A 19-μA Metabolic Equivalents Monitoring SoC using Adaptive Sampling

Mio Tsukahara, Shintaro Izumi, Motofumi Nakanishi, Hiroshi Kawaguchi,| and Masahiko Yoshimoto
Kobe University
Kobe, Japan
shin@godzilla.kobe-u.ac.jp

Hiromitsu Kimura, Kyoji Marumoto, Takaaki Fuchikami, and Yoshikazu Fujimori
Rohm Co. Ltd.
Kyoto, Japan

Abstract - This paper presents a low-power metabolic equivalents (METs) estimation SoC for monitoring physical activity with wearable sensor. Long-term continuous METs monitoring can contribute to detection of non-communicable diseases. The proposed SoC consists of a non-volatile CPU and a dedicated hardware for heart rate extraction and METs estimation to reduce the power consumption. A test chip is fabricated in a 130-nm CMOS process. Evaluation results show that the proposed system, which consists of the test chip and an accelerometer, consumes about 19-μA on average.

I Introduction

Increasing medical costs related to the global prevalence of non-communicable diseases (NCDs) has come to be a severe issue worldwide. Reportedly, 38 million people die each year from NCDs, the four main types of which are diabetes, cancers, cardiovascular diseases, and chronic respiratory diseases.

Proper daily exercise and physical activity are important means of mitigating or forestalling NCDs. For efficient management of exercise, recording daily physical information and analyzing it in real time are important. Wearable devices are a convenient means for individuals to monitor and recognize physical activity (PA).

Because users presumably wear devices for a long time in their daily lives, the devices should be small, with low power consumption. Battery weight is a dominant characteristic of wearable devices. Therefore, this study was undertaken to develop a low-power device for use in long-term PA intensity estimation.

II. Metabolic Equivalents Estimation

Metabolic equivalents (METs) values have been widely used as indicators to quantify PA intensity. The METs value is the amount of oxygen consumed at rest. In fact, it is expressed as 1 MET = 3.5 ml O_2 / kg / min. [1]. The amount of oxygen uptake at rest must be measured to obtain an accurate METs value. However, the method of gathering exhaled gases is too stressful to continue measurements over long periods. Therefore, the method of estimating METs values using a triaxial accelerometer has been developed as a less burdensome measurement method [2].

Fig. 1 shows the relation of the measured METs and acceleration of 42 volunteer participants. The participants performed 23 distinct activities including a rest position. The METs value is estimated accurately from VO2 and VCO2 using Weir's equation [3]. All procedures involving human subjects were approved by an ethical committee. As presented in Fig. 1, the suitable METs estimated equation depends on the range of the synthetic acceleration. Furthermore, Fig. 1 indicates that several activities like stair ascent is difficult to estimate only using acceleration. This issue can be solved using heart rate value as reported in our previous work [4].

Although a subject is not at rest, the heart rate can be extracted using an autocorrelation with low-cost hardware as reported in prior work [5]. However, in the conventional work, it is difficult to reduce the power consumption of an accelerometer. Therefore, the objective of this work is to develop a low-power METs estimation SoC using an adaptive acceleration sampling.

Fig. 2 presents a flow chart of the proposed adaptive sampling method. First, the acceleration of each axis from the accelerometer is passed through a Butterworth filter (high-pass filter) with 0.7-Hz cut-off frequency to eliminate the acceleration of gravity. Next, the synthetic acceleration (vector magnitude: $\sqrt{x^2+y^2+z^2}$) is calculated from each high-pass filter output. Then METs is calculated from the average value of the synthetic acceleration in 10 s duration. Here, ACC_i denotes the mean value of synthetic acceleration for the 10 s epoch. VAR_i denotes the variance of the synthetic acceleration in the same 10 s epoch.

When the physical activity intensity is low, the lower sampling rate is acceptable, because less than 5-mG error is sufficient for METs estimation. The sampling rate is chosen automatically according to the past synthetic acceleration, as presented in Fig. 1. This algorithm is evaluated using long-term measurement data. For the experiment, six participants (ages 21–25 yr; 4 men, 2 women) spent a day wearing the triaxial accelerometer at the waist. The result demonstrates that the proposed algorithm achieves less than 0.1 METs RMS error. It is almost identical RMS error compared with the 16-Hz fixed sampling rate, although the average sampling rate of the proposed method is only 11.3 Hz.

III. Implementation Result

To minimize the power consumption of METs estimation, we designed an SoC consists of a dedicated hardware for the proposed adaptive acceleration sampling method, a low-cost electrocardiogram sensor and heart rate extraction block, and a non-volatile CPU. Fig. 3 presents a block diagram.

The non-volatile CPU [5], which consists of a non-volatile memory and a non-volatile flip-flop based on a ferroelectric capacitor, is employed to reduce the stand-by power of the proposed system. The power gating is an effective power reduction approach for biosignal monitoring because the biosignal including acceleration has very low frequency compared with the CPU. Generally, the active rate of the CPU is less than 0.1% in this application.

The acceleration sampling block consists of high-pass filters, a synthetic acceleration block, and a data buffer. The data buffer is connected to a high speed bus (AHB). An interrupt signal is generated from a timer to wake up the CPU every 10 s. The CPU calculates the METs value from 10 s epoch data. Then, the next sampling rate and filter coefficients are decided by the CPU. The registers of the accelerometer interface are updated. For the rest of the time, the CPU is in a deep sleep state. Then, its power source can be gated.

A test chip was fabricated in a 130-nm CMOS with a ferroelectric capacitor process. Fig. 4 presents a chip micrograph and specifications. To evaluate the power reduction, the conventional algorithm using fixed sampling rate [2] is implemented as software. The implementation result shows that the active rate of CPU is reduced from 2.65% to 0.08%. Fig. 5 shows the total power consumption of the proposed system, which consists of the test chip and an accelerometer (KX022; Kionix Inc.). When the conventional METs estimation algorithm is implemented, the total power consumption is 38.5 µA, on average. This power dissipation can be reduced to 19 µA on average using the proposed method.

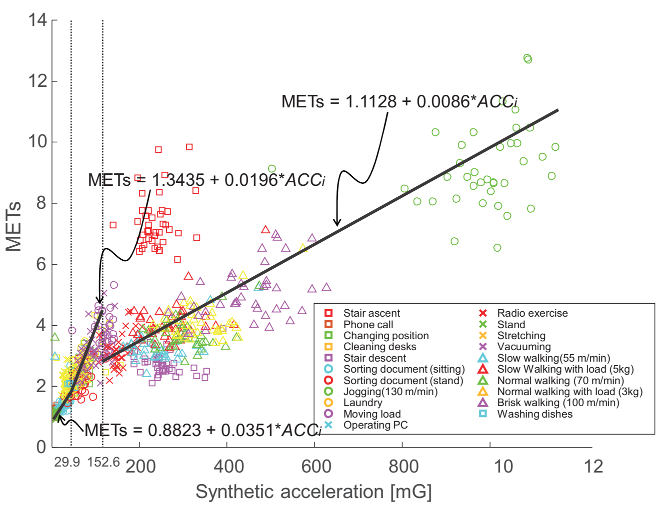

Fig. 1. Relation between measured synthetic acceleration and METs. METs is calculated from measured VCO_2.

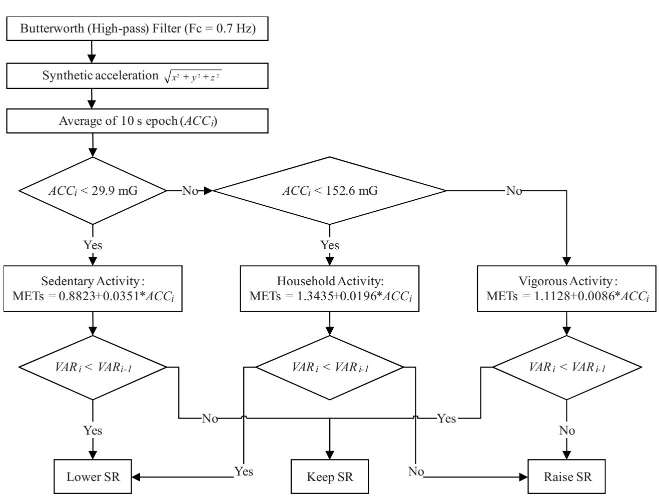

Fig. 2. Flow chart of adaptive METs estimation.

Acknowledgments

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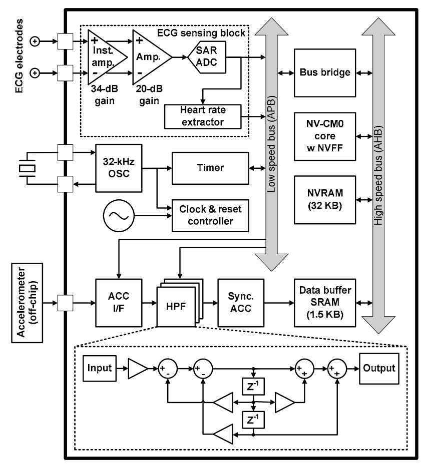
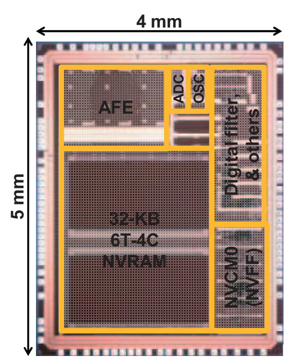


Fig. 3. Block diagram of the proposed SoC.



Technology		0.13 µm CMOS
Supply voltage		1.2 V (AFE, ADC, Logic, Mem.)
		3.0 V (32.768-kHz OSC, I/O)
Chip area		4×5 mm²
Frequency		24 MHz (for processor)
		32 kHz (for other blocks)
Processor		32-bit Cortex M0 (with NVFF)
On chip memory		32-KByte 6T-4C NVRAM
AFE	Gain	54 dB
	Bandwidth	700 Hz
	CMRR	73 dB
ADC	Resolution	8 bit
	Current	0.23 µA@128 S/s, 1.0 µA@1 kS/s

Fig. 4. Test chip micrograph and specifications.

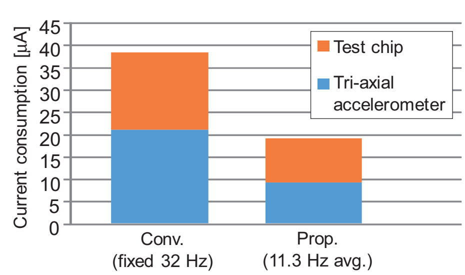


Fig. 5. System-level total current consumption.