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ECG QRS Complex Detection with Programmable Hardware

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***Abstract*—In recent years, algorithm based on Mathematical Morphology and wavelet transform has been proposed for ECG QRS Complex detection. However, its intensity of computation is high. This paper proposes the algorithm and hardware architecture for the whole system of QRS Complex detection based on Mathematical Morphology and Quadratic Spline wavelet transform, with implementation in Field Programmable Gate Array (FPGA). The system consists of Morphological filtering, Quadratic Spline wavelet transform and Modulus Maxima Pair Recognition modules. The parallel and pipelined architecture of system can operate in the maximum 35MHz with throughput of one sample per clock cycle. The QRS Complex detection accuracy for MIT/BIH arrhythmia database recordings and resource consumption are reported. The design is suitable for both batch processing of huge volume ECG data and real time applications for portable devices.**

I. Introduction

Electrocardiogram (ECG) characteristic points retrieval is the basis for ECG automatic diagnosis. QRS Complex is the most significant waveform of ECG and the detection of its position is helpful for the determination of other ECG characteristic points.

Currently there are many algorithms for QRS Complex detection. The Pan-Tompkins method [1] employs bandpass filtering and nonlinear processing for ECG pre-processing. The bandpass filtering is for high frequency noise and baseline wandering removal, whereas the nonliear processing is for the estimation of localized energy corresponding to QRS Complex. The wavelet transform (WT) method [2]-[8] for QRS Complex detection takes advantage of the time-frequency analysis property of wavelet transform. Practically most of the wavelet transform methods transform the QRS Complex to specific pattern of waveform, e.g. modulus maxima pair, for detection. In recent years, the method based on both Mathematical Morphology (MM) and wavelet transform [9] has been proposed for QRS Complex detection. This method is promising because the Morphology filtering can enhance the QRS Complex, attenuate the P and T waves, remove high frequency noise and baseline wandering. The Morphological filtering for ECG signal pre-processing can reduce the complexity of output wavelet coefficients for the subsequent QRS Complex position determination.

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However, the Mathematical Morphology plus wavelet transform algorithm is a computation intense algorithm. It takes long time to compute even with high-end personal computer. For example, it takes 21 minute for personal computer with Pentium M 2GHz CPU and 1GB memory to compute 5-minute ECG signal (360Sa/s) in MATLAB environment with this algorithm. With the development of capacity, speed and design methodology of Field Programmable Gate Array (FPGA), it is feasible to implement computation intense algorithm in FPGA. The advantages are significant, including increase of system performance, decrease of system size, and feasible to form a System-on-Chip (SoC).

This paper proposes the system of QRS Complex detection based on Morphological filtering and Quadratic Spline wavelet transform (QSWT), which is suitable for implementation in FPGA. The architecture of the proposed system is parallel and highly pipelined, with maximum throughput of 35MSa/s. The system is suitable for batch processing of huge volume ECG data and real time applications in portable devices.

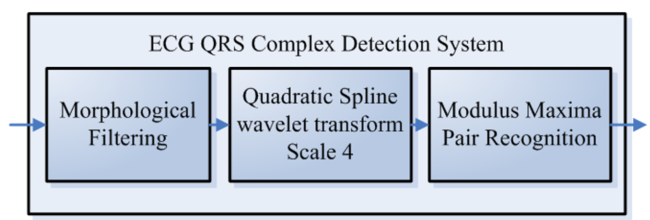

Fig. 1. Architecture of ECG QRS Complex Detection System

II. Algorithm and Implementation

A. System Architecture

The proposed system consists of Morphological filtering, Quadratic Spline wavelet transform (QSWT) and Modulus Maxima Pair Recognition (MMPR). The block diagram of the system is in Fig. 1.

B. Morphological Filtering

In this proposed system, the Mathematical Morphology operations [9]-[12] are for ECG pre-processing, which can filter high frequency noise, remove baseline wandering, enhance the QRS Complex and attenuate the P and T waves.

It employs the so-called structuring element to perform operations. The structuring elements used are shown in Fig. 2, with the names of s, $s1$, $s2$ [9].

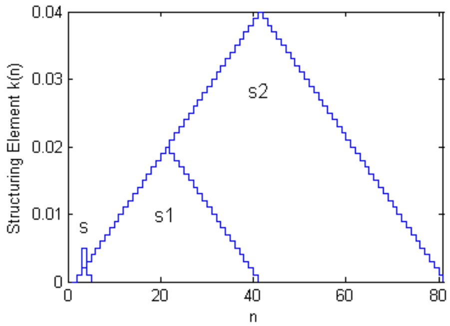

Fig. 2. Triangular structuring elements of s, s1 and s2.

The equations of Dilation operation and Erosion operation are shown in Eq. (1) and (2), respectively. In the equations, X is the sequence of signal; S is the structuring element; m is the current sample of input; L is the length of structuring element [9].

$$X \oplus S(m) = \max_{n=1,\ldots,L} \{X(m-L+n) + S(L-n+1)\} \quad (1)$$

$$X \Theta S(m) = \min_{n=1,\ldots,L} \{X(m+n-1) - S(n)\} \quad (2)$$

The Opening operation (Eq. 3) is the Erosion followed by Dilation operation, whereas Closing operation (Eq. 4) is Dilation followed by Erosion operation [9].

$$X \circ S(m) = (X \Theta S) \oplus S \quad (3)$$

$$X \bullet S(m) = (X \oplus S) \Theta S \quad (4)$$

The equation for high frequency noise filtering is Eq. (5), and equation for baseline wandering removal, QRS Complex enhancement, P and T wave attenuation is Eq. (6). Here x means the input signal; $y1$ means high frequency noise filtered signal; $y2$ is the output signal of Morphological filtering module [9].

$$y1 = \frac{(x \circ s) \bullet s + (x \bullet s) \circ s}{2} \quad (5)$$

$$y2 = y1 - \frac{(y1 \circ s1) \bullet s2 + (y1 \bullet s1) \circ s2}{2} \quad (6)$$

The hardware architectures of Dilation operation and Erosion operation of s are in Fig. 3 and Fig. 4 respectively. The architectures of Dilation and Erosion with other structuring elements are similar but with longer delay line and more levels of comparisons. The Morphological filtering module is implemented with the combination of the Dilation and Erosion operations according to Eq. (3) to Eq. (6).

C. *Quadratic Spline wavelet transform (QSWT)*

Wavelet transform is a mathematical tool for time-frequency analysis. The type of wavelet transform of the proposed system is Quadratic Spline wavelet transform. ECG waves can be mapped into modulus maxima pairs after Quadratic Spline wavelet transform. According to this property, the subsequent recognizer can recognize QRS Complex by detecting the modulus maxima pair (positive maximum negative minimum pair) in wavelet coefficients.

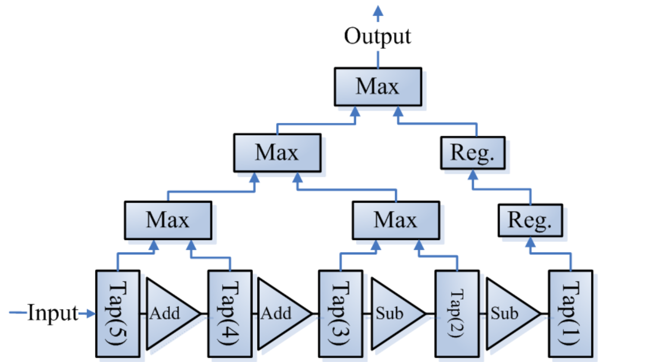

Fig. 3. Architecture of Dilation operation with s (The s is 5-sample structuring element. Here 'Reg.' means register.)

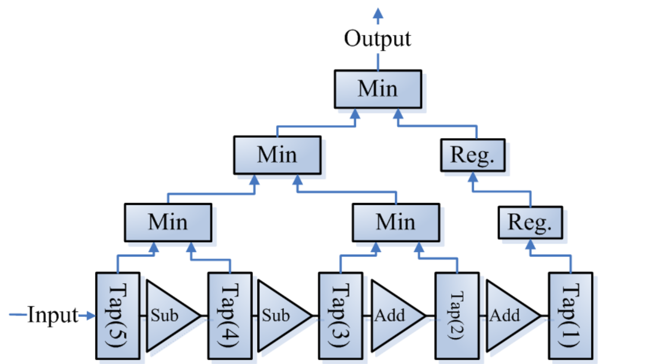

Fig. 4. Architecture of Erosion operation with s (The s is 5-sample structuring element. Here 'Reg.' means register.)

Mallat proposed the fast algorithm [13] for Discrete wavelet transform, which recursively employs decimation, highpass filter and lowpass filter for Discrete wavelet transform. The structure of corresponding filter bank of Mallat's algorithm is shown in Fig. 5. The coefficients [2]-[3] for the corresponding lowpass filter h(n) and highpass filter g(n) are shown in Eq. (7) and Eq. (8).

$$h(n) = [1/8 \quad 3/8 \quad 3/8 \quad 1/8] \quad (7)$$

$$g(n) = [-2 \quad 2] \quad (8)$$

Other than Mallat's algorithm for Discrete wavelet transform, we employ the "algorithme à trous" algorithm by replacing the decimations with inserting zeros in the coefficients of Equ. (7) and Equ. (8). It is for the translation-invariant advantage of "algorithme à trous" algorithm and the convenience for subsequent detection [4].

In this ECG QRS Complex detection system, only the scale four of wavelet transformed signal is used for detection. Thus only the filters in the path of wavelet transform scale four are implemented.

Distributed Arithmetic FIR filter architecture (DAFIR) [14] is employed for the implementation of FIR filter in FPGA. It employs no explicit multipliers in design, only Look-up-Table (LUTs), shift registers, and a scaling accumulator. Since most of calculations are replaced by reading LUTs, the DAFIR filter is feasible to provide high performance.

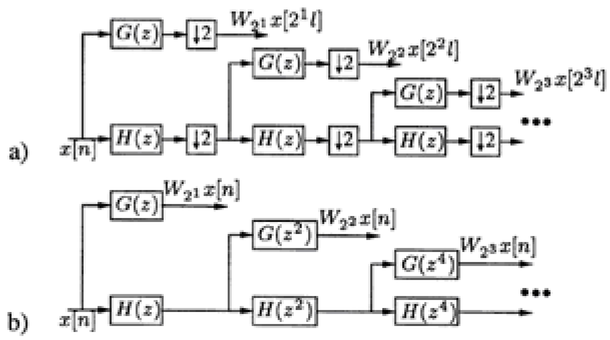

Fig. 5. Filter bank implementations of DWT. (a) Mallat's algorithm. (b) "algorithme à trous" [4]

D. *Modulus Maxima Pair Recognition (MMPR)*

The Modulus Maxima Pair Recognition module consists of two parts. In the first part, various important characteristics have to be retrieved from its input signal, the Quadratic Spline wavelet coefficients of scale 4. Three characteristics including Zero-crossing point positions, stationary point positions, and threshold values of the wavelet coefficients are retrieved.

The second part of MMPR module is implemented by a state machine. The state machine is designed with four states for modeling the shape of modulus maxima pair. The states are Seen_none, Seen_peak, Seen_zero and Seen_opposite. If the state machine finds the valid modulus maxima pair, the zero-crossing point inside the modulus maxima pair will be marked as the position of QRS Complex. Several rules are embedded in the state machine for assisting the recognition process [5].

III. Results and Discussion

The target FPGA chip for implementation of the proposed ECG QRS Complex Detection System is Xilinx Virtex™-4 SX35 with speed grade of -10. The data representation is with 17-bit fixed-point signed number of 13 bits decimal. The performance of the system is tested in the simulation in Xilinx System Generator and Xilinx ISE Foundation. Signals of the system are shown in Fig. 6, Fig. 7 and Fig. 8. In Fig. 6, it can be found that the baseline wandering is effectively removed in the Morphological filtered signal, and the QRS Complex is enhanced and the other waves are attenuated. The QRS Complex, corresponding wavelet coefficients and annotation are shown in Fig. 7. The zero-crossing point of wavelet coefficients is recognized as the position of corresponding QRS Complex. In Fig. 8, noisy ECG signal is used for testing. It can be found that the noise is attenuated by Morphological filtering and the QRS Complexes are successfully detected.

The system can be designed for performance or resource or the trade-off between resource and performance. The proposed system is designed for high performance with high throughput.

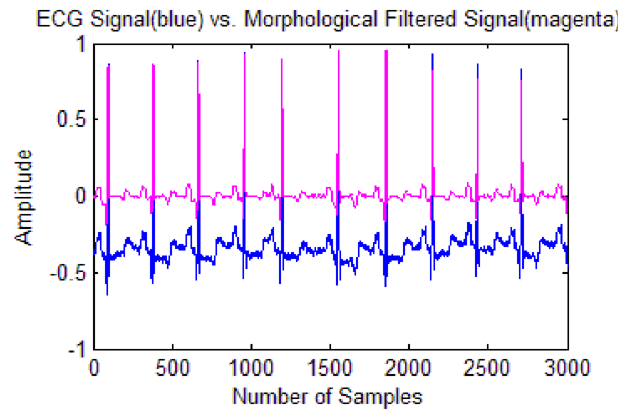

Fig. 6. ECG signal and Morphological Filtered signal

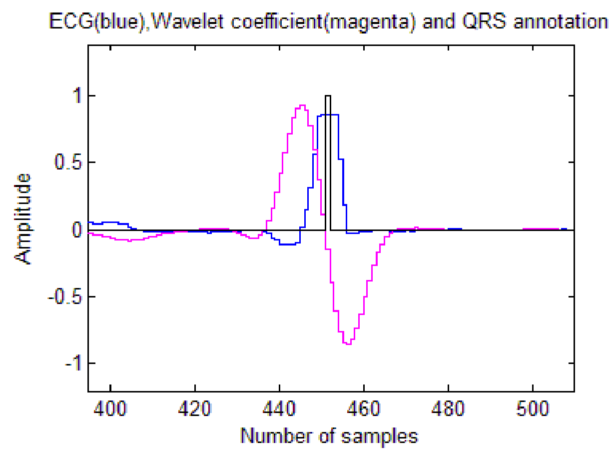

Fig. 7. QRS Complex, Quadratic Spline wavelet transform scale four coefficients and QRS Complex detection result

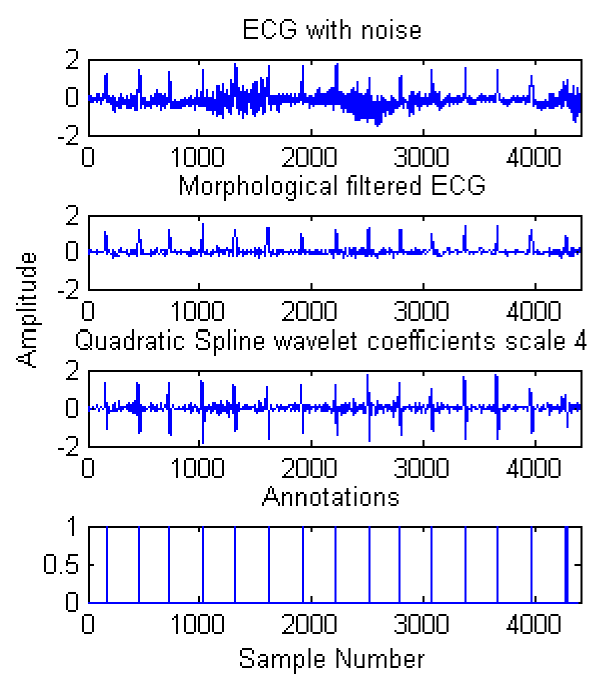

Fig. 8. Test with ECG with noise from MIT/BIH Arrhythmia database record 104.

In Morphological filtering module, the architectures of Dilation and Erosion are of importance, since the complete Morphological filtering module is consists of Dilation and Erosion operations. The architecture of Dilation operation and Erosion operation shown in Fig. 3 and Fig. 4 are fully unrolled for maximum performance. In each level of comparison, the comparison results are registered. Since the values of structuring element is successively increasing or decreasing, the value of structuring element is not directly added or subtracted from the input signal, and the constant adders and constant subtractors are placed between registers in the delay line. These are for shortening the register-to-register delay, so that to increase the maximum frequency of the circuit.

In the Modulus Maxima Pair Recognition module, the decision rule is implemented with a state machine. This is because the state machine is a sequential circuit which is convenient for modeling the decision flow. This architecture is suitable for circuit realization of the decision part. However, some complex decision mechanisms cannot be modeled with state machine in this design yet, such as the loop-back technique, because suitable architecture has not been found.

The QRS Complex detection accuracies for all MIT/BIH Arrhythmia database recordings are tested. There are totally 110,159 heart beats tested, with 2080 missed beats and 925 extra detected points. The averaged accuracy is 97.27% using the Eq. (9). The FP is the number of extra detected points; FN is the number of missed beats; TB is the number of total beats. Half of the missed beats and extra detected points are in the number 108, 114 and 222 recordings. The architecture in FPGA can detect most of QRS Complex with normal morphology. The overall accuracy of this system is higher than the accuracy of the work in [5] with averaged filter for ECG Pre-processing.

$$Accuracy = 1 - \frac{FP + FN}{TB} \tag{9}$$

The resource consumption and maximum frequency of the whole system and the components are shown in Table I. The resource consumption of Morphological filtering is relatively high, because of the architecture designed for performance and the high computation intensity of Mathematical Morphology operations.

TABLE I
RESOURCE CONSUMPTION AND MAX. FREQUENCY OF ECG QRS COMPLEX DETECTION SYSTEM

	Slices	Slice FFs	4-input LUTs	Max. Freq. (MHz)
Proposed System	14695	12960	23933	35.231
Morphological Filtering	13236	9502	21081	40.008
QSWT Scale 4	1363	2402	1537	234.577
MMPR	945	1028	1522	35.276

IV. CONCLUSION

The ECG QRS Complex Detection System has been implemented in FPGA with high system throughput. FPGA is a suitable device for implementation of computation intense algorithms.

Mathematical Morphology processing plus wavelet transform is a promising combination for ECG signal processing, for Mathematical Morphology processing can extract specific morphology in time domain whereas wavelet transform is feasible to do time-frequency analysis of signal. However, the Morphological operations and structuring elements should be carefully selected for the convenience of subsequent recognition and less computation intensity.

Using state machine for implementation of decision rules is suitable for the mechanism of FPGA. Further investigation can be done on the decision rules implementation by hardware, the algorithms suitable for hardware circuit implementation and with less resource consumption.

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