Project Title:
Circuit System Support for HET Testbed and Optical Methods for Biosensing

Team Members:
Project Leader: Alper Bozkurt
Graduate Students (funded by ASSIST):
James Dieffenderfer, Jose Sarmiento, Henry Goodell and Peter Sotory
Contributing Graduate Students: Feiyan Lin

Statement of Project Goals:
1. Design and assemble the Generation 0 (Gen 0) Health and Environmental Tracker (HET) testbed device to provide a baseline measurement platform to benchmark the improvements in Generation 1 (Gen 1) system in terms of power consumption, signal to noise ratio, sensor performance and size. The HET testbed includes a wristband and a chest patch. Obtain IRB approval and perform tests on 10 human subjects with Gen 0 and Gen 1 system to compare the performances of two devices and explore the challenges with practicality and wearability of these systems.
2. Design and tape-out a low power analog front-end circuit for ECG and pulse oximetry measurement to be coupled to the ASSIST System-on-chip on the HET testbed. The aim of this effort is to provide a high dynamic range and low power operation by using chopper-amplifiers and Gm-C filters for ECG amplifiers and logarithmic amplifiers for pulse oximetry recording. The overall power consumption for ECG amplifier is to be less than 50µW and for the pulse oximeter system less than 1mW.
3. Use double-junction photodiodes to register multiple wavelengths simultaneously and separately for the pulse oximetry system. The aim of this effort is to avoid extra circuit elements used for wavelength switching at the input (light source) and sample-and-hold at the output stages to lower the power consumption.

The Project's Role in Support of the Strategic Plan:
This project provides circuit and system support to the HET testbed.

Discussion of Fundamental Research, Educational, or Technology Advancement Barriers and the Methodologies used to Address Them:
Recording biopotentials requires the use of an analog front-end (AFE) circuit to amplify and filter these signals that characteristically have low amplitudes and information content in very low frequency bands. Special design techniques need to be used to overcome the low signal-to-noise ratio of the biopotentials while keeping an ultra-low power consumption for those scenarios where the devices are self-powered using scavenged energy.

Most commercial of the shelf (COTS) pulse oximeter systems rely on switching light sources of different wavelengths at the input while deploying switched integrator based sample-and-hold circuits at the photodiode output to be able to separately register each wavelength. This switching based operation and related circuitry causes an extra power consumption in the order of 5-10mW [1]. Eliminating time-multiplexed (switched) wavelength operation and employing multiple wavelengths simultaneously would be possible by using multiple photodetectors with different...
optical filters. One fundamental challenge about this approach is the lateral layout of the photodetectors. When placed next to each other, these photodetectors detect photons coming from different tissue penetration depths and introduces a physiological noise to the detection. Another challenge is the availability and cost of implementing color filters in standard CMOS processes.

The HET testbed systems are to be tested on the human subjects with a protocol ran in an environmental chamber to explore if continuous measurement of heart rate variability (HRV) and ozone exposure can predict an impending asthma attack. The physiological sensors are attached to the body and external forces on these sensors degrades quality of the signal [2,3].

Foreign Collaborations:
Prof. Alper Bozkurt spent 2 days in KU Leuven and IMEC in October 2014 to explore collaboration opportunities. IMEC has recently announced a new single-chip solution for low-power multiparameter signal acquisition for healthcare applications (MUSEIC) and ASSIST Center will test this product through an evaluation agreement. MUSEIC features 3 ECG readouts as well as a single bio-impedance readout and 2 general purpose analog readouts. Flexible digital interfaces (SPI, I2C, UART and GPIO) are provided to support additional external sensors with digital outputs. The built-in ARM-TM Cortex M0 core and hardware accelerator for matrix multiply/accumulate operations allows on-chip signal conditioning/filtering to be performed. A total of 128kB on-chip SRAM is available for code and data use.

Jose Manuel Valero Sarmiento, a graduate student from NCSU, joined IMEC as an intern for 4.5 months. He will work on ultra-low power circuit design for health applications and his experience will help him to design a low power pulse oximetry system for ASSIST Center over the Summer of 2015.

Achievements in Year 3 and Previous Years:
During the last year, we had presented a flexible wristband PPG platform and tested this system in vitro. We used miniaturized solar panels and Penn State’s ASSIST super-capacitors to power this system where the overall power consumption was 13mW and can be reduced to sub-mW (~0.6mW) by careful duty cycling (5 seconds data collection every minute). During Year 3, we used this system as a starting point to realize the Gen 0 wristband and the chest-patch (Figure 1). The Gen-0 wristband contains COTS ozone, temperature, relative humidity, pulse oximetry, hydration, and 3-axis accelerometer as sensors. The chest-patch contains COTS ECG, pulse oximetry, microphone, hydration and 3-axis accelerometer. The major focus of this project is to design the circuits that will interface COTS sensors with a COTS system-on-chip module (cc2541 from Texas Instruments).

Last year, we had implemented a custom instrumentation amplifier based circuit for ECG recording. To further reduce the size, we used a single-chip ECG signal detection integrated circuit from Analog Devices (AD8232). AD8232 provides a leads off detection that can sense whether or not the ECG electrodes has appropriate contact with the skin. It also features the choice of 2-electrode or 3-electrode configuration. 3-electrode configuration has been chosen due to its ability to be less susceptible to motion artifacts accomplished by using the right leg drive amplifier that improves common-mode rejection.
The hydration level measurements are based on impedance spectroscopy and we implemented this by using a single chip solution from Texas Instruments (AD5933) in very small form factors (2×1cm²). The AD5933 is a high precision impedance converter system solution that combines an on-board frequency generator with a 12-bit, 1 MSPS, analog-to-digital converter (ADC). Since the impedance is a function of the contact of the sensor with the skin, a capacitive pressure sensor located next to the hydration sensor was connected to a custom Wheatstone bridge. The tracking of the external forces would compensate ECG waveform quality degradation.

For pulse oximetry, we used a fully-integrated AFE (AFE4490) from Texas Instruments. The device consists of a low-noise receiver channel with a 22-bit analog-to-digital converter (ADC), an LED transmit section, and diagnostics for sensor and LED fault detection.

Two MEMS based sensors were used for ozone detection (MiCS-2614 from SGX Sensortech) and for inertial sensing (ADXL335). All the circuits and sensors were packaged on a hard fiberglass-based multilayer board and were encased in a 0.5 cm tall box of 3D printed ABS from the Makerspace or printed by SLA using a Form-1 3D printer.

For data acquisition and visualization, a LabVIEW (National Instruments) code was implemented. Practicalities of data logging were overcome by size limiting the exported tab or comma delimited data array with time references. Labview allows for central real-time clock tagging of data and parallelizing the various components of the processing from inputting the data to logging and manipulation of the data.

We have used Gen-0 HET testbed systems to initiate the clinical studies and identify and manage issues related to study design, standardization and patient comfort in an ongoing basis. The aim of these studies with Gen-0 system are: (1) validating the efficacy of the system in a controlled environment where the Gen-0 HET testbed recorded heart rate variability and ozone concentration data are compared with gold standard, (2) fusing the outcome of the two sensor modalities (ECG and pulse oximeter) measuring heart rate variability to improve the immunity to motion artifacts (3) providing a platform to collect environmental and physiological data for correlation studies to predict the onset of asthma related events, (4) using the two pulse oximeter readings (on the chest-patch and the wristband) together with the ECG recordings to track the blood pressure changes.

Towards Gen-1, a low power biopotential AFE was designed and taped-out through On Semi 0.5µ process (Figure 2). The AFE consists of a chopper amplifier implemented using a Low-Noise Amplifier (LNA) in a feedback loop working at a frequency higher than the frequency of the signal.
so the flicker noise at the output is reduced. The gain of this amplifier is set to 40 dB by the ratio of the input capacitors to the loop capacitors. In order to eliminate the up-converted noise of the amplifier and condition the signal, a low-pass Gm-C filter with a corner frequency of 100 Hz was used.

The sample output of the amplifier can be seen in Figure 3 where ECG test was run with two standard Silver/Silver Chloride electrodes placed in the chest. Then, the signal was filtered by using a low-pass elliptic filter with a passband frequency of 30 Hz and a stopband frequency of 45 Hz and a moving average filter of 100 samples.

To support the operation of the multiwavelength photodiode, a custom AFE is in the process of being designed by the graduate student, Jose Manuel Valero Sarmiento, and will be completed after he returns back from his internship at imec. The chip will include an on-chip amplifier with a logarithmic transfer characteristic connected to an integrate-and-hold block based sampling sub-block. The light output will be modulated at 1 kHz at the optical transmitter site with the receiver side including a low pass Gm-C filter and a mixer to demodulate the frequency modulated light.

To benefit from the fact that the penetration depth of light in silicon is wavelength dependent, vertically stacked photodiode junctions have been investigated to achieve a photodetector that can separately detect two different wavelengths (770nm and 900nm) [4]. Such a multilayer and multi-wavelength photodiode recently became commercially available from Foveon and has been ordered to be tested as a part of the HET testbed.

**Summary of Other Relevant Work Being Conducted Within and Outside of the ERC and How this Project is Different:**

Most of the existing work about pulse oximetry technology has focused on optimizing the topology of light source photodetector pair depending on the location of the measurement [5-8]. An extensive list of the patents on pulse oximeters is available in [9]. The major approach to minimize power consumption has been on system level where the clock speed, the employed data transmission scheme, bandwidth and duty cycle of the light source current was optimized or parts of the front-end was switched off when not in use [10-13]. Only a few publication has focused on the analog-front end optimization [1,14] where the front-end transimpedance amplifier (TIA) was designed to allow for operation under low duty cycles achieving a low average power consumption of 4.3 mW. There is almost no prior work focusing on the use of a non-switching simultaneous wavelength scheme for minimizing the power consumption.

As for the ECG systems, some commercially available devices such as the heart rate monitor AD8232 manufactured by Analog Devices (also used in Gen 0 HET) offer adaptable solutions for different applications with low power consumption, in this particular case 170 µA from a 2.0 V supply. However these are not completely self-powered and wearable application-driven as they need external components, which increase the total size, and are not fully optimized. In order to achieve ultra-low power consumption, a custom application specific integrated circuit (ASIC) is
required. Following this approach we were able to create a biopotential amplifier with a consumption of 16 µA from a 2 V supply, comparable to the 12.8 µA in [15]. With further improvements we could reduce this figure even more, reaching values like 1.2 µA from a 1.2 V supply [16].

**Plans for the Next Year:**
Our efforts for next year will be towards supporting:

1. The system integration efforts for a full demonstration of a Gen-1 HET platform and transition towards the Gen-2 HET platform.
2. Testing the taped-out pulse oximetry front-end system that will be designed over the summer and integration of this with multi-junction photodiodes.
3. Lowering the power consumption of the ECG AFE circuit by using process technologies that allows the reduction of the supply voltage and the current consumption.

**Milestones and Deliverables for the Project:**

In vitro testing of the Gen-0 HET testbed for functional validation and modification of the system as needed.

1. In vivo testing of the Gen-0 HET testbed at the UNC EPA facility (correlation of HRV and ozone exposure) and modification of the system as needed
2. Data collection with Gen-0 HET for sensor fusion (ECG and pulse oximetry) for motion artifact rejection
3. Data collection with Gen-0 HET for correlation with blood pressure measurements
4. In vivo studies to validate the hydration sensing capability of the Gen-0 HET
5. Replacing the COTS ECG AFE with the ASIC ECG AFE on Gen-0 HET
6. Replacing the COTS gas sensors on Gen-0 HET with ASSIST Sensors
7. Replacing the COTS ECG electrodes on Gen-0 HET with ASSIST Sensors
8. Integration of the ASSIST SoC with the Gen-0 HET
9. Integration of the ASSIST flexible antennas with the Gen-0 HET
10. In vitro testing of the Gen-1 HET testbed for functional validation and modification of the system as needed.
11. In vivo testing of the Gen-1 HET testbed in the UNC EPA facility (HRV and ozone) and modification of the system as needed
12. Data collection with Gen-0 HET for sensor fusion (ECG and pulse oximetry) for motion artifact rejection
13. Data collection with Gen-0 HET for correlation with blood pressure measurements
14. Modification of the Gen-0 pulse oximetry system to include the multi-junction photodiodes and assessment of power reduction.
15. Design of the pulse oximetry ASIC AFE, simulations, layout and submission for tape out

**Member Company Benefits:**
During our conversation with ASSIST’s potential or current industry partners, we realized the high demand for a low power pulse oximetry system for continuous monitoring. The relevant companies and institutions include MIT Lincoln Labs, Valencell, Samsung, FitLinxx and Army Medical Command. We have previously collaborated with Twisthink on a STTR application to
use our biophotonic monitoring devices for circadian rhythm monitoring. We have recently initiated a collaboration with SunTech Medical to correlate the Gen-0 HET derived pulse transit time measurement with ambulatory blood pressure measurements they provide. It is noteworthy that SunTech Medical provides the only FDA approved blood pressure measurement available in the market. We also collaborate with Smashing Boxes to design the smartphone data aggregation infrastructure for Gen-0 and Gen-1 HET testbeds.

**Commercialization Impacts or Course Implementation Information:** N/A

**References**
