Personalised System-on-chip and Mobile-App for Standard 12-lead Reconstruction from the Reduced 3-lead System Targeting Remote Health Care

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Abstract

Cardiovascular diseases (CVD) are the prime causes of human mortality and morbidity worldwide. However, CVD can be prevented or cured, if detected early or on-time, where technology can be of significant help. Tackling the issue of comfort of patient by reducing the number of electrode, by allowing the remote home monitoring, and by allaying the need of physical presence of patient in hospital is the prime focus. Here, ECG monitoring system has been discussed to increase the comfort level of patient by reducing the number of electrodes and supporting remote health monitoring. In this paper we implement a low complexity real time system to de-noise and reconstruct a standard 12-lead ECG from reduced 3-lead ECG using both hardware and software platform. De-noising is composed of baseline wandering removal, which has been prototyped on VC707 and ATLYS (Spartan 6) evaluation kit and 3-lead to 12-lead signal reconstruction implemented on android platform for mobile devices. The proposed system reconstructs S12 ECG accurately using personalized transformations. PhysioNet's PTBDB has been used for validation. The system generated outputs diagnostic accuracy has been endorsed by two experienced cardiologists.

1. Introduction

Cardiovascular diseases (CVD) being prime cause of human mortality today has led to tremendous research in its detection, prevention and therapy. Increasingly aging population and ubiquitousness of chronic diseases such as CVDs have increased the cost of its treatment. In-hospital treatment involves discomfort, traveling, waiting and occupies space which otherwise could be available to needful patients. Thus, conventional hospital based treatment model seems inadequate for the posed challenges [1]. Recent advances in Information and Communication Technology can provide effective solutions to the aforementioned non-technical constraints via remote healthcare model. In this paper, we envisage Home Monitoring scenario of the remote monitoring model as to allay aforementioned non-technical limitations.

ECG acquisition and analysis serves as the preliminary step in CVD diagnosis and requires physical presence of patients in hospital for Standard 12-lead (S12) system, the clinical standard, to be acquired and analyzed. S12 system uses 10 body electrodes which increase the discomfort of both patients and caregiver and reduces the benefits reaped from Home Monitoring scenario which prefers a Reduced Lead (RL) system with fewer electrodes. Several lead systems have been proposed with reduced number of electrodes or modified electrode placement position viz. EASI [2], Mason-Likar 12-Lead system [3], to address aforementioned problems. However, cardiologists are accustomed to S12 system and hence, sometimes find information obtained from such systems to be inadequate owing to unconventional electrode positions or fewer electrodes[2, 4, 5].

Remote Monitoring which employs wireless and other communication methods face technical constraints viz. bandwidth and storage requirements and transmission time [6]. Such methods, generally, require signal compression algorithms for transmission which would be inefficient if multichannel S12 system is used [7]. A RL system, essentially with 3-4 leads can be a possible solution for meeting the technological limitation. However, this posits a self-contradicting limitation from medical perspective which prefers S12 system. An ostensibly possible solution is to obtain S12 system from RL system which can be performed using lead reconstruction.

Previously, lead reconstruction methodologies have mostly been investigated to address the problems faced by patients and caregivers in hospital-based environments [8–10]. Recently, we communicated several works on personalized lead reconstruction with well defined wavelet based preprocessing module, obtaining superior results compared to previous works, demonstrating several advantages that can be obtained in Remote Monitoring applications [4, 11–13]. In this paper, we present a low-complex implementation of our algorithmic findings by distributing the workload between hardware and software platforms. Preprocessing module involving Discrete Wavelet Transform (DWT), with symmlet 8 wavelet, has been implemented on VC707 (Virtex 7) and Atlys (Spartan 6) evaluation kits and lead reconstruction has been implemented on Android based mobile device application. The interfacing between these two have been performed using Bluetooth LM400 device (BTM 400A2). This is the first work, to the best of our knowledge, which presents a low-complex implementation of DWT based denoising algorithm and cardiologist friendly android app providing reconstructed 12-leads. We have assumed that the denoising module can be integrated with comfortable wireless sensors which are generally employed in home monitoring [14]. Please see fig. 1 for our envisaged scenario and fig. 2 for overall implementation with hardware (FPGA), Software (Android App) and interfacing (Bluetooth device).

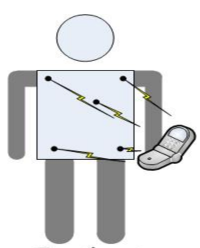

Figure 1: Comfortable wireless sensors on patients body transmitting acquired ECG signals via bluetooth to the mobile device (e.g. smartphone, tablet etc). We envisage the wireless sensors integrated with our denoising module.

2. Material

PhysioNets PTB database (PTBDB) has been used in this investigation [15, 16]. PTBDB is a 290-patient (549 records) 15-lead database with both S12 and Frank system acquired simultaneously and digitised at 1 kHz frequency. In this paper, 32768 (2^{15}) samples of 100 recordings, belonging to different cardiologic disorders viz. healthy control, bundle branch block, myocardial infarction, hypertrophy, cardiomyopathy, heart failure, valvular myocarditis and other miscellaneous disorders, were considered.

3. Performance Metric

In this paper, we have used R^2 statistics as performance evaluation metric. R^2 statistics evaluates the degree of association between two signals. Perfect retracing of one signal by the other will be indicated by a value 100%. [4, 11–13]

$$R^2 = \left\{1 - \frac{\Sigma[Derived(sample\ k) - Measured(sample\ k)]^2}{\Sigma[Measured(sample\ k)]^2}\right\} \times 100 \tag{1}$$

4. Hardware Implementation

The basis leads used in this work are I, II and V_2 and target leads are the missing precordial leads. Preprocessing of ECG involves baseline wandering (BW) removal, frequency range 0-1 Hz, and denoising, frequency range 50-60 Hz. In our previous work, we demonstrated that when both BW removal and denoising is performed R^2 (performance) surplus obtained over just BW removal is less than 1% [12]. However, complete hardware implementation of preprocessing module would invoke greater complexity and resource utilization compared to implementation of just BW removal, which outweighs the performance surplus obtained. Hence, in this work we have implemented only BW removal and left denoising for future implementation.

BW removal methodology was adopted from [17] and its usage has been demonstrated in [4] using MATLAB. As PTBDB's sampling frequency is 1kHz, samples were decomposed down to 9 levels using Symmlet 8 wavelet. Initially a chunk of 4096 samples from each lead is processed i.e 4096 from lead I is processed followed by II and V_2, followed by next 4096 samples. After BW removal, samples are transmitted via Bluetooth using serial UART interface at 115200 Hz (baud rate) in 8 bit packets.

Convolution forms an integral part of any time-frequency domain analysis algorithm such as DWT. Previously, it has been shown that DWT can be performed using cyclic convolutions [18]. Cyclic convolution, on the other hand, is equivalent to linear convolution and time-domain aliasing. Hence, the task of low-complex implementation of linear convolution is left. Here, low-complexity of the architecture has been achieved by avoiding any multiplier or divider, which consume greater power and resources. Convolution operations has been performed by upscaling the wavelet filter coefficients to nearest power of 2 and then the samples were shifted left accordingly, during convolution, for both downsampling and upsampling.

5. Software Implementation

The android based application implements lead reconstruction. The methodology of lead reconstruction were demonstrated in [4, 11–13]. It involves accumulation operation for which processors in mobile devices can be readily

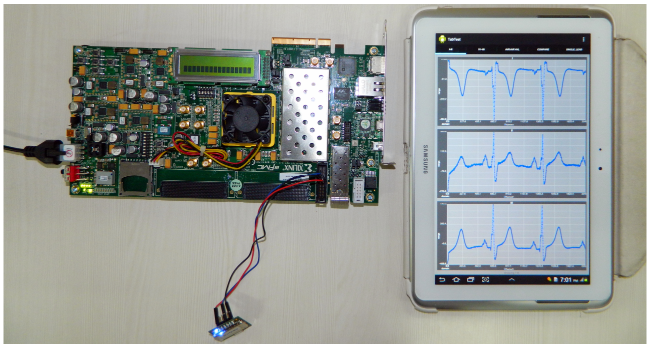

Figure 2: The overall implemented system with hardware (VC707 evaluation kit) and software module (Samsung Tablet) interfaced using bluetooth module (LM400 - BTM400A2).

used. The App after lead reconstruction shows leads in different formats (figure 3) : Leads I, II and III together, leads V_1 - V_6 together, leads aVR, aVL and aVF together, Single lead window to show any desired lead and comparison window to compare any two leads. All the aforementioned features have been added for easy operation and to assist cardiologists.

6. Results and Discussion

Table 1 presents mean R^2 values for 100 recordings comparing the reconstruction results when denoised ECG signals were obtained from algorithm [4, 11–13] and proposed architecture. A set of 4096 samples were denoised using both MATLAB algorithm and architecture (Register Transfer Logic (RTL)) designed using HDL. This set of 4096 samples was used for reconstruction of the missing leads using the personalized coefficients obtained using a disjoint set of 5000 samples and the results were compared. We can see that the performance difference is less than 1%.

As mentioned in section 4, for architectural implementation the recording was divided in to sets of 4096 samples and denoised separately. However, in this case we observed slight deterioration in signals after denoising. To evaluate the deterioration occurred when sample set is divided into subsets and then denoised compared to sample set denoised as a whole, we performed separate simulations on 100 recordings and results have been shown in Table 2. The subset based denoising retraces the signals denoised as a whole with more than 97% success. On increasing the subsets size to 8192, we found an increment of approximately 1% (i.e. 98%) in performance, however, on decreasing the subset size to 2048 results deteriorated to 70% and above. Hence, we adopted subsets with 4096 samples, compromising slightly on the accuracy to reduce the resource utilization and complexity.

Table 3 shows the resource utilization on VC707 (Virtex 7 - XC7VX485T) and ATLYS (Spartan 6 - XC6SLX45) evaluation kits.

Table 3: Resource utilization on VC707 - Virtex - 7(XC7VX485T) and ATLYS - Spartan - 6(XC6SLX45) evaluation kits. (N/A - Not Applicable).

	Virtex - 7	Spartan - 6
No. of Occupied Slices	4412 (5%)	3849 (56%)
No. of LUT FF pairs used	12354	12332
No. of fully LUT FF pairs	4697 (38%)	4587 (37%)
No. of RAMB36E1	51 (4%)	N/A
No. of RAMB16BWERs	N/A	40 (34%)
No. of RAM8BWERs	N/A	5 (2 %)

7. Conclusion

In this paper, we have implemented our algorithmic findings of personalized lead reconstruction methodology including preprocessing module. Preprocessing which includes baseline wandering removal has been implemented on hardware (FPGA) and lead reconstruction has been implemented on Android based mobile platform. The results presented have high diagnostic accuracy.

Acknowledgements

This work is supported by the Department of Electronics and Information Technology (DEITY), India under the Cyber Physical Systems Innovation Hub under Grant number: 13(6)2010-CC&BT, dated 01:03:11.

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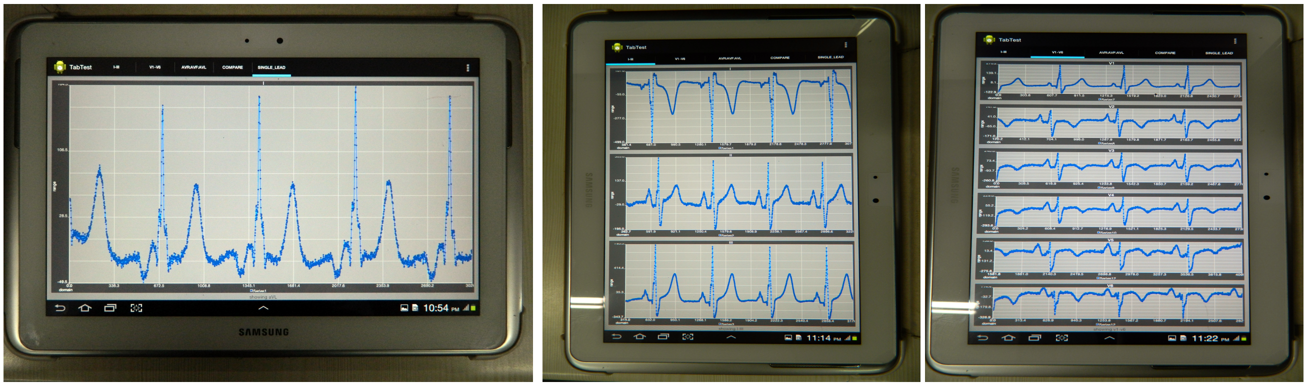

(a) Single Lead display (b) Lead I, II and III display (c) Lead V_1-V_6 display

Figure 3: Features of the Android App has been displayed. a - displays any lead required to be analysed. b - displays leads I, II and III for comparison by the cardiologists. c - displays leads V_1 - V_6.

Table 1: Mean R^2 values for 100 recordings comparing the reconstruction results obtained from algorithm implemented using MATLAB and architecture (RTL) implemented using HDL.

	I	II	III	aVR	aVL	aVF	V_1	V_2	V_3	V_4	V_5	V_6
Architecture	99.79	99.47	99.47	99.69	99.59	99.42	95.36	99.83	96.46	89.30	89.51	93.09
Algorithm	100	100	99.99	100	99.99	99.99	95.45	100	97.2	90.18	90.453	93.642

Table 2: Mean R^2 values obtained, for 100 recording, on comparing the denoised signals when obtained by dividing the recording in sets of 4096 samples and when denoised as a whole sample set without any division.

	I	II	III	aVR	aVL	aVF	V_1	V_2	V_3	V_4	V_5	V_6
2048	80.00	79.21	79.17	78.96	78.96	78.16	78.95	79.94	77.51	74.32	72.47	71.70
4096	97.21	97.16	97.15	97.15	97.16	97.14	97.15	97.2	97.25	97.19	97.18	97.17
8192	97.97	97.97	97.99	97.99	98.00	98.03	98.03	98.11	98.15	98.09	98.12	98.14

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