Design and Implementation of Digital Filters for Mobile Healthcare Applications

Jeong-Hwan Kim, Sang-Eun Park, Jeong-Whan Lee, and Kyeong-Seop Kim
Konkuk University/School of Biomedical Engineering, Chungju 380-701, Korea
Email: zindevil@kku.ac.kr, pse216@naver.com, {jwlee95, kyeong}@kku.ac.kr

Abstract—**Digital filtering process is often necessary to suppress the noisy characteristics embedded in biomedical signals such as ECG (Electrocardiogram), EEG (Electroencephalogram), and EMG (Electromyogram). As the availability and usage levels of Information and Communication Technology (ICT) increases, the applications of ubiquitous healthcare are expected to be accelerated in the form of pervasive healthcare utilizing the mobile devices for the next decade. One of these aspects, ambulatory ECG signals can be transmitted to a mobile device to offer telecardiology healthcare delivery. However the signal is vulnerable to base-line drift and power-line source fluctuations. With this aim, the digital filtering algorithms are implemented with an android platform smartphone to eliminate the noisy components especially in the ECG signal transmitted wirelessly from the wearable patch-style heart activity monitoring system. Graphical User Interface (GUI) is designed and implemented in an Android OS smartphone with programming multi-thread-Java modules to realize FIR (Finite Impulse Response Filter) and IIR (Infinite Impulse Response Filter). With applying our implemented digital filters built in a mobile device, we can conclude the fact that the artifacts in the ambulatory ECG signal due to base-line wandering and power- line instability can be efficiently reduced.**

Index Terms—**electrocardiogram, smartphone, finite impulse response filter, infinite impulse response filter, graphic user interface, mobile healthcare**

I. Introduction

The widespread usage of mobile phones with the advanced skills of Information and Communication Technology, a variety of clinical domains has been emerging in terms of telehealth [1]-[2]. Among these aspects of healthcare awareness, mobile telecardiology systems are developed to monitor heart conditions especially from the high-risk cardiac patients in the patient-centric manner [3]-[6].

To gain a patient's cardiac surveillance outside of healthcare providers' facilities, a smart mobile phone is recognized as the method to acquire personal electrocardiogram from the low-cost hardware utilizing Bluetooth and multimedia messaging service. With the opening of the SMS text message that contains ECG samples, the vital signs about a heart condition are delivered to a PDA or a smartphone to plot the ECG on its screen [7]. Two-smartphone based wearable ECG recording system is also developed to display the waveforms and to detect abnormal beats by determining the isoelectric region around the QRS and reference position for the P and T features [8].

However, the usage of a mobile phone as the device to receive ambulatory data from the wearable ECG monitoring hardware module, the acquired signal with a smartphone is vulnerable to distortion due to poor electrode-skin contact, motion artifacts, power-line interference, or base-line drifting. These noises can induce the false recognition about the ECG fiducial features and may affect the clinical decisions concerning healthcare delivery.

Thus, the digital filters are built with an android platform smartphone to suppress the noisy components especially in the ECG signal transmitted wirelessly from the wearable patch-style heart activity monitoring system. The hardware system measures bio-signals by using concentrate bipolar-electrodes and transmit the data to a mobile phone in Bluetooth communication protocol. With this aim, Graphical User Interface (GUI) is designed with considering the user's convenience and implemented in an Android smartphone by programming multi-thread-Java modules to realize FIR (Finite Impulse Response Filter) and IIR (Infinite Impulse Response Filter). In the filter design, a sampling frequency, a filter type (low-pass, high-pass, band-pass, and band-stop), pass band and stop band cut-off frequency, and window functions can be selected. For IIR filter scheme, a butterworth type can be realized with choosing low pass, high pass, band pass or band stop mode and the diagrams of a frequency response and a pole-zero can be illustrated if necessary.

II. Methods

A. Ambulatory ECG Data Acquisition

To transmit the ambulatory ECG data to a mobile device, the wearable heart activity monitoring system is built which contains the structure of patch-style ECG electrode module (5 cm × 5 cm in a square dimension) [9]. Once it attaches a person's chest, it wires ECG data to a mobile device at a sampling rate of 200 Hz by Bluetooth communication protocol. Fig. 1 shows a block diagram of ambulatory ECG transmitting and receiving system with built in digital filters in a smartphone.

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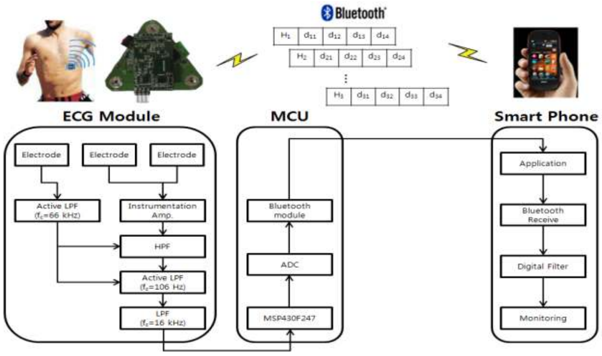


Figure 1. Wearable ECG data acquisition system with a smart-phone.

Each 12-bits-quantized ECG sample data is resolved in a smart-phone with initiating 'a' character in the header and interpreting the successive four bytes in the character format in terms of signal amplitude (Fig. 2). In Fig. 2, d_i means a bit-stream representation of i^{th} ECG sample.

Head (1 Byte)	1 Byte	1 Byte	1 Byte	1 Byte
a	d_{i1}	d_{i2}	d_{i3}	d_{i4}

Figure 2. Data format transmitted by patch-electrode ECG module.

Fig. 3 shows an exemplar of the received ECG data in a mobile device.

tag	Message
ECG Receive Data	a2115a2116
ECG Receive Data	a2120a2128
ECG Receive Data	a2141a2148
ECG Receive Data	a2153a2158a2158a2170
ECG Receive Data	a2181a2152
ECG Receive Data	a2076a1871a1588a1271
ECG Receive Data	a1049a1089
ECG Receive Data	a149
ECG Receive Data	6a1930a2101

Figure 3. The part of received data in a mobile device.

B. *Graphical User Interface for Ambulatory ECG Monitoring with a Mobile Device*

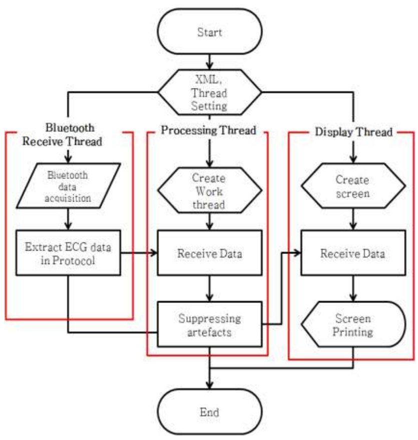


Figure 4. A flowchart for implementing GUI and application modules to display and filter the ECG signal out with a mobile device.

Using Eclipse and Android-platform SDK (Software Development Kit) with a smart-phone, GUI is designed and the application modules for displaying and filtering (it necessary) the ambulatory ECG signal are developed with multi-thread Java programming (Fig. 4).

Fig. 5 illustrates a screen capture of the ECG data displayed in a mobile device (Android OS smart-phone: IM-A860S, Pantech, Korea).

Figure 5. Illustrations of the ECG signal displayed in a smart-phone.

Due to the limited monitor size of a mobile device, M number of ECG samples (M is the maximum number of graphical pixels that can be displayed on the screen) are initially stored and visualized as the first segment of ECG signal (Fig. 6). As the new ADC data arrives, the input stream to a smart-phone is updated by discarding the oldest sample and storing the newest one (Fig. 7).

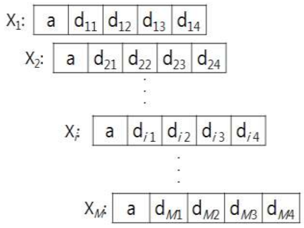


Figure 6. Sequential acquisition of the ECG data for initial display on the screen of a smart-phone.

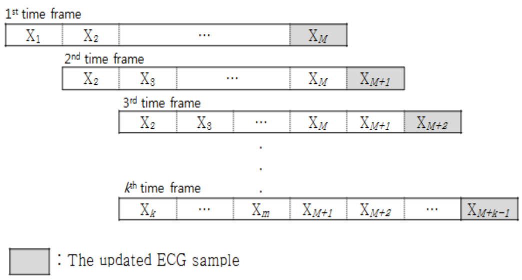
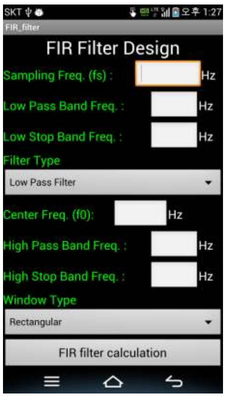


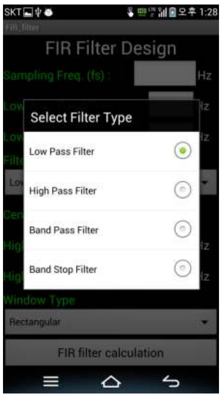
Figure 7. Acquisition of the ECG data for real-time display.

C. *Design and Implementation of FIR Filter*

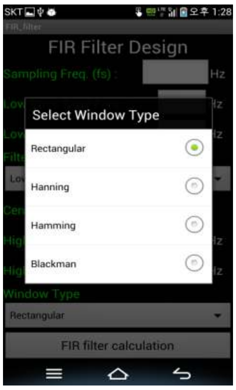
Fig. 8 presents the screen shot of GUI design and implementation for FIR filter with a mobile device (Android OS smart-phone: IM-A860S, Pantech, Korea). The design specifications include sampling frequency, filter type (low pass, high pass, band pass, and band stop), pass-band cut-off frequency and stop-band cut-off frequency. The order of FIR filter is calculated based on the sampling frequency, filter type and cut-off frequencies.



(a)



(b)



(c)

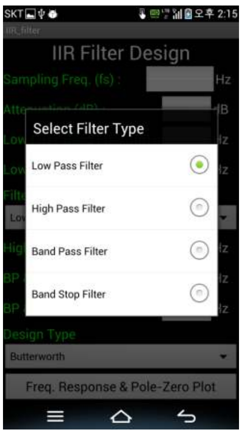
Figure 8. (a) FIR filtering parameters. (b) Pass-band type. (c) Window functions type.

The window functions can be selected to reduce ripple effects due to considering finite number of ECG samples in calculating the convolution operation for FIR filtering process. Rectangular, Hanning, Hamming or Blackman window function can be used [10].

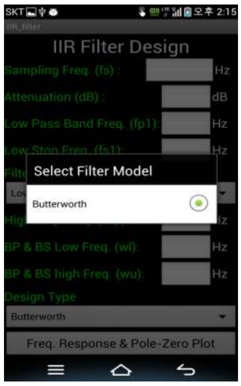
D. Design and Implementation of IIR- Butterworth Filter

Fig. 9 shows GUI design and implementation for Butterworth- IIR filter. The design parameters consist of sampling frequency, attenuation gain in dB scale, pass and stop cut-off frequency, filter type. The additional diagrams of pole-zero and frequency response can be visualized if necessary.

(a)



(b)



(c)

Figure 9. (a) IIR-Butterworth filtering parameters. (b) Pass-band type. (c) Butterworth-filter type.

III. RESULTS

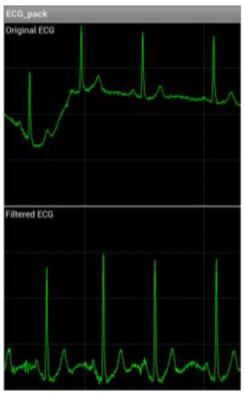
Table I shows the design specifications for FIR filter computation to eliminate the base-line wandering from the patch-electrode ECG data. Fig. 10 depicts the result of eliminating base-line drifting by applying high-pass FIR filter with a smartphone and also shows the impulse and frequency response of the designed FIR filter. Based on the selected design parameters, the order of FIR filter is determined to be N = 665. Here the cut-off frequencies for pass-band and stop-band are initially designed to meet the cut-off frequency specification of a low pass filter. The impulse response of the low pass filter $h_{low}[n]$ is converted to the high pass filter $h_{high}[n]$ by

$$h_{high}[n] = h_{low}[n] \cdot \cos(n\Omega_o) \tag{1}$$

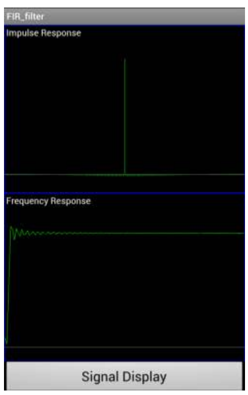
where Ω_o is selected to set the center frequency of the two-sided filter shape [11].

TABLE I. FIR HIGH-PASS FILTER DESIGN SPECIFICATIONS

Filter Parameters	
Parameter	**Value**
Filter type	High-pass
Window function	Hanning
Sampling frequency	200 Hz
Pass-band cut-off frequency	98 Hz
Stop-band cut-off frequency	99 Hz



(a)



(b)

Figure 10. (a) Cancellation of base-line wandering with a smartphone. (b) Impulse response and frequency response of FIR high pass filter.

To demonstrate the design and implementation of band stop digital filter with a mobile phone for suppressing the power supply disturbance, we exemplified the simulated signal by adding 60 Hz sinusoidal signal to the acquired ECG samples. Table II shows the design specifications for band-stop FIR filter computation to remove power supply noise in the simulated patch-electrode ECG signal with a sampling frequency of 200 Hz. Fig. 11 illustrates the result of suppressing 60 Hz frequency component.

TABLE II. BS-FIR FILTER DESIGN SPECIFICATIONS

Filter Parameters	
Parameter	**Value**
Filter type	Band-stop
Window function	Hanning
LF pass-band cut-off frequency	58 Hz
LF stop-band cut-off frequency	59 Hz
HF pass-band cut-off frequency	38 Hz
HF stop-band cut-off frequency	39 Hz
Order of a filter	665

Similarly the design parameters for determining high pass-band frequencies specified in Table II are initially interpreted as low pass-band and are transformed into high pass filter as in (1). The impulse response of the band stop filter $h_{BS}[n]$ designed by Table II is

$$h_{BS}[n] = h_{low}[n] + h_{high}[n] \qquad (2)$$

(a) (b)

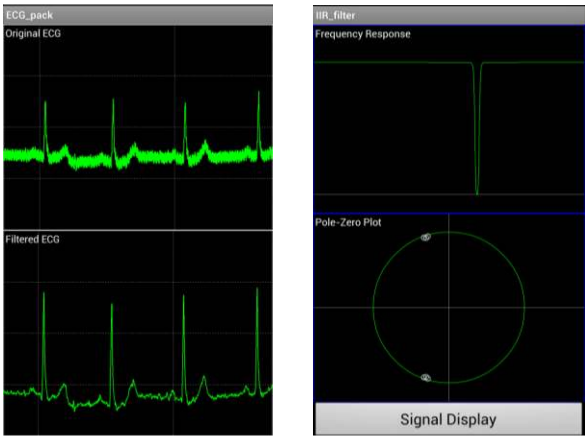
Figure 11. (a) Removal of 60 Hz power disturbance with a smartphone. (b) Impulse response and frequency response of FIR band stop filter.

The impulse response of the designed FIR filter is always stable but it requires a large memory space to store the filter coefficients due to the high order. The number of filter coefficients can be lessened if the required specifications are implemented with an IIR filter. However, it can be unstable because of the recursive calculations. Table III shows the design specifications for band-stop IIR filter to remove 60 Hz noise and Fig. 12 shows the result with additional illustration of pole-zero plot to check the stability.

TABLE III. BS-IIR FILTER DESIGN SPECIFICATIONS

Filter Parameters	
Parameter	**Value**
Filter type	Butterworth Band-stop
Sampling frequency	200 Hz
Attenuation	30 dB
Low pass band edge frequency	40 Hz
Low stop band edge frequency	80 Hz
Lower cut-off frequency (w_l)	59 Hz
Upper cut-off frequency (w_u)	61 Hz
Order of a filter	7

The transfer function of a low pass filter with cut-off frequency w_p (rad/sec) which is the 3 dB-attenuation frequency from low pass band edge is converted into the band stop filter. Each cut-off frequency w_p, w_l and w_u was pre-warped to avoid the degradation of the filter shape [11].



(a) (b)

Figure 12. (a) Removal of 60 Hz power disturbance with a smartphone. (b) Frequency response and pole-zero plot of IIR band stop filter.

IV. CONCLUSIONS

With the widespread usage of a mobile device for the pervasive healthcare, it is often necessary to build digital filtering algorithm into the embedded device to eliminate the noisy disturbance in the ECG signal because the distorted characteristics may hinder a healthcare provider from deciding clinical decisions. Thus this research aims at the implementation of a FIR and IIR filter coefficients with an Android platform mobile phone by specifying the required parameters with graphical user interface. From our experimental results, we can conclude that a set of FIR and IIR filter coefficients can be designed and implemented in a mobile device for eliminating baseline fluctuations or power supply interference especially in the ambulatory ECG signal.

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Jeong-Hwan Kim received the B.S. and M.S. degrees in biomedical engineering from the Konkuk University, Chungju, Korea, in 2011 and 2013, respectively. He is currently working toward the Ph.D. degree in biomedical engineering at Konkuk University, Chungju, Korea. Mr. Kim's current research interests include signal analysis of electrocardiogram, and biometrics for cryptographic applications.

Sang-Eun Park received the B.S. degree in biomedical engineering from the Konkuk University, Chungju, Korea, in 2013, respectively. She is currently working toward the M.S. degree in biomedical engineering at Konkuk University, Chungju, Korea. Ms. Park's current research interests include signal processing, and color image processing analysis for clinical applications.

Jeong-Whan Lee received the B.S. and M.S. degrees in electrical engineering in 1992 and 1994, respectively, and the Ph.D. degree in electrical and computer engineering from the Yonsei University, Seoul, Korea, in 2000. From 2000 to 2004, he was a Member of the Technical Staff of the Application Project Team at the Samsung Advanced Institute of Technology, Kyounggi, Korea. Since September 2004, Dr. Lee has been a Faculty Member of the School of Biomedical Engineering, Konkuk University, Chungju, Korea. Dr. Lee's research interests include biomedical signal processing and instrumentation, wearable/wireless devices for pervasive healthcare, sensing of vital signs/signature, and biological signal measurements by electromagnetic waves and microwave radiothermometry.

Kyeong-Seop Kim received the B.S. and M.S. degrees in electrical engineering from the Yonsei University, Seoul, Korea, in 1979 and 1981, respectively, the M.S. degree in electrical engineering from Louisiana State University, Baton Rouge, in 1985, and the Ph.D. degree in electrical and computer engineering from the University of Alabama in Huntsville, in 1994. From 1995 to 2001, he was a Principal Researcher of the Medical Electronics Laboratory, Samsung Advanced Institute of Technology, Kyounggi, Korea. Since March 2001, Dr. Kim has been a Faculty Member of the School of Biomedical Engineering, Konkuk University, Chungju, Korea. Dr. Kim's research interests include pattern recognition for classifying biomedical signals, medical image processing and biometrics for cryptographic applications.