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FIELD-PROGRAMMABLE GATE ARRAY IMPLEMENTATION OF EMPIRICAL MODE DECOMPOSITION ALGORITHM FOR ELECTROCARDIOGRAM PROCESSING

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ABSTRACT

The electrocardiogram (ECG) signal contains important information that is utilized by physicians for the diagnosis and analysis of heart diseases. Therefore, good quality ECG signal is required. Hilbert-Huang transform (HHT) is a method to analyze non-stationary and non-linear signals. Empirical mode decomposition (EMD) is the core of HHT. EMD breaks down signals into smaller number of components. These components form a complete and nearly orthogonal basis for the original signal. This algorithm is implemented on field-programmable gate array using the process of extrema generation, envelope generation, and stopping criterion.

Keywords: Hilbert-Huang transform, Electrocardiogram, Empirical mode decomposition, Field-programmable gate array.

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INTRODUCTION

Electrocardiogram (ECG) is the recording of electrical activity of the heart. Fig. 1 shows the normal ECG without any kind of interferences. In clinical practice, ECG is the most commonly used cardiovascular signal because it gives us plenty of diagnostic information. Doctors use ECG to find heart-related problems. ECG from healthy hearts has a characteristic shape. Any damage to heart muscles can change the electrical activity of heart causing change in the characteristic shape of ECG. While recording, ECG contains different types of noises such as power-line interferences, baseline wandering, motion artifacts, electrosurgical noise, and EMG noise which need to be filtered. An ECG contains three main parts: p-wave which denotes atrial depolarization, the QRS complex which denotes ventricular depolarization, and T-wave that represents ventricular repolarization [1]. The most important part in ECG processing is the detection of QRS complex which has an essential role in the diagnosis of heart rhythm irregularities [1,2].

Many methods exist to detect QRS complex that are based on standardized filtering and wavelet transform. Each technique has its own advantages and drawbacks. One of the influential signal detection technique considered in literature is adaptive filtering method. One of the most widely used algorithms is least mean square algorithm introduced by Widrow and Hoff in adaptive filtering. It is very simple in structure and is easy to compute [3]. Geophysicist Morlet put forward the concept of wavelet transform in analysis and processing geophysical data in France in 1984. Wavelet transform has the advantage that the windows will adapt, and thus, it is possible to generate an infinite set of possible basis functions [4].

This paper concentrates on the implementation of Empirical mode decomposition (EMD) using field-programmable gate array (FPGA) for denoising of ECG [5,6]. EMD is widely used for non-stationary and non-linear signal analysis procedures. The decomposition method that is used in the EMD algorithm is called shifting process. It has proved versatile in a wide range of applications for signal extraction from non-linear and non-stationary processes. It is an iterative algorithm which computes the maximum and minimum extreme. Main advantage of the EMD is that the basis functions are derived from the signal itself. Hence, the analysis is adaptive as compared to the traditional methods where the basis functions are fixed. The EMD is based on the sequential extraction of energy linked to various intrinsic time scales of the signal, starting from finer temporal scales (high-frequency modes) to coarser ones (low-frequency modes). Thus, according to this, decomposition of any signal can be represented as the sum of intrinsic mode functions (IMFs) and a residue. An IMF is defined as a function with equal number of extreme and zero crossings with its envelopes, as defined by all the local maxima and minima [7].

Different EMD applications require different precision, data lengths, extrema extraction method, envelope generation method, and stopping criterion. The proposed algorithm is evaluated using MIT-BIH arrhythmia database.

EMD ALGORITHM

EMD breaks down ECG signal into various data sequences and a final residue. Each data sequence is called as an IMF, which must fulfill the given conditions [7,8].

i. The number of extrema points should be equivalent to the number of zero-crossing points in the signal.
ii. The mean values of upper envelope and lower envelope of local extrema should be equal to zero at all points in the signal.

In EMD, the input signal x (t) can be decomposed as

$$x(t)=\sum_{j=1}^{m} c_j(t)+d(t)$$

Where m is the total number of IMFs, $c_j(t)$ is the j^{th} IMF, and d(t) is the final residue. The following are steps of EMD:

i. Find the local maxima and minima of signal x (t).
ii. Obtain the upper envelope e_{upper} (t) and lower envelope e_{lower} (t) from local maxima and local minima, respectively.
iii. Calculate the local mean:

$$mn(t)=\frac{e_{upper}(t)+e_{lower}(t)}{2}$$

iv. Do subtraction, d(t) = x(t) - mn(t).
v. If d(t) satisfies the stopping criterion, then d(t) is defined as an IMF. Otherwise if

vi. d(t) does not satisfy the stopping criterion then set x(t) to d(t) and repeat process from step (i).
vii. Update the residue by subtracting obtained IMF from the previous value.

The signal x(t) can be decomposed into different frequency bands using EMD technique. The resultant decomposed waveform showed variations in the IMFs mainly due to extrema extraction, envelope generation, and stopping criterion. These variations are due to different methods used in extrema extraction, envelope generation, and stopping criterion.

Fig. 2 shows flow chart of EMD algorithm which is used to decompose the signal into various components.

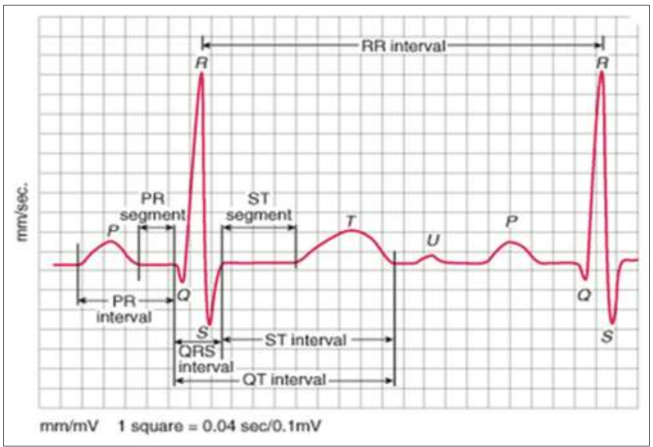
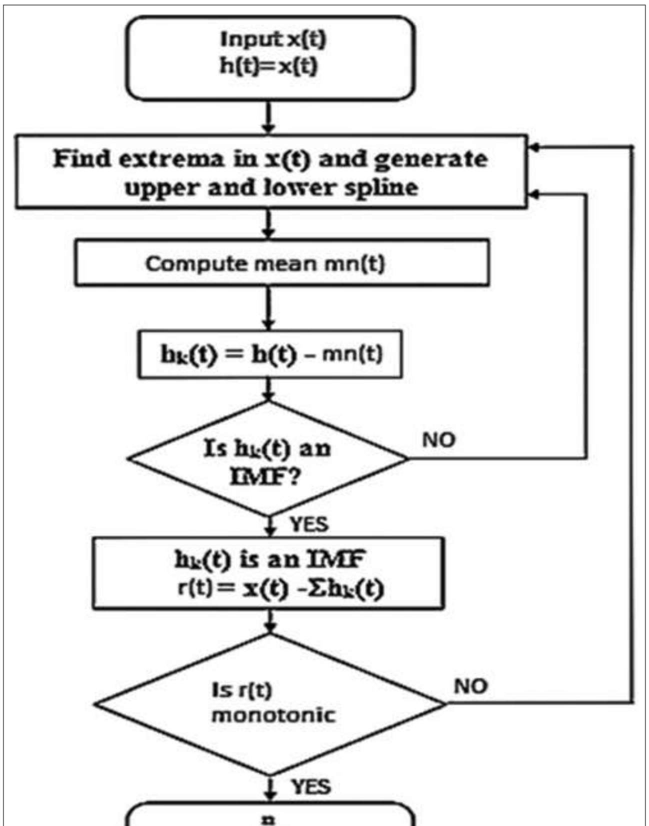


Fig. 1: Electrocardiogram signal



$$x(t) = \sum_{i=1}^{n} h_i + r_n$$

Fig. 2: Flow chart of empirical mode decomposition algorithm

Extrema extraction

The first process in EMD is to extract local maxima and local minima points (local extrema points). The extraction method is based on the neighboring points given by [7]:

i. Local minima: $h_j[x]<h_j[x-1]$ and $h_j[x]<h_j[x+1]$.
ii. Local maxima: $h_j[x]>h_j[x-1]$ and $h_j[x]>h_j[x+1]$.

Where x is the position index of a current sample which has to be evaluated, h_j [x−1] and h_j [x+1] are the neighboring signal values of $h_j[x]$.

Envelope generation

Envelope generation is a very difficult process in EMD process. An appropriate interpolation method must be used to connect the local maxima and local minima points, respectively. Three envelope generation methods are cubic spline interpolation (CSI) [8], Sawtooth interpolation, and Hermite Spline Interpolation (HSI) method [8]. HSI requires less computation compared to CSI.

Stopping criterion

There are three methods:

i. K number (KN)

KN method is the simplest method. In this method, when the count reaches the count defined by the user, the stopping criterion is satisfied.

ii. Standard deviation bound (SDB)

This method ensures that the IMF retains sufficient information of the signal by limiting the size of SD computed. When SD is lower than that defined by the user, stopping criterion is satisfied.

$$SD = \sum_{x=1}^{L} \frac{(h_j^0(x)-h_j^m(x))^2}{(h_j^0(x))^2}$$

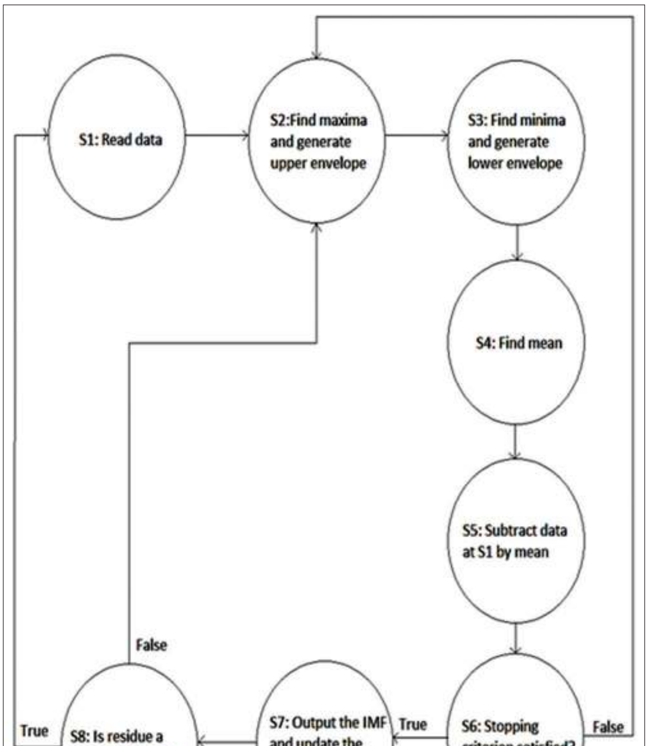


Fig. 3: State diagram of empirical mode decomposition algorithm

Where L is the length of the signal.

iii. Energy difference tracking (EDT)

EDT determines stopping criterion depending on the integrity and orthogonality of IMFs [9]. Equations used are:

$$E_x = \int_{-\infty}^{\infty} rs_{j-1}^2(t)dt$$

$$E_{tot} = \int_{-\infty}^{\infty} [h_j^m(t)]^2 dt + \int_{-\infty}^{\infty} [rs_{j-1}(t) - h_j^m(t)]^2 dt$$

$E_{err} = E_{tot} - E_x$

Where E_x is the energy of residue $rs_{j-1}(1)$ and E_{tot} is the energy sum of $h_j^m(t)$ and $rs_{j-1}(t)-h_j^m(t)$.

PROPOSED WORK

To implement EMD, each module, that is extrema (local maxima and local minima) extraction, envelope generation, and stopping criterion, was programmed using Matlab then it is converted to Verilog HDL using HDL Coder from Matlab tool. Fig. 3 shows the developed state diagram of EMD algorithm for hardware implementation.

Extrema extraction

In the proposed work, the extrema extraction module used is done using a comparator array (CA). In CA technique, if evaluated sample within the search window is maxima or minima then the sample is treated as an extrema.

Envelope generation

In the proposed work, the technique used for envelope generation of the signal from local maxima and local minima is CSI. CSI generates smooth upper and lower envelopes but requires complex computation.

Stopping criterion

The stopping criterion used in the proposed work is SD bound. In SDB, the user will set a threshold, and if SD of the signal goes below the threshold, then the process stops.

HDL coder

HDL Coder generates a synthesizable and testable Verilog and VHDL code from Matlab functions and Simulink models [10]. The HDL code generated using HDL Coder can be used for FPGA programming. HDL Coder provides traceability between your Simulink model and the generated Verilog code, enabling code verification.

HARDWARE IMPLEMENTATION

The hardware architecture of CA used for extrema extraction is shown in Fig. 4.

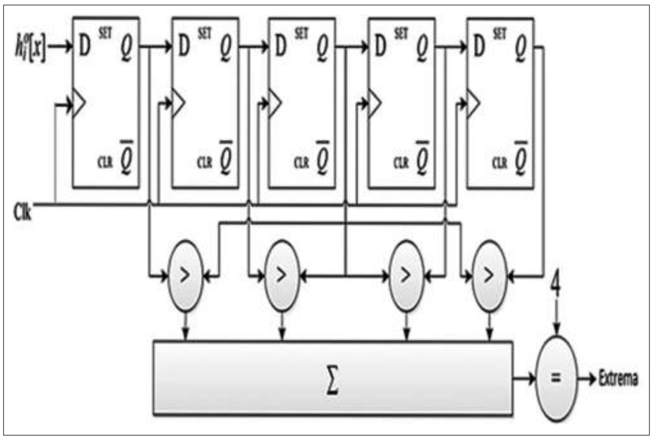


Fig. 4: Hardware architecture of comparator array

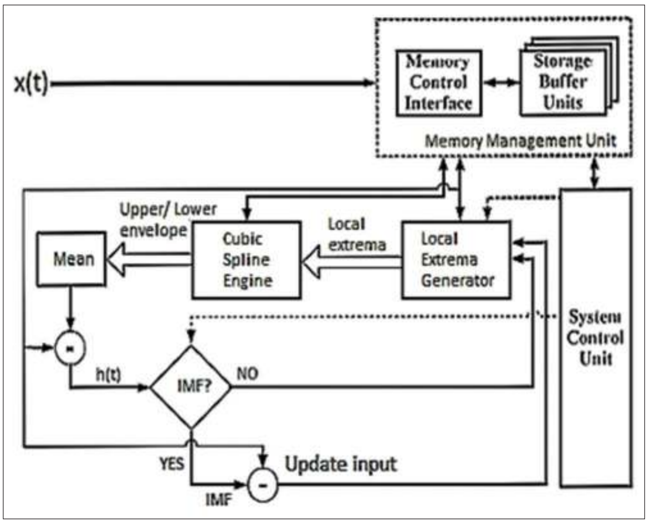


Fig. 5: Overall system architecture of empirical mode decomposition algorithm

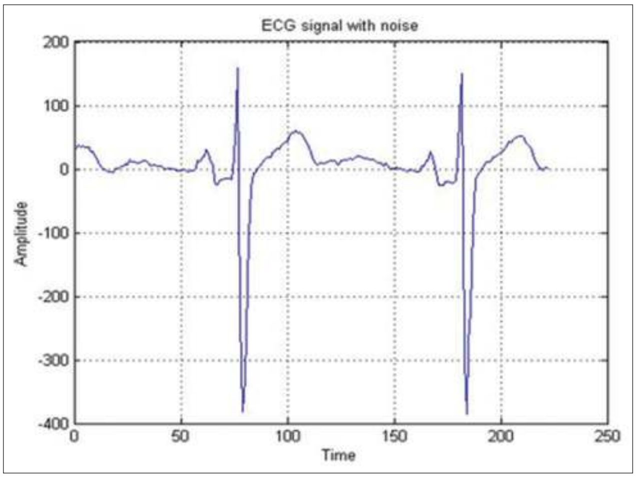


Fig. 6: Input electrocardiogram signal with noise

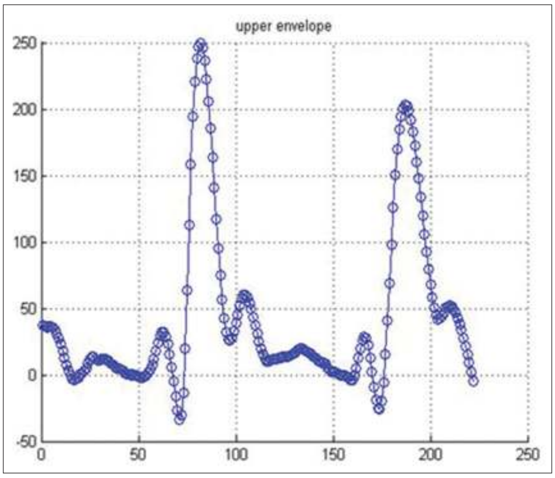


Fig. 7: Upper envelope of input signal

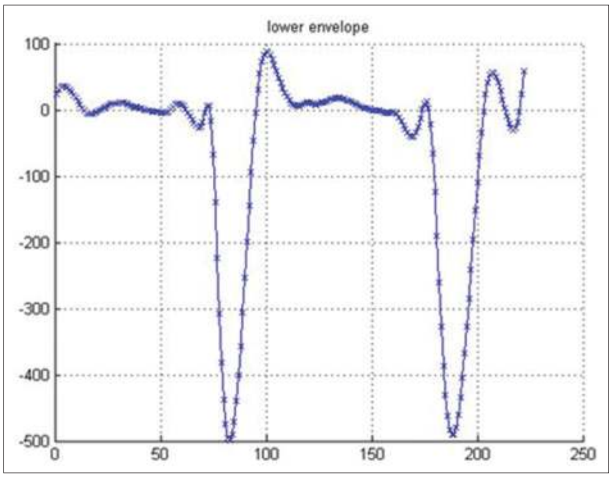


Fig. 8: Lower envelope of input signal

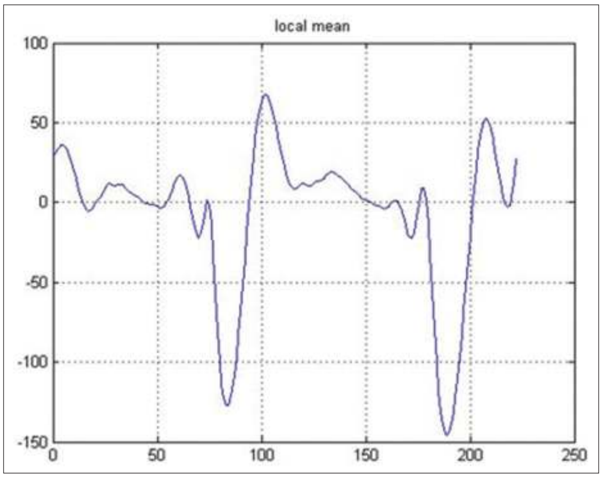


Fig. 9: Local mean

CA technique is used for extrema extraction. In this hardware architecture of CA, the search window size is chosen as 5.

Fig. 5 shows overall system architecture of EMD algorithm implemented in FPGA. The input signal is given as x(t), and the output is a set of IMFs and a residue.

RESULTS AND DISCUSSION

ECG signal is obtained from MIT-BIH arrhythmia database. This database is a real-time record of ECG with more than 4000 samples. In this work, ECG is downloaded from PhysioBank of MIT-BIH arrhythmia database which has a sampling rate of 360 Hz. The study was conducted on 8 ECG signals in normal and also 12 ECG signals in abnormal conditions. This database contains 48 records, each containing two-channel ECG signals of 30 minutes duration selected from 24 hrs recordings of 47 individuals. There are 116,136 numbers of QRS complexes in the database. It is given as an input as shown in Fig. 6. Using interpolation method, the upper envelope and the lower envelope of the input signal are generated as shown in Figs. 7 and 8, respectively. Fig. 9 shows calculated local mean of upper and lower envelope.

The results obtained for the EMD for 200 samples of ECG signal in MIT-BIH database. Fig. 10 shows the IMF levels for a 50 Hz noisy ECG signal from 1 to 11 and the final residue.

This algorithm is implemented using FPGA using the process of extrema generation, envelope generation, and stopping criterion.

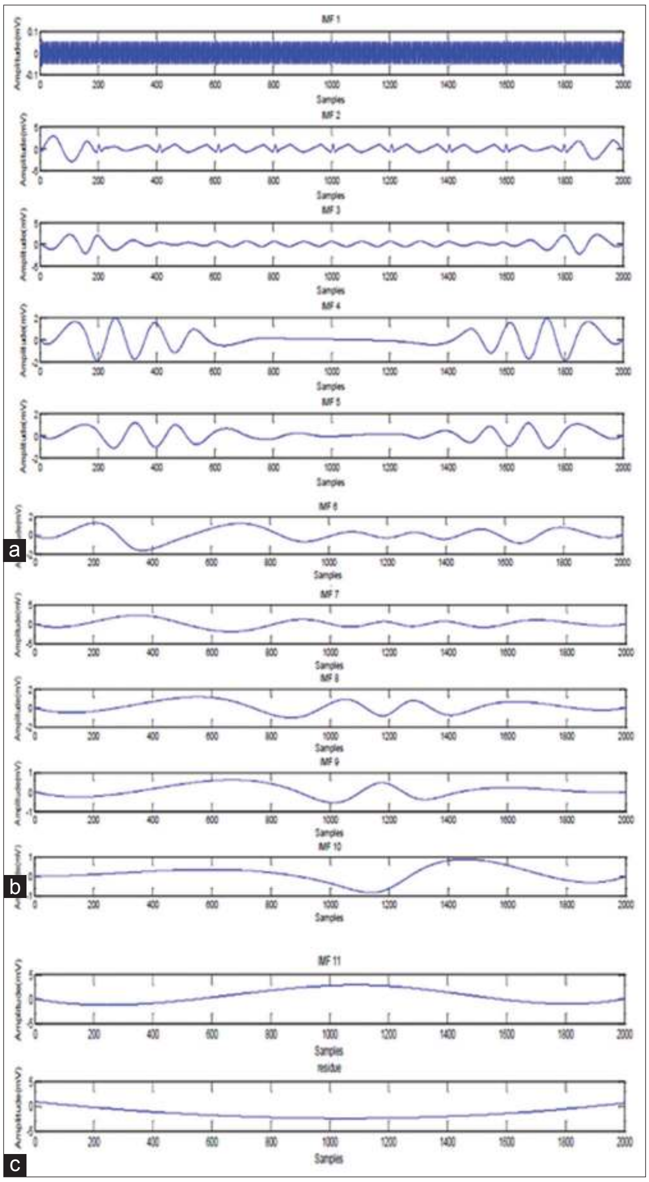


Fig. 10: (a-c) Intrinsic mode functions 1-11 and residue

CONCLUSION

This paper has discussed in detail the implementation of EMD algorithm using VLSI for extraction of original ECG signal from 50 Hz noisy ECG signal with the aim of conserving the highest attainable precision in the hardware module. This hardware helps to utilize the design for diagnostics and it has less complexity.

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