Design of Low Cost Virtual Patient for Real Time ECG Analyzers

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ABSTRACT
ECG analysers have proved out to be very useful in the analysis of human heart beat and subsequently diagnosis of various human cardiovascular diseases. The design of these real time ECG analyzers is difficult since real time environment is not always available for the performance analysis of these analyzers. The existing ECG analyser makers are making use of expensive data restitution boards which generate real time signals for the performance analysis of ECG analyzers, which make the system even more expensive. Thus in this paper a virtual patient is proposed, which creates a real environment for the analysis of ECG analyzers by generating real time ECG signals from the database of real acquired data, by making use of simple Microcontroller. The signals generated by Microcontroller are seen as real signals coming from the instantaneous heart activities by the analyzer. The use of Microcontroller makes the system cost efficient and can be utilized as a test bench for the study of ECG signals at the laboratory level.

General Terms
ECG Signal Generators, Biomedical equipment, electrocardiography, real-time systems, signal generators, systems engineering, test equipment.

Keywords
Signal compression, ECG signal Database, arrhythmias generation, Holter monitoring,

1. INTRODUCTION
The cardiovascular diseases are the major cause of deaths these days owing to the lifestyle. Ever since the Electrocardiogram was developed, it has proved out to be very useful in the detection and diagnosis of cardiac diseases. The ECG signal is extracted by placing 3 to 12 electrodes on specific points on the body and then potential difference between points is measured. These potential difference values when put together forms ECG signal. The ECG recorded for few minutes is called short term monitoring and is usually done by cardiologist who is able to give correct diagnosis of the disorder depending on the study of the signal. But some patients require continuous or long term monitoring for their episodic diseases. This long term monitoring is called Holter monitoring. These signals are monitored on ECG analysers, whose design and manufacture is difficult since its performance validation is tough due to the unavailability of real time environment. The current Holter manufacturers use expensive data restitution boards (National Instruments PCI-6711) for the artificial generation of ECG signals. Since the data restitution boards are very expensive, these ECG signal generators become expensive.

The virtual patient concept proposed here describes an innovative approach in computerized re-generation of bio-medical signals [1] [2]. In this paper, the methodology, modifications on current systems and the results obtained in a 'low cost' implementation which has similar functionality has been shared. Standard database of real time ECG signals is readily available like the MIT-BIH (Boston's Beth Israel Hospital), AHA (American Heart Association), and European ST-T which can be used to regenerate ECG signals using C programs in a personal computer. However, the cost of interfacing a Digital to Analogue Converter (DAC) with a PC is quiet high (like National Instruments Data Resolution Board), making the overall system expensive. This task can however be performed using customized substitutes like ATMEL's ATmega32 if suitable conversion of the ECG database is done. The main requirement for such conversion is compression of the ECG signal, owing to the limited size of memory which can be interfaced with ATmega. Further, it must be noted that here the compression algorithm can be computationally intensive (since it is executed by a PC) whereas the de-compression algorithm has to be simple enough (which is to be implemented in real-time by the microcontroller).

2. ECG SIGNAL DESCRIPTION
The ECG signal is a time varying signal that reflects ionic current flow that is caused because of contraction and subsequent relaxation of heart [3]. The surface ECG signal is obtained by recording the potential difference between two electrodes placed at various points on the surface of the skin. A single normal cycle of the ECG represents the successive arterial depolarization /repolarization and ventricular depolarization/repolarization which occur with every heartbeat. These can be approximately associated with the peaks and troughs of the ECG waveform labeled P, Q, R, S, and T as shown in Fig. 1.

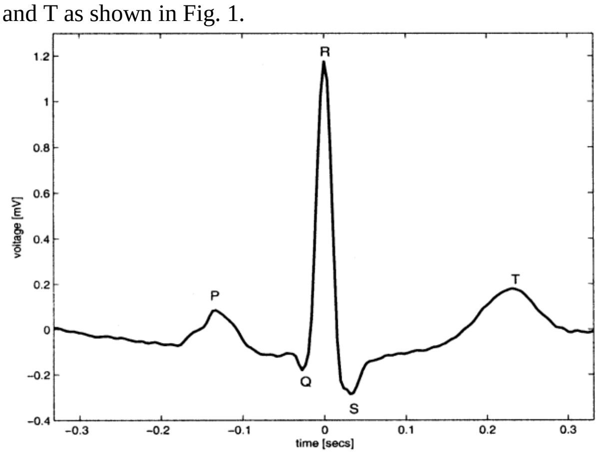

Fig1: An ECG recorded form a normal Human

The ECG signal is a series of deflections away from the baseline due the electrical heart activity as a result of muscle contraction. A single normal cycle of the ECG, corresponding to one heartbeat, is labeled with the letters P, Q, R, S, and T on each of its turning points as shown in figure 1 above. The ECG can be divided into following parts:

- P-wave: Prior to the atrial contraction a small low voltage deflection away from the baseline is caused by the depolarization of atria which propagates from SA (Sino Atrial) node through atria.
- PQ-interval: The time period between the beginning of atrial depolarization and the beginning of ventricular depolarization.
- QRS-complex: The largest-amplitude portion of the ECG, caused by currents generated when the ventricles depo-larize prior to their contraction. Although atrial repolar-ization occurs before ventricular depolarization, the latter waveform (i.e. the QRS-complex) is of much greater amplitude and atrial repolarization is therefore not seen on the ECG.
- QT-interval: The time between the onset of ventricular depolarization and the end of ventricular repolarization. Clinical studies have demonstrated that the QT interval increases linearly as the RR interval increases. Prolonged QT interval may be associated with delayed ventricular repolarization which may cause ventricular tachyarrhythmia leading to sudden cardiac death.
- ST-interval: The time between the end of S-wave and the beginning of T-wave. Significantly elevated or depressed amplitudes away from the baseline are often associated with cardiac illness.
- T-wave: Ventricular repolarization, whereby the cardiac muscle is prepared for the next cycle of the ECG.

3. REAL TIME ECG ANALYZER

ECG analyzers are battery operated devices whose generalized block diagram is as shown in figure 2 below. The electrodes are placed on various points on the patient's body, which include chest, wrist and ankle. These electrodes measure small potential difference between these points which are usually 1mV peak to peak. Such a small voltage needs to be pre amplified. Therefore the preamplifier is placed closed to the sensors. The raw analogous ECG signal is then filtered in order to further improve signal to noise ratio (SNR). The first filter implemented here is a band-pass filter whose lower cut-off frequency is so chosen that the baseline drift due to respiration is removed and the low frequency noise due to motion artifacts are removed. The higher cutoff frequency is well under the Nyquist frequency rate that suppresses the aliasing effect introduced by digitization of any analog signal. The second filter implemented here is a Notch filter that attenuates power- line interference which is usually 50Hz in Europe and 60Hz in U.S. The signal now obtained is noiseless and should be amplified to use the full dynamic range of the ADC.

The sampling frequency is low, i.e., between 250 Hz for long-term monitoring and 1 kHz for a heart rate variability analysis system. For example, the sampling rate for the MIT-BIH database is 360 Hz. However, in modern ECG analyzer systems, a sampling rate that is more than 500 Hz is recommended. This signal is then amplified to drive the full range of Analog to Digital converters. The digitally converted signals are then fed to the Digital Signal Processing Units which has rather complex architectures. The DSP processor then applies various signal processing algorithms and analyses the ECG signal. Apart from signal processing, the complex operations include driving the LCD display and ADC, taking into account the input acquisition parameters from the keyboard, storing the ECG signals and real time data on memory card, transmitting the signals over wireless or wired links at remote monitoring locations. Since the processing power required for executing these signal processing algorithms is high, these basic operations are carried by a microcontroller in order to efficiently utilize the available power.

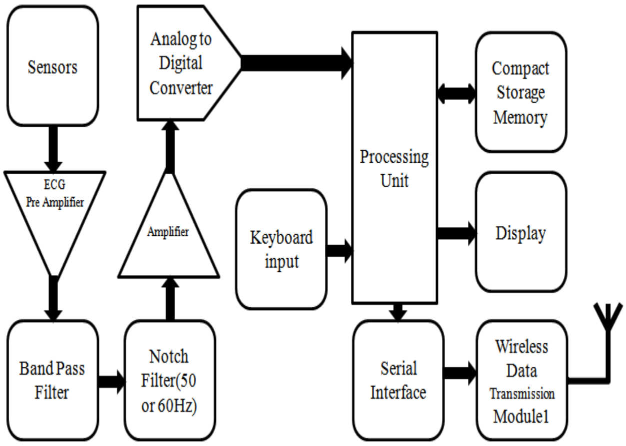

Fig 2: Block Diagram of a Real Time ECG Analyzer

After a detailed study of the make of ECG signal and the ECG analyzer, it can be seen that the real time ECG signal should contain following key elements:

- ECG information (P wave, QRS complex, T wave) that indicates electrical heart activities of heart.
- Baseline drift.
- Motion Artifacts noise.
- Electrodes noise.

The generation of these real time signals through microcontroller programs requires exact values of amplitude and time duration of waves which can be taken from the database.

4. PROPOSED VIRTUAL PATIENT

The proposed ECG virtual patient is presented on the block diagram of Figure 3. The main part of this ECG waveform Generator is built around the Database and the microcontroller used.

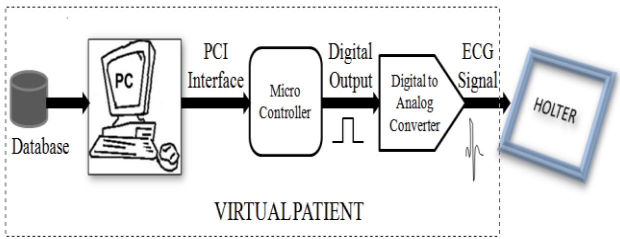

Fig 3: Functional Block Diagram of Virtual System

The heart research community prefers to use standard databases such as the AHA database, European ST-T database, and MIT-BIH arrhythmia database [4]. The database which proposed system uses is MIT-BIH database since it is made for Asian power line standards of 50Hz. Since 1975, laboratories at Boston's Beth Israel Hospital (now the Beth Israel Deaconess Medical Center) and at MIT have supported researchers into arrhythmia analysis and related subjects. One of the first major products of that effort was the MIT-BIH Arrhythmia Database, which completed and began distributing in 1980 [5]. The database was the first generally available set of standard test material for evaluation of arrhythmia detectors, and has been used for that purpose as well as for basic research into cardiac dynamics at more than 500 sites worldwide. Originally, the database on 9-track half-inch digital tape at 800 and 1600 bpi, and on quarter-inch IRIG-format FM analog tape was available. Later the CD-ROM version of the database was released. The MIT-BIH Arrhythmia Database contains 48 half-hour excerpts of two-channel ambulatory ECG recordings, obtained from 47 subjects studied by the BIH Arrhythmia Laboratory between 1975 and 1979. Twenty-three recordings were chosen at random from a set of 4000 24-hour ambulatory ECG recordings collected from a mixed population of inpatients (about 60%) and outpatients (about 40%) at Boston's Beth Israel Hospital; the remaining 25 recordings were selected from the same set to include less common but clinically significant arrhythmias that would not be well represented in a small random sample. The recordings were digitized at 360 samples per second per channel with 8-bit resolution over a 10 mV range.

The database available is not readable by standard softwares, hence needs conversion [9]. This conversion can be achieved by WFDB (Waveform Database) library. This Waveform Database interface library (the WFDB library) is a package of C-callable functions that provide clean and uniform access to digitized, annotated signals stored in a variety of formats.

This database is used by the microcontroller to generate various arrhythmias waveforms. The signal values are out on output ports of microcontroller. The generated signal is digital in nature which needs conversion to analog form with the help of Digital-to-Analog Converter. The DAC used is R-2R ladder type which converts each 8-bit sample values into its corresponding analog one. This real time ECG signal which gives the impression of instantaneous electrical heart activity can be then fed to Holter which is our DUT (device under test)

5. DATA COMPRESSION

Effective storage space is essential for storing large quantities of ECG information [6] [7]. Holter monitoring usually needs continuous 12 or 24-hours recording. For acceptable diagnostic quality, ECG signal should be sampled at a rate of 250-500 Hz with 11-12 bits resolution. The information rate is thus approximately 11- 22 Mbits/hour. The monitoring device (”Holter”) must have a memory space of about 100-200 Mbytes for a 3-lead recording. Memory costs may render such a solid state Holter device impractical. If efficient compression methods are utilized, memory requirements may drastically fall to make the solid state high quality Holter device commercially viable. Thus the compression method used to compress the database [8] is described as shown in the flowchart below.

At first a standard ECG cycle is defined using standard values of a normal ECG signal. A typical ECG waveform obtained is shown in Figure 5. Let X_1 denote the standard ECG cycle. Then subsequent cycles are input and the difference between the standard cycle and subsequent cycle is calculated. Let X_n denote the subsequent cycle. The difference between the X_1 and X_n , i.e. X_d is given by $X_d = X_1 - X_n$. As X_1 and X_n are assumed to be chosen from the same patients, it is, therefore expected that the difference between the X_1 and X_n, i.e. X_d has low amplitude as shown in Fig. 5 and the difference signal has low energy. Now, DCT transformation is applied to the difference signal X_d and it is displayed in Figure 6. DCT transformation is applied on sample cycles because the DCT coefficients contain 99.99% energy of the energy contained in the sample cycle. For that calculate $E\{Xd\}$ and DCT transformation is applied by $X_d = DCT(X_d)$. The M_n DCT coefficients are stored such that the energy stored in the M_n coefficients is such that energy preserved in these M_n coefficients ($E\{X_d(1:M_n)\}$) is just greater than $\alpha \times E\{X_d\}$, where α is a constant. Now the DCT transformation is applied to X_n, i.e., $X_n = DCT(X_n)$ and the first Mn coefficients are taken in such a way that energy preserved in these M_n coefficients ($E\{X_n(1:M_n)\}$) is just greater than $0.99 \times E\{X_d\}$. Now the values of these M_n coefficients may be stored, quantized and encoded.

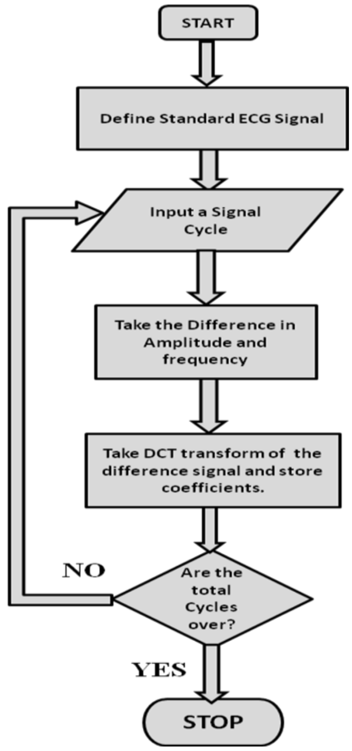

Fig 4: Flowchart of Data Compression method

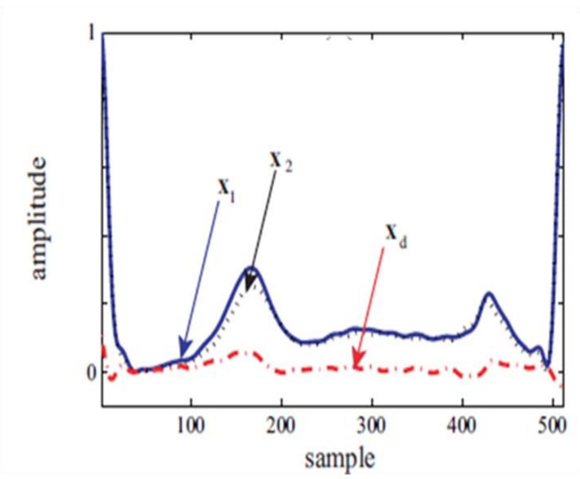

Fig 5: Waveform of a Standard sample cycle X_1, Input cycle X_2 and the difference cycle X_d.As the sample cycle and the input cycle are taken from the same signal record the difference cycle posses' low energy.

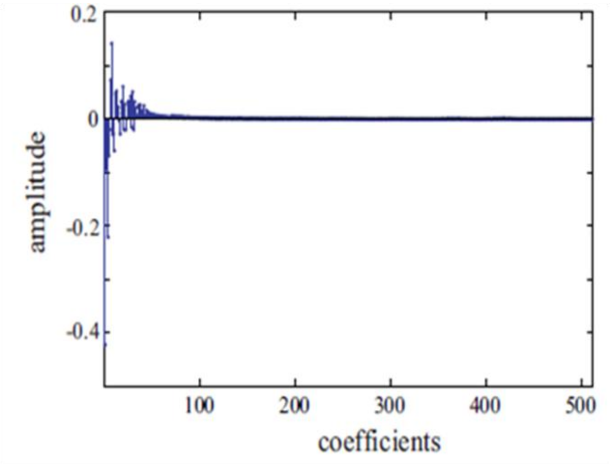

Fig 6: DCT of X_d. It is illustrated that difference energy is spread over a low number of DCT coefficients.

6. RESULTS

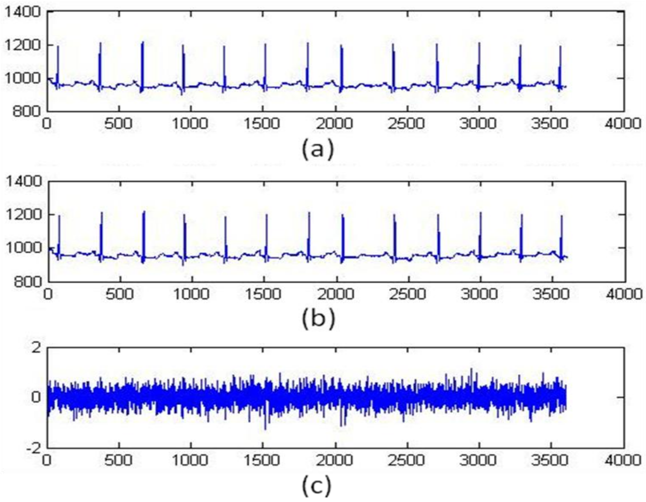

Fig 7: Record no. 100 from MIT-BIH Database:
(a) Recorded Signal (b) Generated Signal (c) Error Signal

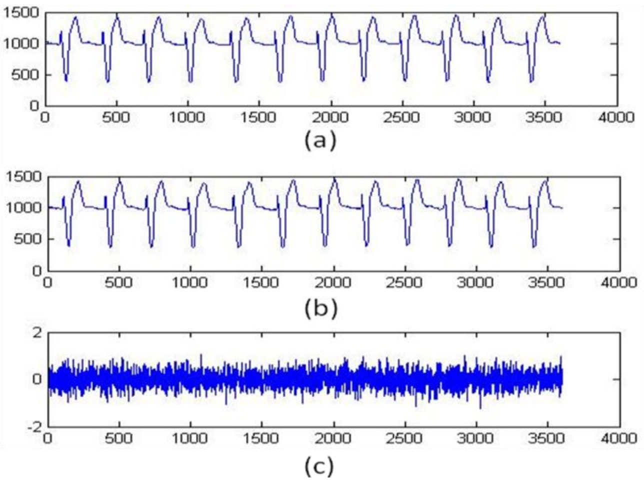

Fig 7: Record no. 101 from MIT-BIH Database:
(a) Recorded Signal (b) Generated Signal (c) Error Signal

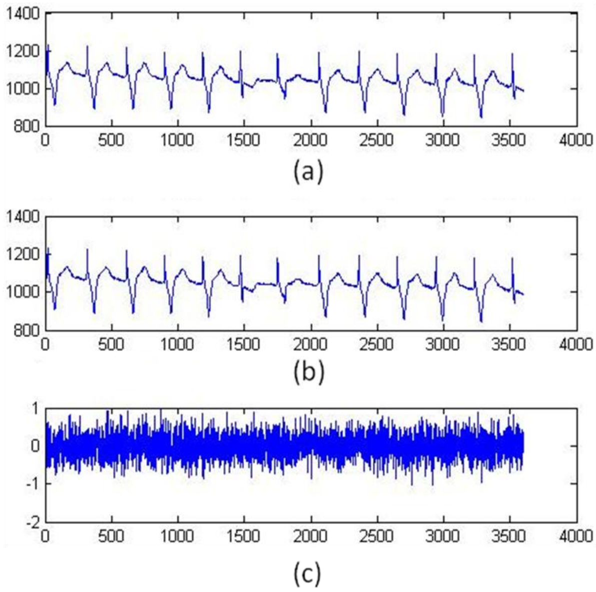

Fig 7: Record no. 102 from MIT-BIH Database:
(a) Recorded Signal (b) Generated Signal (c) Error Signal

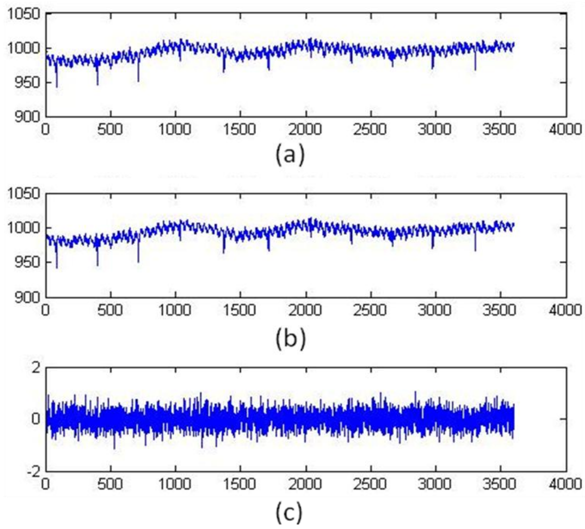

Fig 7: Record no. 103 from MIT-BIH Database:
(a) Recorded Signal (b) Generated Signal (c) Error Signal

The figures above shows (a) Recorded signal from the MIT-BIH waveform database, (b) Signals generated by the virtual patient and (3) Error signal between recorded signal and generated signal. Each of the signals generated by the virtual patient is in accordance with the actual database signal. It is observed that the error introduced due to the compression and decompression of the signal is minimal in nature and within acceptable limits. For example, for the record 100, the Root Mean Square (RMS) error is 0.36 while the peak error does not deviates beyond -1.22, that is around 0.122%. The table below shows the RMS error recorded for the first ten seconds of few records.

Record Number	RMS Error	Peak Error Value
100	0.36	-1.22
101	0.58	-1.61
102	0.29	1.74
103	0.41	-1.90

7. CONCLUSION

As can be seen by the generated signals the proposed method of ECG generation produces signals exactly the same way as found in the globally accepted databases. The ECG virtual patient has been used to evaluate the real time performance of a laboratory DUT, showing the ability of the system to deliver more realistic statistics. The influence of the quantification bit number has also been carried out, showing that only 8 bits of a microcontroller are necessary on the condition that the entire dynamic range is used. Simulated or real artifacts or noises can also be added to raw ECG waveforms of the databases, making performance evaluations possible with respect to the type of noise added and the SNR values. This approach of signal generation is capable of replicating many of the important features of the human ECG. The new model presented here reflects a data-driven approach to modeling the electrical activity of the heart. The virtual patient is also applicable for multichannel inputs.

Moreover the virtual patient provides a cost efficient approach towards the modern generation of Signal generators.

8. REFERENCES

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