Near threshold pulse transit time processor for central blood pressure estimation

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***Abstract*—In this work a digital peripheral that can measure pulse transit time for central blood pressure estimation is presented. To do so, it processes ECG and BCG signals in real time by detecting the R-waves in the ECG and using this as time reference for measuring intervals of interest such as RJ, IJ and RR. The circuit was fabricated in a 180 nm process and experimental results are presented. The peripheral works at the near-threshold region and consumes 7 pJ/cycle with 0.43 V of supply voltage while operating at 8 kHz. We showed that state of the art performance can be achieved in the processing required for wearable estimation of central blood pressure while operating the digital circuit in the near-threshold region.**

***Index Terms*—ECG, biomedical signals, ultra-low power, near-threshold**

I. Introduction

The continuous advances in electronic devices have led to the new era of wearable devices that can monitor health. A key physiological parameter that allows us to monitor our health is the blood pressure (BP). Ample research efforts have been devoted to achieving a wearable, unobtrusive way to continuously monitor blood pressure. Most of these approaches do not apply the traditional inflatable cuff used for BP measurement (i.e. are cuff-less) and rely on the correlation of BP with the time it takes for the pressure wave to travel between two arterial sites, known as pulse transit time (PTT) [1]. Since PTT is a time difference, two time references are required to extract it. Multiple methods have been attempted [1] for getting these time references. The most common ones are taken from electrocardiogram (ECG) and photoplethysmography (PPG) signals and target to estimate the BP commonly applied in clinical practice, i.e. the peripheral or brachial BP, which is the one usually measured in the brachial artery with a cuff around the arm. These research efforts have led to devices reaching the market [2]. Main smartwatches manufacturers are including the BP estimation capability in their products and have started to receive regulatory clearance in several markets [3].

This work focuses on the integrated implementation of the digital signal processing for PTT estimation in an ultra-low-power wearable device. The processing considered is the one required for estimation of the central BP (i.e. in the aortic domain, close to the heart) instead of the peripheral BP, as proposed in [4], [5]. Central BP provides a better estimate of cardiovascular health close to key organs, such as the heart and kidneys. Central BP is obtained based on timing references extracted from the ECG and ballistocardiogram (BCG) waves. BCG is a measurement of the mechanical response of the body to the blood pumped during a cardiac event. The BCG signal can be obtained in a wearable device using sensors such as a microelectromechanical accelerometer.

Most research literature on BP estimation focuses on the validation of the algorithm and performs the signal processing after transmitting the relevant signals from the wearable device to other device (e.g. PC, tablet or smartphone). An example of signal processing on the wearable device is [6] where one microcontroller performs the signal acquisition and a second one takes care of signal processing and handling the display of the smartwatch like device. Custom peripherals or co-processors for biomedical signal processing have been proposed, particularly for ECG processing. Some of them focus on heart rate monitoring [7]–[9], while others integrate more complex processing such as wavelet transforms [10] or arrhythmia detection algorithms [11].

The goal of this work was to assess the feasibility of providing an ultra-low-power peripheral specialized in processing PTT for central BP estimation. The custom digital circuit was intended to operate in near-threshold region (with a supply voltage near the threshold voltage of the transistors) to optimize the power consumption - performance trade-off. As far as we know there are no similar studies in the open scientific literature.

The article was organized as follows. Section II summarizes the algorithm implemented in the specialized peripheral. Section III describes the overall wearable device architecture where the peripheral would operate. Section IV presents the peripheral design including techniques applied to optimize the area and power consumption. Experimental results on the manufactured chip are detailed in section V and section VI summarizes the main conclusions.

II. Algorithm

The algorithm developed in [4] and implemented as custom peripheral in this work is presented further on. This algorithm allows to process the ECG and BCG signals to obtain the PTT and estimate the BP. Figure 1 shows typical ECG and BCG signals.

In this work, the PTT is estimated as the time between the R-wave in the ECG and the J-wave in the BCG (RJ interval) [4]. The inputs of the algorithm are the ECG and BCG signals, sampled at 250 Hz from an ADC. Both signals are bandpass filtered with a 15^{th} order Finite Impulse Response (FIR) filter, which also has a notch characteristic for the power grid interference. The algorithm uses a programmable interval of ECG and BCG signals, where they are processed to obtain the RJ interval. During this time, an R-wave in the ECG signal is detected if there is a local maximum greater than a configured threshold. With each detected R-wave during the total time, 200 ms of BCG signal are acquired. All acquired BCG signals are averaged aligned with the R-waves. After the configured time has elapsed, the J-wave of the BCG is found as the absolute maximum of the 200 ms averaged signal.

Additionally, some extra parameters of interest are extracted. The I-wave of the BCG is found as the first local minimum before the J-wave. Also the mean RR interval (which corresponds to the duration of one cardiac cycle, i.e. the inverse of the heart rate) is calculated by counting the total number of R-waves detected and saving a timestamp for the first and last R-waves.

III. System description

Figure 2 shows a block diagram of the complete system. The wearable device has an analog front end (AFE) that acquires the BCG and ECG signals that are used by the algorithm to estimate the BP. Additionally, there is a microcontroller with

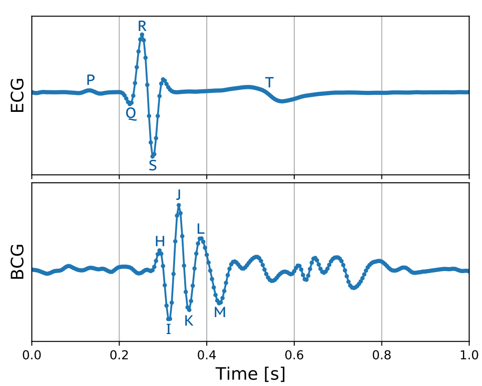

Fig. 1. Example of acquired ECG and BCG signals after the FIR filter detailed below.

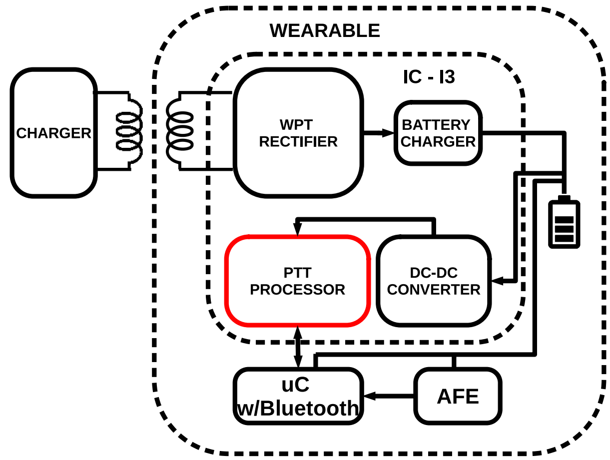

Fig. 2. Wearable device block diagram.

a Bluetooth transceiver to send and receive information and configuration. Finally, the system has a custom IC which consists of the power management unit (PMU) and the peripheral that implements the algorithm described in Section II. The PMU includes the rectifier for the wireless power transfer, the battery charger and the DC-DC converter to adjust the supply voltage of the PTT processing block.

In the current proof of concept implementation, the BCG and ECG signals are sampled at a frequency of 250 Hz by the ADC of the microcontroller which sends them via SPI to the digital peripheral for the estimation of the PTT. To take full advantage of the lower power consumption provided by the peripheral, it should also include the ADC so that the data transmission from the microcontroller is avoided.

IV. PTT processor design

A block diagram of the PTT processor unit is presented in Fig. 3. The block is divided into two voltage domains. The first one, at 1.8 V, includes a 16-bit Serial Peripheral Interface (SPI) to communicate the peripheral with the microcontroller. The second voltage domain corresponds to the core of the PTT processor and can be adjusted as low as 430 mV into the near-threshold region of the applied 180 nm CMOS process. To interface the two voltage domains, level shifters were added between the SPI and the register bank.

To read a PTT processor's register, the microcontroller has to send the 16-bit address in a transfer, and then read 16-bits through a second transfer. To write one of them, the microcontroller has to send the 16-bit address OR `0x8000` in a transfer, and then write 16-bits through a second transfer. All the PTT processor registers are displayed in Table I.

The algorithm begins by writing to the "Start" register. The number of samples the algorithm lasts and the threshold for detecting R-waves are configurable through SPI in two other registers. Both ECG and BCG signals are fed through SPI to registers "ECG" and "BCG" respectively. The results of the algorithm are the sample number of the first and last R-waves,

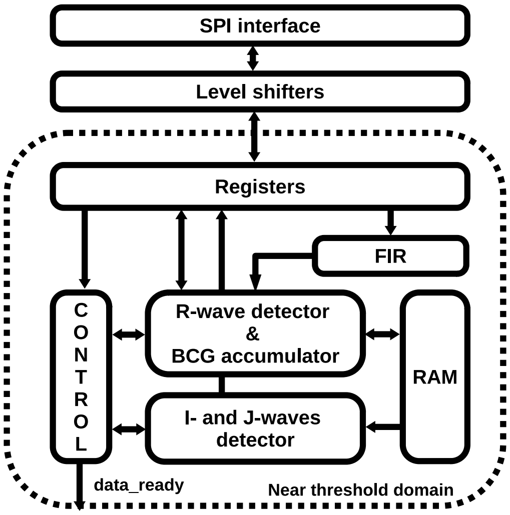

Fig. 3. PTT processor block diagram.

the number of R-waves detected, and the intervals RJ and IJ in samples.

As the ECG and BCG signals are sent, the 15$^{\text{th}}$ order FIR filter stores them in shift registers and filters them. The FIR filter, which consists of 16 FIR constants, 16 multiplications and 15 additions, is implemented with only one multiplication and one addition block. The inputs to the products and additions are selected with a multiplexer and the operations are serialized in time to save area. Each FIR data sample takes 32 clock cycles (16 clock cycles for the ECG sample and 16 clock cycles for the BCG sample) to be filtered.

The control block determines when the "R-wave detector and BCG accumulator" and the "I- and J-waves detector" are active. These two blocks work in series: first the R-waves are detected and the BCG aligned with the R-waves and accumulated and stored in a Random Access Memory (RAM) of 50 words x 18 bits, and then, with the aligned and accumulated BCG signal stored in the RAM, the I- and J-waves are determined.

The "R-wave detector" detects by finding ECG local maximums that are greater than the configured threshold. Whenever an R-wave is detected, the BCG signal is added to the BCG signal accumulated so far, and stored in a RAM. In order to minimize the area of the circuit, not all the BCG cycle is saved.

Name	Length (in bits)	Read/Write	Address
Start	1	Read/Write	0x0000
Number of samples	13	Read/Write	0x0001
Threshold	11	Read/Write	0x0002
ECG	10	Read/Write	0x0003
BCG	10	Read/Write	0x0004
First R-wave	13	Read	0x0005
Last R-wave	13	Read	0x0006
Number of R-waves	7	Read	0x0007
RJ	7	Read	0x0008
IJ	7	Read	0x0009

TABLE I
PTT PROCESSOR'S REGISTERS.

On the contrary, just 200 ms of BCG data after the R-wave is stored, which guarantees that the J-wave can be found in most individuals [12].

When the configured number of samples have elapsed, the RAM contains the accumulated BCG signal[1], and the control block acts. The "R-wave detector" block also stores the sample number of the first and last R-waves and the number of R-waves detected during the configured number of samples. These parameters are useful to calculate the average heart rate.

When the "I- and J-waves detector" is activated, it goes through the accumulated BCG RAM, and finds the absolute maximum (J-wave) and the first local minimum before that maximum (I-wave). Then it calculates and stores the RJ and IJ intervals.

Finally, the control block sends a pulse in a digital output pin "data ready" indicating there are valid data in the output registers of the algorithm.

V. RESULTS

The circuit was fabricated using standard cells in a 180 nm technology and Fig. 4 shows a photograph of the IC. In this section, the measurements of the PTT processor are presented as well as a comparison with state of the art ECG processing units.

In order to test the PTT processor, around 10 sets of ECG and BCG signals were used. These were acquired from members of this research group. The same algorithm described in the previous sections was implemented in a PC and the results were used as the golden output to be compared with the outputs of the test circuit. For the testing and measurements, a Digilent Analog Discovery 2, a Digilent Digital Discovery and Keysight U2722A SMUs were used. Characterization was automated using Digilent WaveForms SDK and Python as programming language. The different supply voltages and current measurements were obtained with the SMU while all the digital inputs and outputs were generated and analyzed with the Analog and Digital Discovery instruments.

[1]The "accumulated BCG signal" is equivalent to the averaged BCG signal except for a positive multiplicative constant.

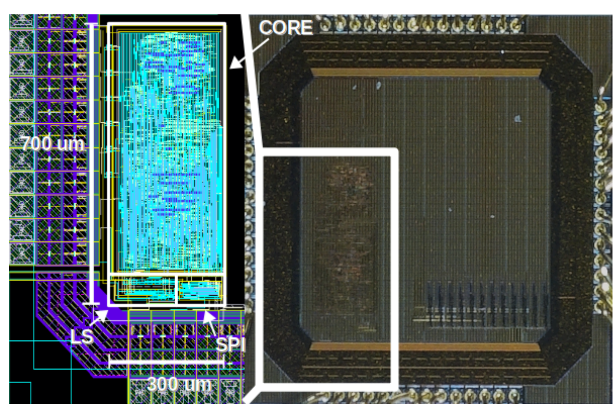

Fig. 4. Fabricated IC microphotograph and PTT processor layout.

Reference	[7]	[9]	[8]	[10]	[11]	This work
Process (nm)	180	130	45	65	65	180
V_{DD} (V)	0.5	0.24	0.26	0.41	0.9	0.43
Frequency	10 MHz	475 kHz	80 kHz	49.8 kHz	128 kHz	8 kHz
Signals	ECG	ECG	ECG	ECG	ECG	ECG and BCG
Area	N/A	300 μm x 300μm	700 μm x 700μm	200 μm x 300μm	1000 μm x 1000μm	700 μm x 300μm
Energy/cycle (pJ)	20.4	1.51	3	2.28	17.7	7

TABLE II
COMPARISON WITH BIOMEDICAL PROCESSORS.

The PTT processor core was measured with different supply voltages and operating frequencies and the results are shown in Fig. 5. To validate each measured point shown in the figure, the results obtained from the tests were compared with the golden ones. The PTT processor needed a minimum frequency of 8 kHz to fulfill all the timing restrictions. This frequency could be achieved with a supply voltage as low as 430 mV and consuming only 58 nW which corresponds to 7 pJ/cycle. Additionally, the SPI interface working at a nominal voltage of 1.8 V consumed 49 nW while receiving the samples at a frequency of 250 Hz with an SPI clock frequency of 15 kHz.

The measurements results of the proposed PTT processor are compared with state of the art ECG processors in Table II. It can be seen that the proposed block achieves state of the art energy consumption. It is important to notice that a full comparison between the different ECG processors is out of the scope of this paper and requires a detailed analysis of the processing performed by each of them.

VI. CONCLUSIONS

This paper presents a PTT processor for BP estimations based on ECG and BCG signal processing. Measurements of the digital peripheral in 180 nm technology are presented. By working in the near-threshold regime, the circuit achieves an energy consumption of 7 pJ/cycle working at 0.43 V with a frequency of 8 kHz. With this peripheral, the PTT can be obtained as the RJ interval, and the average heart rate can be estimated with the total number of R-waves detected and the timestamps of the first and last R-waves in a programmable interval.

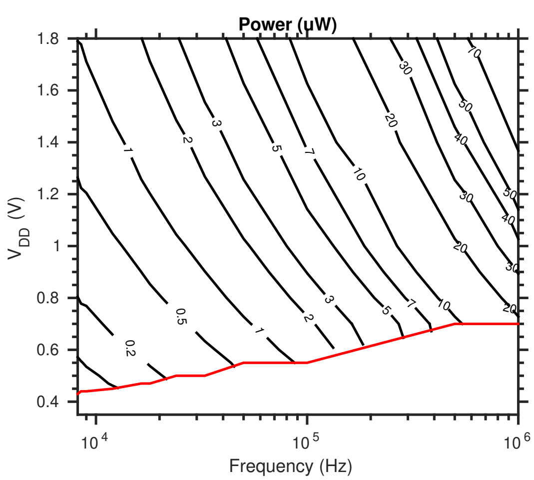

Fig. 5. PTT processor core power consumption vs VDD and operating frequency.

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