Solar powered wrist worn acquisition system for continuous photoplethysmogram monitoring

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***Abstract*— We present a solar-powered, wireless, wrist-worn platform for continuous monitoring of physiological and environmental parameters during the activities of daily life. In this study, we demonstrate the capability to produce photoplethysmogram (PPG) signals using this platform. To adhere to a low power budget for solar-powering, a 574nm green light source is used where the PPG from the radial artery would be obtained with minimal signal conditioning. The system incorporates two monocrystalline solar cells to charge the onboard 20mAh lithium polymer battery. Bluetooth Low Energy (BLE) is used to tether the device to a smartphone that makes the phone an access point to a dedicated server for long term continuous storage of data. Two power management schemes have been proposed depending on the availability of solar energy. In low light situations, if the battery is low, the device obtains a 5-second PPG waveform every minute to consume an average power of 0.57 mW. In scenarios where the battery is at a sustainable voltage, the device is set to enter its normal 30 Hz acquisition mode, consuming around 13.7 mW. We also present our efforts towards improving the charge storage capacity of our on-board super-capacitor.**

I. INTRODUCTION

As a part of a collaborative effort under the National Science Foundation Nanosystems Engineering Research Center for Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST), SoliBand (Fig.1) is our first efforts at creating a self-powered, wrist-worn health and environmental monitoring device in the hopes that correlations between physiological and environmental parameters can be obtained with a high statistical significance. In order to create opportunities for these correlative studies, this device proposes to create large volumes of data through continual and wireless acquisition. Photoplethysmogram (PPG) is one of such common diagnostic and wellness tracking parameters that can be obtained using relatively few electronic components. With a single optical emitter and detector, PPG waveforms can be collected from a variety of different locations on the body. Because of its relatively low cost and non-invasiveness, PPG has been the subject of a number of studies showing correlation to parameters such as heart rate and cardiac cycle monitoring, diagnosing arterial aging and hypo-/hyper-volemia and even predicting intradialytic hypotension [1,2].

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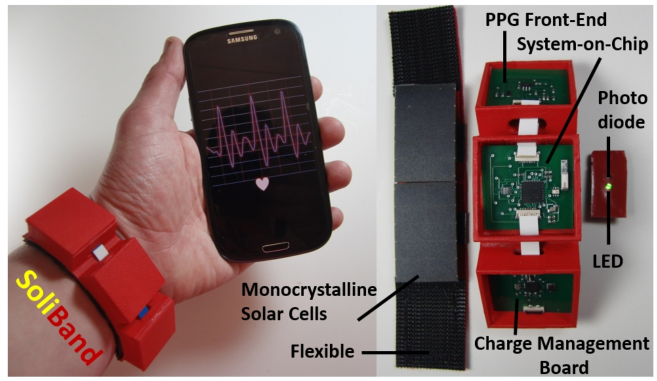

Figure 1. (Left) PPG data being displayed on a smart phone. (Right) The opened device with probe board extended far right for display.

II. OPTICAL INFERENCE OF PLETHYSMOGRAPHS

Photoplethysmographs are obtained by observing the effect of a certain region of organic matter on a photon population. When photons are injected to tissue through coupled light sources, a modulated component will be observed on the back-scattered or transmitted photon population if an intersection with an artery has occurred. This is due to the extinction of photons as they are absorbed by hemoglobin at wavelength dependent rates. Inside of the wrist is the most common location to check pulse rate using tactile sensing of fingers (Fig.2). Inherent with SoliBand's deployment on the wrist comes the inability to obtain PPGs using a direct transmittance system as used in most fingertip PPG devices. The large distance that photons would need to travel from one side of the wrist to the other limits the measurement to reflectance measurements. For this, the emitter and the detector reside in close proximity with each other on the same side of the extremity.

A. Transmittance Loss

Most wrist-worn PPG devices rely on extended wired probes to perform transmittance measurement at the finger tip. Obtaining PPGs through the measurements of backscattered photons is known to suffer from lower SNR, especially when signals are extracted from non-uniform areas (Fig.2). Although positioning the SoliBand on the wrist would take advantage of the location of the strongly pulsating radial artery inside of the wrist, the segmented structure of the bone beneath and limiting the assessment to reflectance measurements are show-stopping factors.

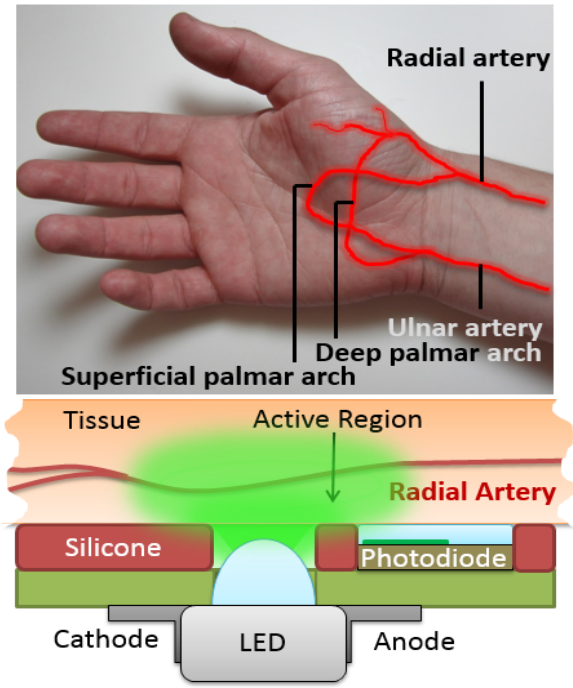

Figure 2. A low profile probe is obtained by use of reverse mount LED. Probe sits atop the radial artery just before the branches to the palmar arches.

B. Signal Conservation through High Backscatter

The typical PPG systems use red and near-infrared light to differentiate the concentrations of oxygenated and deoxygenated hemoglobin in the arteries. These wavelengths are highly absorbed in the tissue, further limiting the reflectance measurements (Fig.3). In order to increase the quantity of returned photons, in this study we selected a wavelength of 574nm as it has a shorter mean free path. This increase in backscatter translates to an increase in returned photons, but a decrease in photon penetration depth. Because of the superficial location of the radial artery, this decrease in penetration depth was irrelevant. An additional benefit of using 574nm light is the increased absorption coefficient of deoxy- and oxyhemoglobin over traditional red and infrared wavelengths as well as a decreased absorption coefficient for

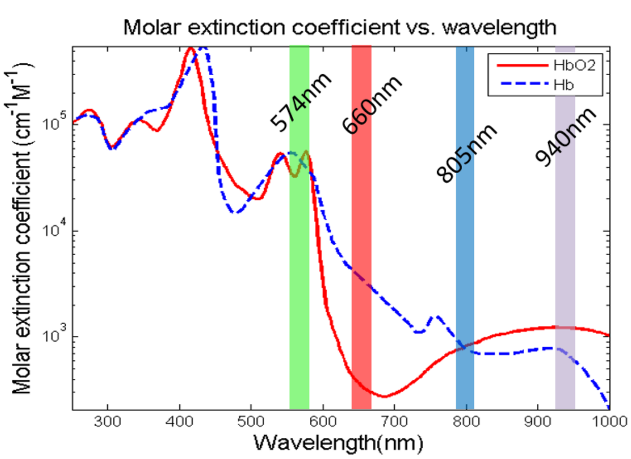

Figure 3.Extinction coefficients for deoxygenated and oxygenated hemoglobin

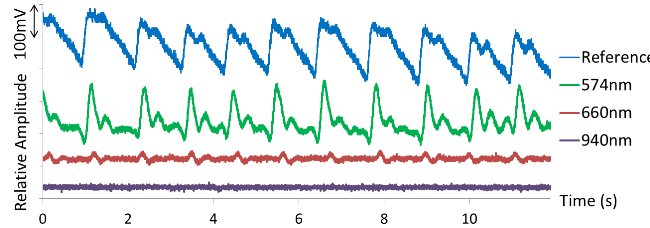

Figure 4. PPG measurement from radial artery with 0.4 mA sent to LEDs with wavelengths in green, red and infrared regions. The reference waveform was obtained using a standard transmittance finger probe (805nm).

water [3, 4]. With a higher absorption coefficient, the change in hemoglobin concentration causes an increased the peak to peak value of measured arterial pulses (Fig.4).

III. System Overview

The SoliBand device can be thought of as three systems interconnected wirelessly (Fig.5): the wrist-worn device acquires the data, the smart phone receives the data for short term storage and the dedicated server stores the data for analysis over long sample durations. The smartphone's connection to the dedicated server can be through WiFi or cellular network. For the connection from SoliBand to the phone, Bluetooth Low Energy (BLE) was chosen as the wireless protocol (Fig.6).

A. Data Acquisition

In order to achieve a low power Bluetooth system, the microcontroller must spend the majority of its time in a sleep state, waking up only for critical processes and transmission/reception events. In order to minimize the quantity of wake-ups, the data acquisition and the transmission are made subsequent of each other, such that both occur during a single wake--up. Thus, the device's sampling rate of 30 Hz is also its transmission rate. Because the PPG signals pertain to a relatively low frequency range [5], a 30Hz sampling rate is sufficient to accurately capture

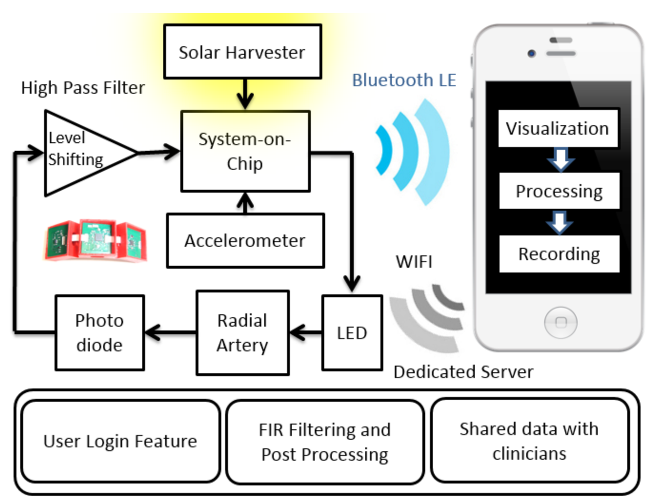

Figure 5. System diagram showing the flow of data from the wristband to the server.

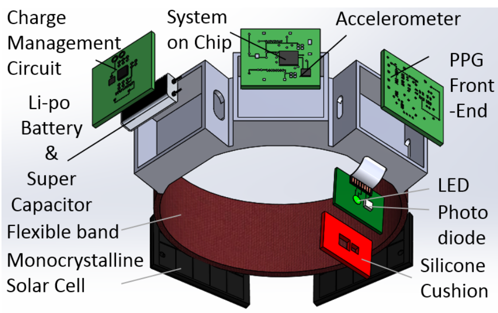

Figure 6. Exploded view of all the components of the device.

the waveform. The subsequent transmission event from the SoliBand is then sent to a paired smart phone, which stores the data for a certain amount of time. The current system sends a single 12 bit value per message representing the voltage measured at the analog to digital converter. Once the data has been sent to the smartphone, the phone's mobile software app manages the influx of readings and periodically pushes data to a server.

B. Motion Artifact Filtering

Due to the device being worn on the wrist, large magnitude accelerations will be frequently experienced by the device. PPGs are notoriously susceptible to motion artifacts as the cross-sectional area of the measured blood vessel will experience a force and thus undergo a deformation [7]. This deformation causes artifacts to appear in the received signal, creating a corrupted PPG. The noise present in the corrupt waveform, however, is highly correlated with the experienced acceleration [8]. The SoliBand contains an onboard 3-axis accelerometer, allowing it to accurately measure up to 8g in a given direction. A delay is then applied to the measured acceleration to increase correlation between the motion and the noise present in the signal. Once an estimated noise signal has been generated, it is subtracted from the corrupted waveform to recover a useable signal. Because of the computational costs, this adaptive filtering will take place on either the smartphone or the dedicated server as a post processing step.

C. Hardware

SoliBand is comprised of four printed circuit boards (PCBs) that are compartmentalized in the underbelly of the device (Fig.6). These PCBs are interconnected using ZIF cables that extend through openings between the compartments. Each one of the PCBs handles a different operation of the device.

The control board houses the CC2540 (Texas Instruments) System-on-Chip (SoC), a 3-axis accelerometer, a voltage regulator and a 32 kHz external crystal used for sleep mode regulation. Embedded in the microcontroller is a BLE radio, which is used in tangent with the external balun and chip antenna. Due to the low power consumption of the light emitting diode (LED), the drive current can be directly sourced from the microcontroller. This allows for software controlled adjustment of the drive frequency as well as steady state driving.

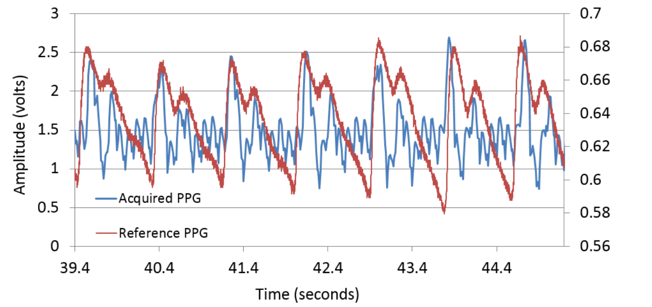

Figure 7.Sample PPG wirelessly acquired from the radial artery via Bluetooth using SoliBand. The periodic noise seen on the signal is noise introduced by the energy harvesting circuit.

The PPG front-end board enhances the signals being measured from the probe board that couples the LED and photodetector (PD) to the tissue. In order to achieve a low profile probe board and still have efficient photon generation, a reverse mount LED was used with an output rating of 800 mcd. A hole was then drilled in the probe board and the board itself, in addition to a silicone buffer, served as a simple collimator. To further reduce the power consumption while preserving signal amplitude, a PD with relatively low response time is used in place of an anti-aliasing filter. High frequency noise is smoothed over by a 5 ms fall/rise time and is then sent to an active high pass filter biased at half the supply voltage. The signals hovering safely on this bias are then sent to an analog to digital (ADC) pin on the microcontroller to be digitized and subsequently transmitted. Fig.7 shows the PPG signal after digitization and wireless transmission have occurred.

All of these three boards are powered by the charge management board. The charge management control circuit centers around the MCP73871, a constant-current/constant-voltage charge algorithm enabled integrated circuit (Microchip). The charge management board is able to simultaneously charge SoliBand's onboard 20 mAh lithium polymer (li-po) battery and supply power to the other boards during exposure of the solar panels to light.

IV. POWER MANAGEMENT

As presented in Fig. 8, the average power consumption during normal acquisition is 13.73 mW. In the case where the onboard battery is fully charged, SoliBand can run in acquisition mode for 4 hours without exposure to sunlight (Fig.9). On the other hand, when the battery is in a discharged state, exposure to indirect or direct sunlight will bring it to its nominal voltage of 3.7 V in less than 10 minutes.

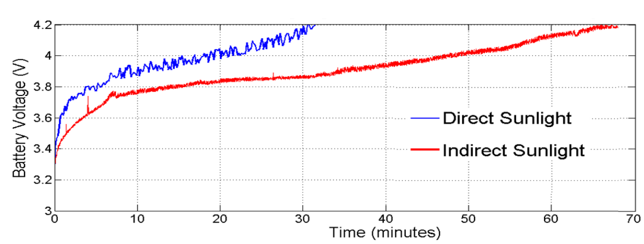

Figure 8. Battery charging profile for indirect and direct sunlight.

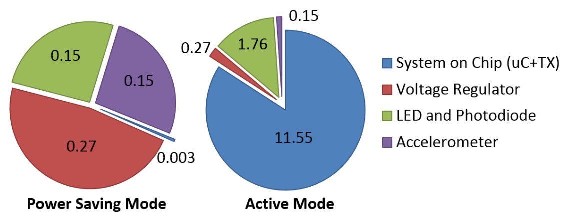

Figure 9. Power consumption in mW for both proposed power schemes

A. Power Scheme for Low Light Exposure

In order to maintain a reliable connection with the smartphone during low battery situations, we utilize a super capacitor along with its additional power management circuitry. In this case, the microcontroller monitors the battery voltage through an ADC and switch the power source to the super capacitor upon low battery using an analog switch. The super capacitor is advantageous in that it requires less time to charge, which maximizes the effect of infrequent exposure to sunlight. At the same time, due to the lower charge density of capacitors, the microcontroller will need to enter a power savings mode. In this mode, 5 seconds of 30 Hz measurements will occur periodically every minute. This 1:12 duty cycle, coupled with a sleep timer in the microcontroller, brings our total average power consumption from 13.73 to 0.57 mW. Whenever the battery is recharged to a certain threshold with the light exposure, SoliBand resumes sampling at 30Hz with a 1:1 duty cycle.

B. Super Capacitor Fabrication

Reliable solar powering of SoliBand requires flexible electrochemical capacitors to maximize the energy density while maintaining a low profile device. We began our studies using a commercially available aqueous electrochemical double layer capacitor (EDLC) from a commercial supplier. The commercial packaged EDLC occupied a total volume of 1.14 cm^3. We also fabricated high voltage non-aqueous symmetric EDLC and lithium ion capacitor using high purity carbon electrodes. High purity carbon spheres were first synthesized with very low oxygen content (less than 2%) [6]. Electrodes were then fabricated by mixing 85 wt% carbon, 10 wt% Teflon binder and 5 wt% acetylene black and punched out to produce an electrode with an area of 0.4 cm^2 and thickness of 100 microns. A polyvinylidene fluoride (PVDF) gel electrolyte membrane was used as separator. The capacitors were fabricated by sandwiching the electrodes using the PVDF membrane inside stainless steel 2032 coin cell prototypes. The coin cells were assembled inside a dry glove box which was maintained at O_2 and H_2O content < 1 ppm. 1M Tetraethylammonium hexafluorophosphate dissolved in propylene carbonate was used as an electrolyte for high voltage EDLC and 1M Lithium hexafluorophosphate dissolved in a mixture of dimethyl carbonate and ethylene carbonate (1:1 by wt.) was used as electrolytes for our study. Preliminary results show that the fabricated lithium ion capacitor demonstrate high power density per unit volume (based on electrode and separator) and further optimization can significantly enhance the performance as shown in Figure 10. The high voltage capability of non-aqueous designs can also be very attractive for these applications.

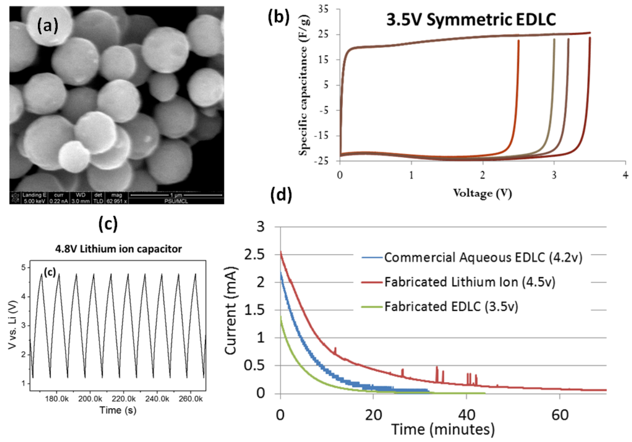

Figure 10. (a) SEM micrograph of high surface area carbon spheres, (b) Cyclic voltammogram of 3.5v EDLC fabricated using the carbon sphere electrodes and (c) Constant current charge/discharge measurements of lithium ion capacitor made using the carbon sphere electrode capable of being cycled to 4.8v at 0.1 A/g (d) Capacitor current discharge profiles for the fabricated single cell capacitors and a commercial five cell capacitor. Each capacitor was charged to capacity under galvanic conditions and connected in parallel to an LED with a 1kohm current limiting resistor.

V. Conclusion

A continuous monitoring device for PPG creates opportunities that were previously unachievable. Because of SoliBand's dependence on a smartphone, further development will utilize sensors found on the cellular device, such as the global positioning satellite (GPS), magnometer and gyroscope. These sensing modalities offer physiological insight towards the individual of interest, and could further empower clinicians through the use of informatics on a large population of user adopted devices.

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