. Since the DAC does not suffer from droop, very slow sampling is possible. In faster applications, the DAC and amplifier settling time are comparable to the acquisition time for most sample-and-hold circuits.

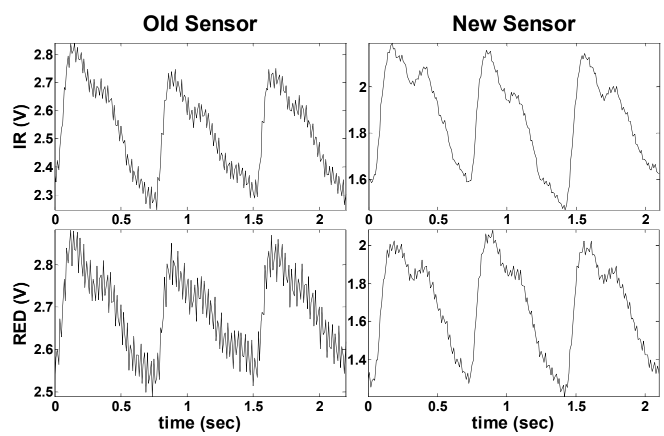

Fig. 5. Data from the old (left) and new (right) reflectance sensors obtained with the improved circuit design (subject C).

TABLE 1. Signal-to-noise comparison for the two sensor types.

Signal	SNR – Old Sensor	SNR – New Sensor
IR	13.65 dB	24.78 dB
Red	6.59 dB	19.32 dB

V. Conclusion

The ADC-DAC feedback loop approach presented in this paper fills a niche, serving applications where well understood effects are required, but computational intensity and high data volume are acceptable. Since very little filtering is done by the circuit, any filtering must take place instead in the controlling computer (or on the microcontroller, assuming simple digital filtering routines can be developed). The combined effects of the ADC-DAC circuitry and the radial sensor design yield a dramatic increase in signal quality.

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