HARDWARE APPROACH OF A NOVEL ALGORITHM OF R-PEAK DETECTION FOR THE SIMULTANEOUS MEASUREMENT OF FETAL AND MATERNAL HEART RATES DURING PREGNANCY

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Key words: Field-programmable gate arrays (FPGA), Electrocardiogram, Very high speed integrated circuit hardware description language (VHDL), Digital signal processing (DSP), Fetal heart rate.

Fetal condition may change abruptly during the pregnancy period. Therefore, continuous fetal electrocardiogram (FECG) monitoring will ease the fetal well-being. An algorithm has been developed to detect R-peak for the simultaneous measurement of the fetal and maternal heart rates during pregnancy. The algorithm is based on cross-correlation, adaptive threshold and statistical properties in the time domain. The performance achieved for the R-peak detection for the heart rate measurements shows that the model can extract R-peak for both maternal and fetal utilizing a single-lead configuration. The algorithm has been implemented into Altera's Stratix EP1S10. Test case results showed an error percentage of around ±0.3% and ±0.5% for the R-peak detection of maternal and fetal respectively. The system is capable to run at a maximum clock frequency of 48.56 MHz, and consumed 9 633 logic elements.

1. INTRODUCTION

The electrocardiogram (ECG) is the electrical signal produced by the heart and contains the distinctive shape known as the QRS complex. The time between two successive R peaks of the QRS complex is known as the RR interval and the heart rate is the reciprocal of the RR interval and expressed in beat per minute (BPM). Electronic fetal heart rate (FHR) monitoring is used to determine if the fetus is free from any complications such as antenatal uteroplacental insufficiency and fetal hypoxia, and to determine the fetal health [1].

At present, Doppler ultrasound has become a popular technique of monitoring the FHR abdominally but attempts to produce a portable system have

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Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **57**, *4*, p. 432–443, Bucarest, 2012

not been successful because of its sensitivity to movements [2]. Method utilizing the abdominal electrocardiogram (AECG) has a better prospect for long-term monitoring but requires much signal processing to be done [2, 3]. This method is non-invasive and has potential to convey the electro-physiological information, which helps to determine the conditions of the fetus such as stress and acidosis, and uterine activity [3, 4]. A better single-lead method has been adopted and improved to extract the maternal and fetal QRS complexes from the AECG [5].

The Field-programmable gate arrays (FPGA) provides a potential alternative to speed up the hardware realization [6]. FPGA comes with the merits of lower cost, higher density, and shorter design cycle [7]. It comprises a wide variety of building blocks consists of programmable look-up table and storage registers, where interconnections among these blocks are programmed through the hardware description language [8]. It allows the users to easily and inexpensively realize the logic networks in hardware. FPGA also allows modifying the algorithm easily and the design time frame for the hardware becomes shorter by using FPGA [9].

In this work we proposed the framework of FPGA-based hardware realization of fetal heart rate detection algorithm. The Very High Speed Integrated Circuit Hardware Description Language (VHDL) is selected as the hardware description language, which could be used to realize the maternal and fetal QRS complex extraction to measure both the FHR and maternal heart rate (MHR). The use of VHDL for modeling is especially appealing since it provides a formal description of the system and allows the use of specific description styles to cover the different abstraction levels (architectural, register transfer and logic level) employed in the design [6]. In the computation of method, the problem is first divided into small pieces; each can be seen as a sub-module in VHDL. Following the software verification of each sub-module, the synthesis is then activated. The synthesis helps integrate the design work and provides a higher feasibility to explore a far wider range of architectural alternative [7]. In this study, to validate the effectiveness of the method, various maternal ECG have been used.

2. **METHODOLOGY**

2.1. R-PEAK DETECTION OF MATERNAL QRS

The detection of maternal QRS complexes is started with cross-correlating the signal with an average maternal QRS template (Fig. 1). The cross-correlation output of the signal $x(n)$ at each instant n with the template $s(k)$ is given by the convolution theorem (where, the impulse response is $h(k)$, $k = 0, 1, \ldots M$ signal samples):

$$y(n)=\sum_{k=0}^{M} h(k)x(n-k)\,, \tag{1}$$

where $h(k)=\begin{cases} s(M-k), & 0\le k\le M \\ 0, & \text{elsewhere} \end{cases}$.

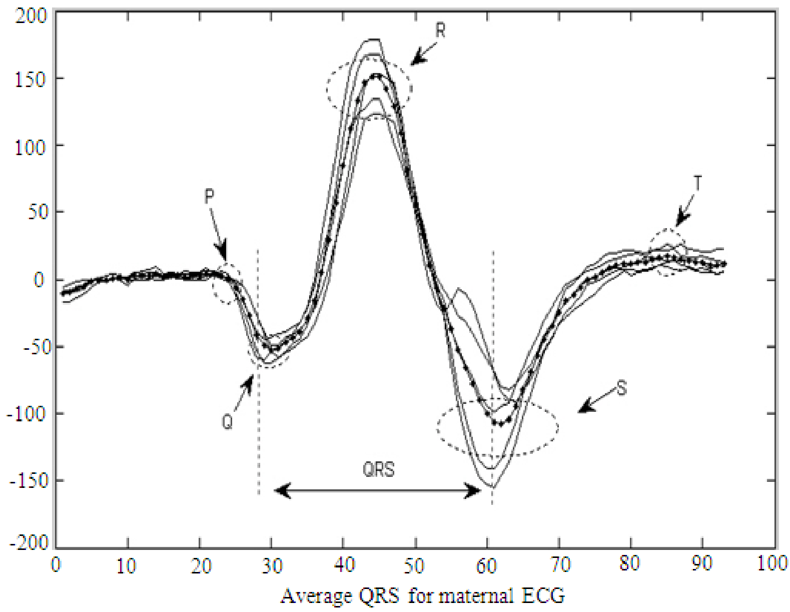

Fig. 1 – Average maternal QRS template [12].

The template $s(k)$ with $(M + 1)$ equally spaced points over 80 ms has been empirically found to be optimized for the detection of maternal QRS complexes when $M = 8$ [10]. The width of the template is based on the normal width of the maternal QRS complex [11]. The concept of the maternal average template has been described details more in our recent published article [12]. The template is continuously updated with the detection of R peaks to take into consideration the variation of shape of the maternal QRS complexes in AECG. The local maxima search routine measures the slope of the cross-correlated. The differentiated of the cross-correlated output is implemented as

$$y'(n)=y(n)-y(n-1). \tag{2}$$

Assumes a maximum at sample $(n–1)$ when the slope changes from $y'(n–1) \geq 0$ to $y'(n) < 0$. If no maximum is found in the subsequent 20 ms (assumed to be the minimum fetal QRS duration), the sample value $y(n-1)$ and corresponding instant are saved as the local maximum. This 20 ms search interval is necessary to avoid taking small spikes on the slopes of the QRS complexes as maxima.

Three local maxima (local maxima denotes by V) values, $V_{M1} > V_{M2} > V_{M3}$, and their time instants corresponding to the largest three local maxima are stored within an R wave search interval. The length of the search interval is initially one second (in fact 1024 ms for computational simplicity). The length of the R wave search interval is considered as adaptive basis and it has been updated after finding the first RR interval. In addition, this update has been determined for each beat-to-beat basis where a new RR interval has been quantified. The one-second search interval and the saving of 3 local maxima assume that the MHR does not exceed 120 BPM which means at most 2 maternal R peaks can be found in the initial search interval. If V_{M1} is validated as the R peak then the value V_{M2} is taken as the noise. V_{M3} is kept for cases when V_{M2} is validated as the R peak. The threshold used in the detection is set initially by assuming a minimum maternal R peak of 10 μV and it is continuously updated based on the levels of both R peak and noise [13]. A possible maternal R peak is assumed to be found when the value V_{M1} exceeds this threshold. V_{M2} is also considered as an R peak if the value is comparable to that of V_{M1} and the resulting heart rate is below 120 BPM, as earlier assumed. Hence the criteria:

$$2\,V_{M2} > V_{M1}\,, \tag{3}$$

$$|t_{M2} - t_{M1}| > 512\,\text{ms}. \tag{4}$$

If V_{M2} also exceeds the threshold, the QRS template is compared with the complexes associated with both V_{M1} and V_{M2}. The one with the least mean square error is taken to be the R peak. The other peak is assumed to be a spike in the signal and its position is saved for use in the fetal R peak validation routine. If V_{M2} has the larger error, its position is saved only if inequality in Eq. (3) applies, because smaller V_{M2} may be associated with an actual fetal R peak. We assumed that the smaller local maxima V_{M2} may have association with the actual fetal R peak. Therefore, if the threshold is lower than V_{M2} than it is considered that the V_{M2} is smaller. The running average used in this algorithm is performed to average the QRS templates, RR intervals, levels of R peak and noise. Assume that the b-th signal sample value of the running average; $A(b)$ is given by a weighting of the previous average $A(b-1)$ plus that of the new signal sample value i.e. $C(b)$ as shown in the following equation [10]:

$$A(b) = \{1 - k(b)\}A(b - 1) + k(b)C(b)\,, \tag{5}$$

where $k(b) = \begin{cases} \frac{1}{b}, & b \le B \\ \frac{1}{B}, & b > B \end{cases}$.

The running averages of noise and R peaks (A_N and A_R) are estimated over B recent values where, B = 8 in Eq. (5) has been empirically found to be effective. Based on these averages, two thresholds, TM_1 and TM_2 are used in the R wave search. The quantities of the thresholds are mainly depending on A_N and A_R are as follows by:

$$TM_1 = A_N + \frac{A_R - A_N}{4}, \tag{6}$$

$$TM_2 = \frac{TM_1}{2}. \tag{7}$$

The adaptation of the threshold to varying R peak and noise levels, and the R wave search interval are based on the method proposed in [14]. If the maximum search limit is reached while the local maximum V_{M1} has a value less than TM_1, then V_{M1} is taken as a possible R peak if it exceeds the second threshold, TM_2. If no such V_{M1} is found, a signal loss is assumed. The local maxima values are then set to zero for the subsequent R wave search. Four latest maternal RR intervals are maintained in record for the purpose of checking coincidences of the maternal with the fetal R waves.

2.2. R-PEAK DETECTION OF FETAL QRS

The maternal electrocardiogram (MECG) complex is then subtracted upon detection of a maternal QRS to remove the maternal contribution from the abdominal signal. This complex is of fixed duration, 160 ms before and 320 ms after the maternal R peak instant. This duration assumes that the average MHR is less than 125 BPM and it should normally include the P and T waves, if any. The MECG template is matched with actual MECG in the abdominal signal by scaling it with the factor $K = \sqrt{\frac{\text{Value1}}{\text{Value2}}}$, where Value1 < Value2.

These values are obtained from the cross-correlation of abdominal signal with maternal template and auto-correlation of the maternal ECG template. If the cross correlation is greater than the auto-correlation, then the abdominal signal is multiplied by the factor K and MECG template is subtracted, if not, MECG template is multiplied by factor K and subtracted from the abdominal ECG signal [10].

The detection of the fetal QRS complex is begun with differencing of local maxima and minima on the output of the subtracted signal when the time marker count, which was initiated at the second accepted maternal R peak, has reached 2 048 ms [15]. This duration ensures that the 2 second delayed samples are already within the MECG subtracted region of the signal. As the fetal ECG amplitude is quite smaller than the MECG amplitude and sometimes due to the noise in the AECG signal, it might be possible that the noise and fetal ECG has similar amplitude. However, our proposed algorithm is able to differentiate even the noise and fetal ECG amplitude is similar in magnitude (Fig. 3).

This is partly because of the rapid and large deflections between a local maximum and the following local minimum when a fetal beat has occurred. From Eq. (2), a minimum is assumed at sample (n–1) when the slope changes from $y'(n-1) < 0$ to $y'(n) \geq 0$. The absolute value of the difference between successive peak and valley is computed for each max-to-min interval.

The local maxima search routine is performed on the output of the differencing of local maxima and minima routine as denoted by V_F, and three largest maxima, $V_{F1} > V_{F2} > V_{F3}$ are kept as before. The initial search interval is 640 ms so that at most two fetal R peaks can be found by assuming the FHR does not exceed 187 BPM during the initial search interval. The first search is repeated for another subsequent 640 ms if the largest local maximum V_{F1} is concurrent with a maternal QRS complex and V_{F2} is smaller than a threshold or is also concurrent. The threshold used in the FHR detection is set initially by assuming a minimum fetal R peak of 5 μV and it is continuously updated [13]. The routine is similar to that for the maternal case but uses the criteria to accept V_{F2} as a possible fetal R peak:

$$1.5V_{F2} > V_{F1}\ , \tag{8}$$

$$|t_{F2} - t_{F1}| > 320\ \text{ms}. \tag{9}$$

The second search is repeated if the accepted first fetal R peak is found to be concurrent with a maternal QRS complex or if $2V_{F3} > V_{F1}$ i.e. the signal is noisy with all its three local maxima having comparable values. The fetal and maternal QRS complexes are concurrent if $|t_F - t_M| < 64\ \text{ms}$, where t_F and t_M are the fetal and maternal R peak instants, respectively. The range in this equation accounts for possible overlap of the two complexes, which are assumed to have widths of 50 and 80 ms respectively. The overlap is checked by relating the fetal R peak instant to the four latest maternal RR intervals.

The subsequent fetal R wave detection procedure is the same as that for the maternal R wave using two thresholds, TF_1 and TF_2, which are set as in Eq. (6) and Eq. (7), according to the running average of the R peaks and noise with B = 8 in

Eq. (5). The determination of the fetal R wave search interval is also based on the method proposed in [15]. The second threshold, TF_2 is used when the maximum search limit is reached. A signal loss is assumed when no maximum exceeding the threshold. When the 2nd threshold identify a fetal *R* peak, the peaks are averaged with $B = 4$ so that the first threshold will quickly adapt to the smaller signal.

After a possible fetal R wave is found, a continuation of the search for up to 220 ms is carried out unless the maximum search limit is reached. This forward searching reduces the possibility of false *R* wave detection with the assumption that the heart rate does not exceed 270 BPM. Then the program branches to the validate and update routines. The validation routine first checks if $V_{F3} > TF$ and $1.5V_{F3} > V_{F1}$, where TF is the threshold used to detect V_{F1}. These conditions mean that the fetal *R* peak was obtained in a very noisy signal. Otherwise, similar checks are made with V_{F2}, where $V_{F2} > TF$ and $1.5V_{F2} > V_{F1}$ also imply a noisy signal.

If V_{F1} is the only maximum above the threshold then it is taken as a fetal *R* wave. If V_{F2} also exceeds the threshold, then V_{F1} is checked for coincidence with possible spikes by relating its instant to the four maternal values which were kept in the record. The spike position, t_S and the position, t_{F1} in the signal associated with the local maximum, are compared for $|t_S - t_{F1}| < 40$ ms which allows for the difference in correlation delay when obtaining t_S and t_{F1} respectively. If V_{F1} is identified as a large spike in the signal, then V_{F2} and V_{F3} are assumed to be the fetal *R* peak and the noise, respectively.

Thresholds and search interval limits are updated according to the procedure described earlier and the local maxima values are then set to zero for the subsequent R wave search.

2.3. SYSTEM REALIZATION IN HARDWARE

The QRS detection algorithm was initially implemented in Visual C++ because it is simpler and faster to verify the functionality and reliability. Then, the algorithm was implemented in VHDL; where Altera's Quartus II version 4.0 is used as the platform. Fig. 2 shows a simplified block diagram of the implementation of the system. Basically, the system is categorized into three main sections, the common, maternal and fetal sections. The pins for the system PIN_NEWDATA, PIN_DATA and PIN_DATAREQ are used to interface with an external module to retrieve new data. When the system is done, PIN_RB_RE, PIN_RB_RADD and PIN_RB_RDATA are used to access the DPRAM to retrieve the stored maternal and fetal RR interval results from their corresponding memory segment.

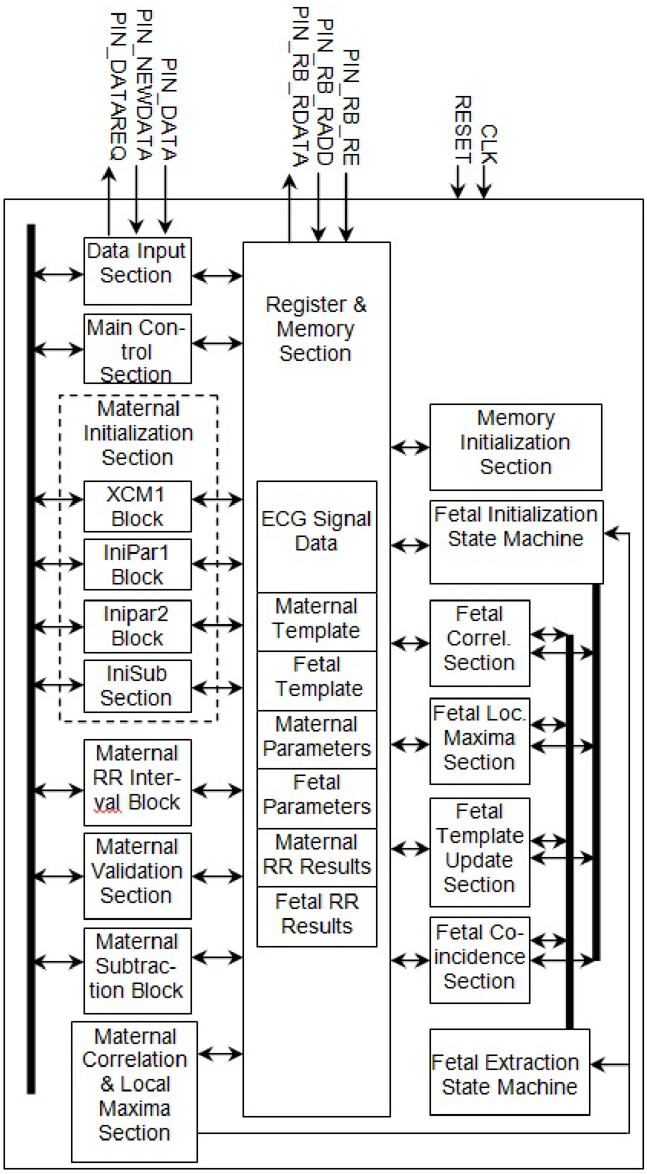

Fig. 2 – Top level block diagram.

3. RESULTS AND DISCUSSION

The result in Table 1 using Visual C++ shows encouraging results with the test case, where the fetal *R* peak could be detected up to 98 %. Upon completion of the test case simulation using VHDL, the system performs a read request to retrieve all the maternal and fetal results. A sample read operation for maternal and fetal *R* peaks detection is shown in Fig. 3 with the initial 4 900 sample data. In this figure, *some arrows indicate* the missing *R* peak in the corresponding beat between 10 and 11as well as after 15 beat in the fetal ECG. In addition, *other arrows refer* the corresponding beat in maternal and fetal ECG. The Quartus simulation result shows that the VHDL models are functioning almost similar to the Visual C++ function.

The results for both versions are shown in Table 2. Comparing the maternal and fetal *RR* interval values (in terms of number of samples between the intervals), the maternal error is consistently less than 0.3 %, and the fetal error percentage is within 0.5 %. All the differences are caused by the rounding effect during computation. However, when a fetal peak loss happens, an error rate up to 4 % might be occurred, owing to slightly different search limit implemented in the VHDL. Despite this, the VHDL interpretation of the system displays great similarities to the Visual C++ version.

Table 3 shows the resources consumed during compilation to fit the system into an Altera's Stratix EP1S10 device. The Digital Signal Processing (DSP) units are used for the implementation of the accumulator and multiplication between the signal and template points for both the Fetal and Maternal Correlation Block.

Table 1

Test simulation using Visual C++

Description		Value
Maternal	Total R peak	164
	Detected	164 (100 %)
Fetal	Total R peak	235
	Detected using first threshold	182 (77 %)
	Detected using second threshold	5 (02 %)
	Coincidence	46 (19 %)

Table 2

Comparison between VHDL and Visual C++ results detecting number of maternal RR intervals

Sample No.	Maternal RR Intervals		% Diff	FETAL RR Intervals		% Diff
	VC++	VHDL		VHDL	VC++	
1	297	297	0%	194	194	0 %
2	299	299	0%	197	197	0 %
3	301	301	0%	195	195	0 %
4	295	295	0%	197	198	0.5 %
5	296	297	0.3%	197	196	–0.5 %
6	294	293	–0.3%	198	199	0.5 %

7	297	297	0%	196	195	–0.5 %
8	292	292	0%	201	201	0 %
9	299	298	–0.3%	197	197	0 %
10	296	295	–0.3%	312	323	3.5 %
11	296	295	–0.3%	290	279	–3.8 %
12	290	291	0.3%	212	213	0.5 %
13	289	288	–0.3%	190	189	–0.5 %
14	290	291	0.3%	201	201	0 %

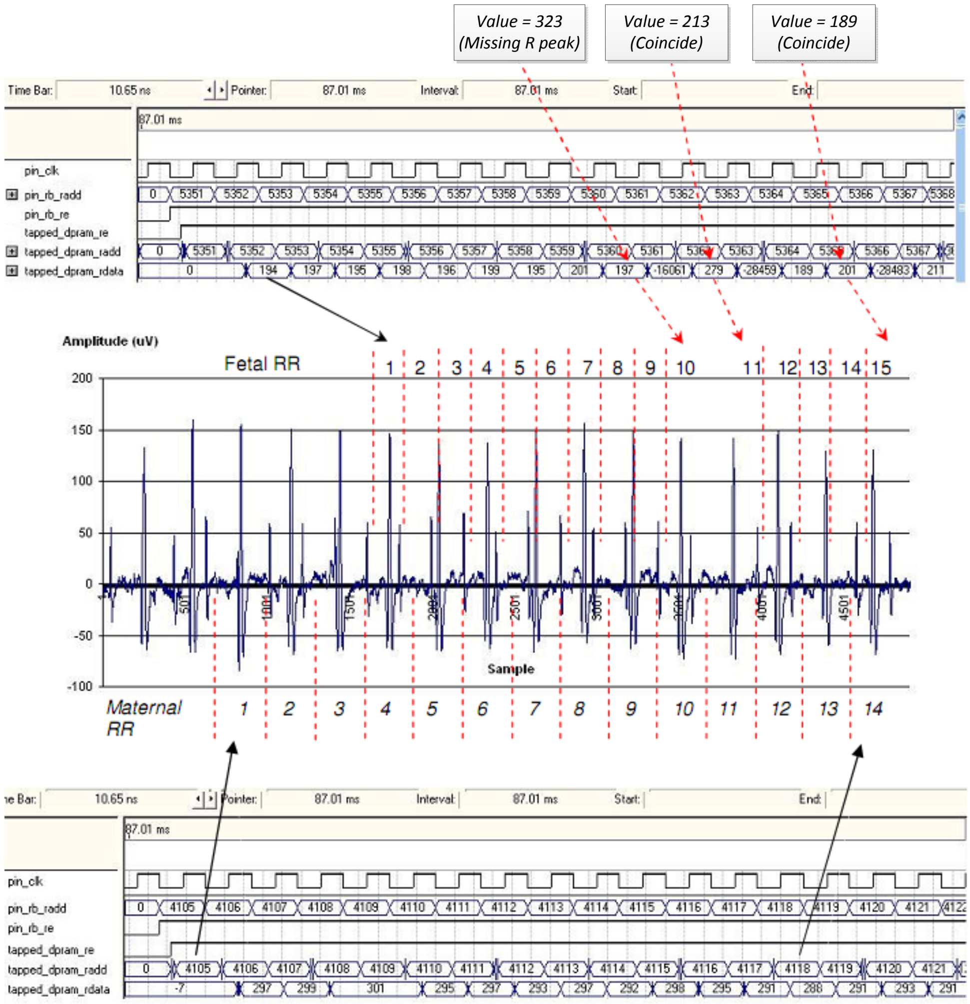

Fig. 3 – *R* peak detection of maternal and fetal heart rates with 4 900 data.

Table 3

Summary of resource fitting

Description	Total
Device	EP1S10F780C5
Netlist Size	10376 Nodes
Usage	9,633/10,570 (91 %)
Total Memory Bits	101,616/920,448 (11 %)
DSP Blocks	4/48 (08 %)
Total Pins	346/427 (81 %)

5. **CONCLUSIONS**

The performance achieved for the heart rate measurements from the AECG shows that the hardware model can extract *R*-peak separately for maternal and fetal ECG. In addition, the proposed model may be suitable for a single-lead configuration of ECG measurement. The result using Visual C++ shows that the fetal *R* peak can detect with accuracy up to 98%. Test case results also show an error percentage of around ±0.3% and ±0.5% for the *R*-peak detection of maternal and fetal respectively, with a maximum clock frequency of 48.56 MHz.

In conclusion, we have considered some algorithms, which has already been used in biomedical signal processing and we have used that algorithm here to do the signal processing. In addition, we have implemented the algorithm in FPGA and found almost same results, which shows the proof of the claim.

Received on November 29, 2011

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