Wearable Depression Monitoring System with Heart-rate Variability

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Abstract— **A wearable depression monitoring system is proposed with an application-specific system-on-chip (SoC) solution. The SoC is designed to accelerate the filtering and feature extraction of heart-rate variability (HRV) from the electrocardiogram (ECG). Thanks to the SoC solution and planar-fashionable circuit board (P-FCB), the monitoring system becomes a low-power wearable system. Its dimension is 14cm × 7cm with 5mm thickness covering the chest band for convenient usage. In addition, with 3.7V 500mAh battery, its lifetime is at least 10 hours. For user's convenience, the system is interfacing to smart phones through Bluetooth communication. With the features of the HRV and Beck depression inventory (BDI), the smart phone application trains and classifies the user's depression scale with 71% of accuracy.**

I. Introduction

Recently, Centers for Disease Control and Prevention [1] announced that mental illnesses are an increasing proportion of disability in developed countries. The increasing number of depressed patients is one of the biggest worldwide social problems [2]. Especially, mood anxiety or depression caused by mental and emotional stress is one of the frequently occurring illnesses in the mental health. For the efficient treatment of mental illness, patient's physiological signals in his living environment are measured for early diagnosis. As human emotion changes, the organs of human body are affected by nervous system and hormonal control. Monitoring these changes enables mental stress detection [3]. Specifically, monitoring heart's states enables depression scale estimation

Several heart monitoring systems which can monitor cardiac signals anytime and anywhere have been developed for home healthcare applications. The battery-less electro-cardiogram (ECG) monitoring system was reported [4]. In [5] it was able to remove motion artifacts so that clean ECG signal is acquired while the users are active. Also, several instruments for psychiatric diagnosis have been introduced. For example, EmWave by HeartMath is using the heart-rate analysis by photoplethysmography (PPG) for a stress monitor [6]. Moreover, autonomic nervous system (ANS) testers with ECG are widely used in psychiatry.

In this paper, a cardiac monitoring patch system is proposed for depression detection. The patch system is based on planar-fashionable circuit board (P-FCB). It enables convenient implementation of circuit with the chip directly on a cloth. Fabric electrodes are used to acquire required physiological signals during daily life.

The rest of this paper is organized as follows. In section II, the system architecture will be introduced. Then, the data analysis methodology is explained in section III. After that, the implementation results of the proposed system are described in section IV. Finally, the conclusions will be made in section V.

II. System Architecture

Fig. 1 shows the proposed system which is composed of a dedicated stress monitoring SoC, a Bluetooth module for wireless connectivity and a power management IC for battery operation. The custom designed stress monitoring SoC contains an analog front-end for acquisition of ECG and digital signal processor for low power signal analysis.

A 3.7V 500mAh rechargeable battery can supply the required power for at least 10 hour. In order to generate 1.2V and 3.3V from 3.7V, a power management device is integrated outside the SoC. In addition, for wireless connectivity, Bluetooth module is embedded in the system and the serial port profile (SPP) is used to communicate with Android-based smart phone.

1) Planar Fashionable Circuit Board

As shown in Fig. 2, the structure of the P-FCB of the system can be divided into 2 layers: the P-FCB electrode layer and the P-FCB circuit layer. The P-FCB electrode layer has 3 electrodes: 1 pair of positive and negative inputs and 1 reference electrode. The diameter of each electrode is designed as 3cm. Its surface facing to the skin is covered by adhesive materials. On the circuit layer, circuit patterns are printed directly on the fabrics for high flexibility. An application

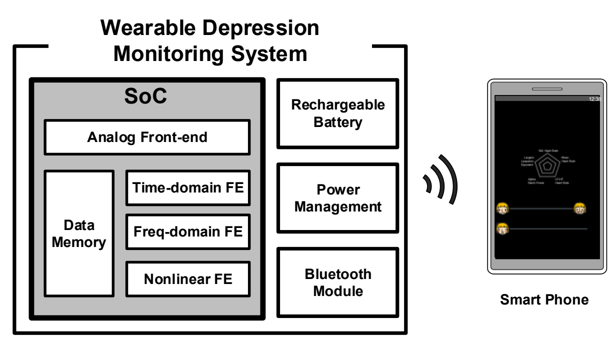

Figure 1 System architecture

specific SoC is attached on P-FCB and molded for preventing external shock. Conventional packages such as SMD type

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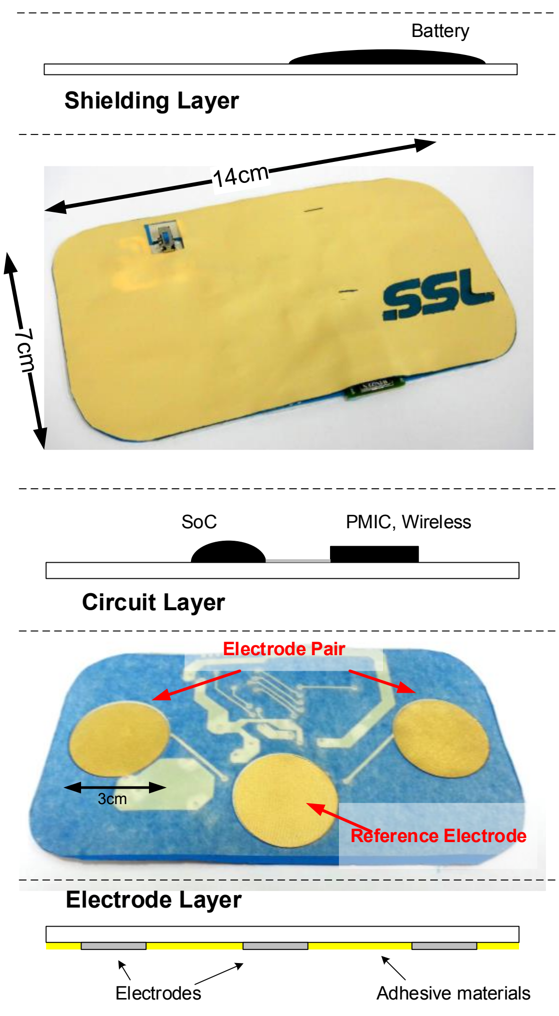


Figure 2 Structure of P-FCB layers

packages and passive devices are also assembled on P-FCB circuit layer.

2) Reduced Instruction Set Computer

A specific 16b RISC is integrated on the SoC monolithically to manage data and to control the accelerator. It has 16 general purpose registers. It has 4kB on chip memory for instruction storage and 32kB on chip memory for signal data storage. The instruction set consists of simple arithmetic operations including AND, OR, ADD, SUB and so on.

3) Low-power analog front-end

The capacitive coupled analog front-end (AFE) and successive approximate (SAR)-analog-digital converter (ADC) are integrated in the SoC for the acquisition of the physiological signals [7]. AFE contains programmable gain amplifier (PGA) to configure the gain as well as the bandwidth. The configurable gain range of AFE is measured from 52.69dB to 77.12dB under 0.6-105Hz of bandwidth. SAR-ADC is designed and implemented for the digitization of the amplified signal. The sampling rate of the SAR-ADC can be configured from 256Hz to 1kHz and measured effective number of bits (ENOB) is 8.4 bit.

4) Nonlinear Accelerators

In this SoC, a nonlinear feature extraction accelerator is implemented as an accelerator [7]. It can extract nonlinear features, such as largest Lyapunov Exponent (LLE), Sample Entropy (SampEn) and Correlation Dimension (CD).

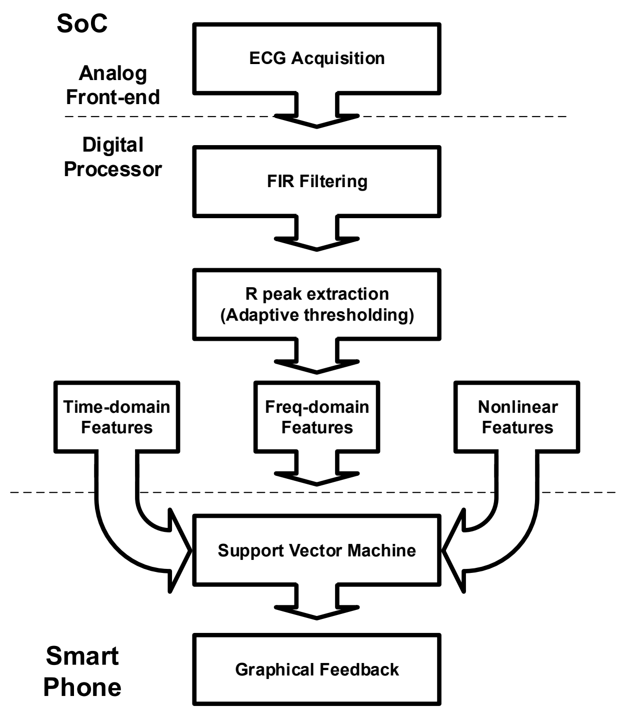


Figure 3 Signal processing flow

III. METHODOLOGY

Fig. 3 shows signal processing flow diagram from signal acquisition to regression analysis. After the acquisition of ECG from analog front-end, digital filtering is applied to remove the noise from the signal. Then, conversion from ECG to HRV is performed by R peak detection. With HRV, several features are extracted for the metal state analysis. Those features are sent to the smart phone to show the individual's mental states on the graphical interface.

A. Preprocessing

1) Finite Impulse Response Filtering

Finite impulse response (FIR) filtering is adopted to remove the noise of which the analog front end cannot get rid. Filtering requires multiple cycles of multiply and accumulation (MAC) operations. In order to reduce the power consumption in filtering operation, multiply-less architecture is adopted.

As shown in Fig. 4, FIR filtering accelerator is based on canonic signed digits (CSD) representation, which reduces the number of non-zero coefficient digits. CSD representation helps to substitute MAC into arithmetic operation so that its power consumption can be reduced. CSD coefficient can be described in (1).

$$c = \sum_{j=0}^{L} d_j 2^{-p_j} \tag{1}$$

where c is coefficients of filter, L means the number of terms which denotes the power of two, and d_j and p_j are defined as below.

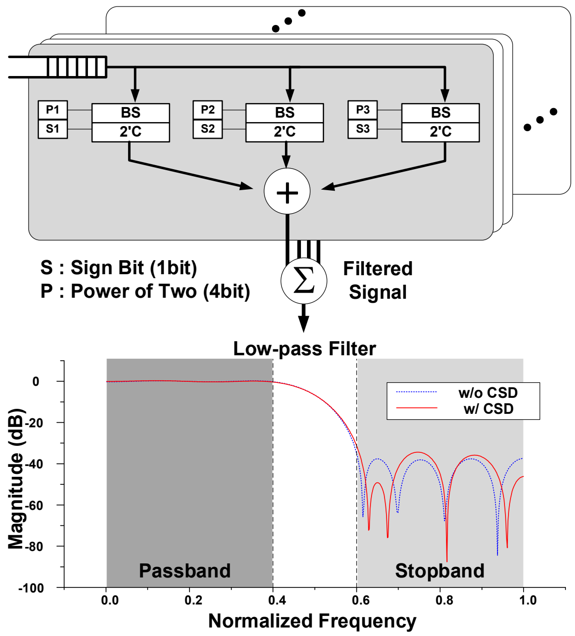


Figure 4 Canonic signed digits FIR accelerator

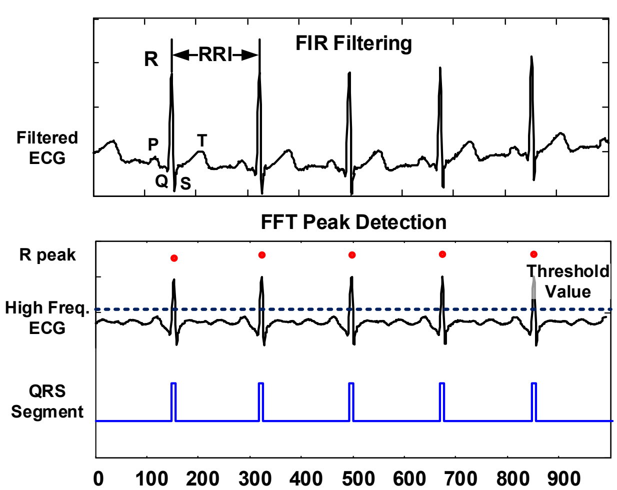
$$d_j \in \{-1, 0, 1\}$$
$$p_j \in \{0, 1, \ldots, N\}$$

2) R peak extraction

HRV can be obtained by R peak extraction from ECG. Fig. 5 shows the normal waveform of ECG. The beat intervals from R peak detection or R-R Interval (RRI) are calculated at each pumping cycle of the heart and it can be regarded as HRV.

FFT-based extraction algorithm is adopted for R peak detection. In the first step, the low-frequency components such as baseline fluctuation and other peak amplitude are removed. After the initial FFT, an inverse FFT is applied to the ECG signal again to make R-peak more pronounced. In next step, the QRS complex is segmented from ECG waveform by applying a proper threshold. Finally, R peak is determined from the segmented QRS complex because it is the local maximum of QRS complex.

Fig. 5 shows the waveform results of R-peak detection. The upper chart is the filtered ECG signal after the FIR filtering. With the R peak detection, the R peak can be extracted.



B. Feature extraction

Estimation of the mental stress and emotions from the measured physiological signals has been studied for several decades. The correlation features of physiological signals with mental stress [3]. In addition, the nonlinear feature extraction method has been researched to find the correlation [7]. In this paper, the feature analysis is performed in time-, frequency- and nonlinear domain. This analysis is based on the certified self-report inventory.

1) Self-report Inventory

Beck Depression Inventory (BDI) scale is a self-report inventories to estimate the severity of an individual's depression for diagnosis in psychiatry. The inventory consists of 21 multiple-choice questions, which have 4 multiple choices. The overall scores are 63 and depending on the score, the severity can be diagnosed. In this paper, these self-report inventories are used as the reference data for machine learning.

2) Time-domain features

Mean and standard deviation of time-series data and the interval related values are obtained.

- HR : Mean heart rate
- SDNN : Mean standard deviation of the interbeat intervals
- pNNx : The number of pairs of successive beat intervals that differ from each other by more than 50ms

3) Frequency-domain features

Frequency domain features are the features obtained after Fourier transform. Especially low-frequency components and high-frequency components represent sympathetic and parasympathetic effects, respectively.

- LFHF : low- and high-frequency power ratio
- peakLF : the peak frequency of low-frequency band
- peakHF : the peak frequency of high-frequency band

4) Nonlinear features

Nonlinear features are the features extracted from the Poincare plots. From this plot, the nonlinearity or chaotic degree is converted into the meaningful values.

- Largest Lyapunov exponents (LLE) : indicator for predictability or chaotic degree
- SampEn, ApEn : the amount of regularity and the unpredictability of fluctuation

C. Support Vector Machine

For the training and classification, the support vector machine (SVM) is used. The input dimension consists of 10 different features of time, frequency and nonlinear domain. The reference group is set by the self-report inventory, or BDI scale.

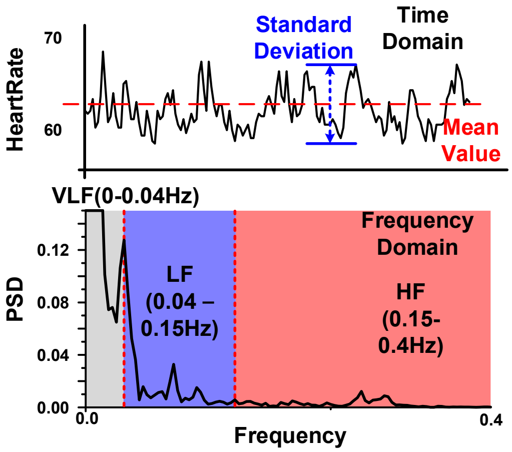


Figure 6 Time- and Frequency-domain features

IV. IMPLEMENTATION RESULTS

In Fig. 6, the example waveforms of the extracted HRV from ECG are described. On the top chart of the figure, mean value and standard deviation are depicted in time-domain. Meanwhile, on the bottom chart, the frequency-domain features are shown. 0.15 Hz is used as the reference frequency which divides the low frequency band and the high frequency band.

Fig. 7 shows the implemented system and chip photograph. The size of HRV monitoring patch is 14cm x 7cm covering the chest. Three circular electrodes with 3cm diameter are implemented on the bottom surface. They keep the skin dry without any inconvenient feeling and also prevent the skin irritation. As the monitoring patch is implemented based on P-FCB, its thickness is less than 5mm. Because adhesive materials are printed on the bottom surface, the patch is stuck on the body even with heavy motion. The chip is fabricated in 4mm x 2mm in 0.13um CMOS process. Its supply voltage is 1.2V and operating frequency is 1MHz.

With this wearable depression monitoring system, the 23 patient data are dealt with to estimate the performance of accelerated functions. According to the clinical reference, criteria of depression is determined by whether BDI is less than 10 or not. For example, the records which have less score of BDI than 10 belong to group 0 while the others belongs to group 1. For the training of support vector machine, the 12 records are sampled randomly. Classification is tested with other records and the average accuracy of the classification is measured as 71%.

The proposed system is compared with other commercial products in Fig. 8. The system of this work is lighter than other systems because main materials are fabric and many parts are integrated monolithically on a single SoC.

V. CONCLUSION

Wireless wearable monitoring system is proposed for mental stress analysis. With the self-report inventory BDI, the proposed system can estimate the degree of depression through the physiological signals. With 3.7V rechargeable battery, the system works continuously for more than 10 hour. In addition, the application specific SoC can obtain the features on HRV faster with low power consumption because most of complicated signal analysis functions are implemented on the silicon hardware. The average accuracy of the classification is measured as 71%. The P-FCB realizes 5mm thickness system and serves flexible and attachable electrodes in itself. Finally, the features collected from the system are transmitted to Android-based smart phone via Bluetooth connectivity for the convenient user feedback.

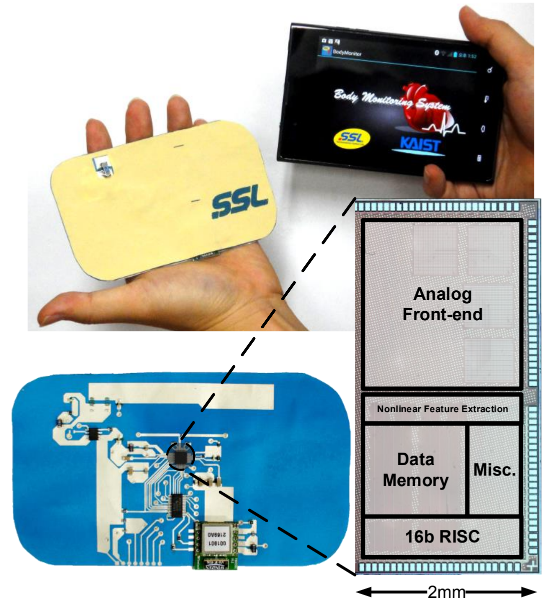


Figure 7 System and chip photograph

			
Name	**HeartMath Emwave2**	**ANS Monitor**	**This work**
Dimension (mm^3)	85×55×14	400x500x1000	14×7×5
Sensor Type	Ear Sensor	Device	Chest Patch
Signal Source	PPG	ECG, APG	ECG
Weight	62.4g	> 1kg	< 50g

Figure 8 Comparison results

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