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Development of an Efficient Algorithm for Fetal Heart Rate Detection: A Hardware Approach

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Abstract: - An algorithm has been developed for the simultaneous measurement of the fetal and maternal heart rates from the maternal abdominal electrocardiogram during pregnancy and labor for fetal monitoring. The algorithm is based on cross-correlation, adaptive thresholding and statistical properties in the time domain. The algorithm was initially developed and simulated in Visual C++. Once the functionality is verified, it is then converted in VHDL - hardware description language for FPGA implementation. The design is synthesized and fitted into Altera's Stratix EP1S10 using the Quartus II platform because of its enhanced DSP capability. Test case results showed an error percentage of around ±0.3% and ±0.5% for the detection of maternal and fetal heart rate respectively.

Key-Words: - Fetal Heart Rate, Electrocardiogram, VHDL, FPGA

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 (HR) 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]. Continuous efforts are being made to produce more efficient and accurate methods to extract the fetal RR interval, and gain a better interpretation of the FHR patterns by researchers.

At present, Doppler ultrasound has become a popular technique of monitoring the FHR abdominally but attempts to produce a portable system have 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]. A better single-lead method [4] has been adopted and improved to extract the maternal and fetal QRS complexes from the AECG.

2 Methods

2.1 Maternal QRS Detection

The detection of maternal QRS complexes is begun with cross-correlating the signal with an average maternal QRS template. The cross-correlation output of the signal *x* at each instant *n* with the template *s(k)* is given by

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

where

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

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 $M = 8$. The width of the template is based on the normal width of the maternal QRS complex [5]. 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 output by

$$y'(n) = y(n) - y(n-1) \qquad \ldots (2)$$

and 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 [6]), 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 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) and it is then continuously updated after the first RR interval measurement. The one-second search interval and the saving of 3 local maxima assume that the maternal heart rate (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 [6] and it is continuously updated based on the levels of both R peak and noise. 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:

$$2V_{M2} > V_{M1} \quad \text{…. (3a)}$$

and

$$|t_{M2} - t_{M1}| > 512\, ms \quad \text{…. (3b)}$$

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 large 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 Equation (3a) applies, because smaller V_{M2} may be associated with an actual fetal R peak.

The running average used in this algorithm is performed to average the QRS templates, RR intervals, levels of R peak and noise. The b-th value of the running average $A(b)$ is given by a weighting of the previous average $A(b-1)$ plus that of the new value $C(b)$ as shown in the following equation:

$$A(b) = \{1 - k(b)\}A(b-1) + k(b)C(b) \quad \text{…. (4)}$$

where

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

The running averages of noise and R peaks (A_N and A_R) are estimated over B recent values where, B = 8 in Equation (4) 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. They are given by

$$TM_1 = A_N + \frac{A_R - A_N}{4} \quad \text{…. (5a)}$$

$$TM_2 = \frac{TM_1}{2} \quad \text{…. (5b)}$$

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 [7].

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 Fetal QRS Detection

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,

$$K = \sqrt{\frac{Value1}{Value2}} \quad \text{… (6)}$$

where, $Value1 < Value2$. These values are obtained from the cross-correlation of abdominal signal with maternal template and auto correlation of the maternal template. If the cross correlation value is greater than the auto correlation value, 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.

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 2048 ms. This duration ensures that the 2 second delayed samples are already within the MECG subtracted region of the signal. Observing the waveforms, it is possible to differentiate between fetal events and noise even if the amplitudes are similar. 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 Equation (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, 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 [6] and it is continuously updated. The routine is similar to that for the maternal case but uses the following criteria to accept V_{F2} as a possible fetal R peak:

$$1.5V_{F2} > V_{F1} \quad \text{.... (7a)}$$

and

$$\left| t_{F2} - t_{F1} \right| > 320\ ms \quad \text{.... (7b)}$$

The second search is repeated if the accepted first fetal R peak is found to be concurrent with a maternal QRS complex or if

$$2V_{F3} > V_{F1} \quad \text{.... (8)}$$

i.e. the signal is noisy with all its three local maxima having comparable values. The fetal and maternal QRS complexes are concurrent if

$$\left| t_F - t_M \right| < 64\ ms \quad \text{.... (9)}$$

where t_F and t_M are the fetal and maternal R peak instants, respectively. The range in Equation (9) 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 Equation (5), according to the running average of the R peaks and noise with B = 8 in Equation (4). The determination of the fetal R wave search interval is also based on the method proposed in [7]. 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 is found. When the second threshold is used to 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 validate routine first checks if

$$V_{F3} > TF \quad \text{.... (10a)}$$

and

$$1.5V_{F3} > V_{F1} \quad \text{.... (10b)}$$

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

$$V_{F2} > TF \quad \text{.... (11a)}$$

and

$$1.5V_{F2} > V_{F1} \quad \text{.... (11b)}$$

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 are 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

$$\left| t_S - t_{F1} \right| < 40\ ms \quad \text{.... (12)}$$

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 Hardware Implementation

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. As a result, for VHDL implementation the algorithm has to be thought of as a structural, behavioral and physical version of the algorithm. The advantage of using Quartus II is that the system could be synthesized into a physically available FPGA, or the built-in simulation device models. The built-in simulation device models emulate the real device with the actual timing and power values. Thus, its performance in terms of timing, speed, power consumption, total logic element counts and functionality could be ascertained. Modifications can be easily performed and its impact to the physical implementation, especially in terms of timing and functionality can be immediately known.

Fig. 1 shows a simplified block diagram of the implementation of the system. Basically, the system is categorized into three main blocks, the common, maternal and fetal blocks. The common blocks, shared by both maternal and fetal blocks are the Data Input Block, Memory Register Block, Memory Initialization Block and Main Control Block. Maternal blocks consist of the Maternal Initialization Blocks (XCM1 Block, Inipar1 Block, Maternal Inipar2 Block and IniSub Block), Maternal RR Interval Block, Maternal Validation Block, Maternal Subtraction Block and Maternal Correlation & Local Maxima Block. Fetal blocks consist of Fetal Initialization Block, Fetal Extraction Block, Fetal Correlation Block, Fetal Local Maxima Search Block, Fetal Template Update Block and Fetal Coincidence Block. 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.

3 Results and Discussion

3.1 Simulation Results and Comparison

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.

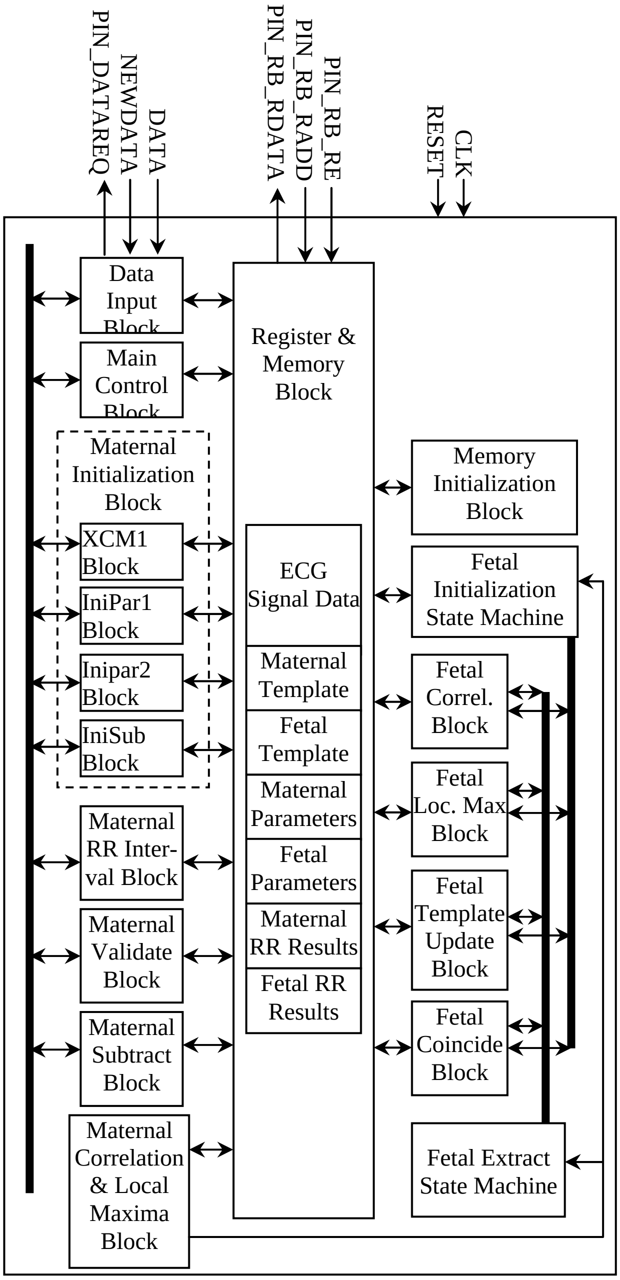

Fig. 1: Top Level Block Diagram

Table 1: Visual C++ Test Case Simulation Results

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%)

A sample read operation for maternal and fetal R peaks detection is shown in Fig. 2 with the initial 4900 sample data. 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 and 3. 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 2: Visual C++ versus VHDL Results for Maternal RR Interval

No	RR Interval (Number of Samples)		% Diff.
	VC++	VHDL	
1	297	297	0%
2	299	299	0%
3	301	301	0%
4	295	295	0%
5	296	297	0.3%
6	294	293	-0.3%
7	297	297	0%
8	292	292	0%
9	299	298	-0.3%
10	296	295	-0.3%
11	296	295	-0.3%
12	290	291	0.3%
13	289	288	-0.3%
14	290	291	0.3%

4 Conclusion

The performance achieved for the heart rate measurements from the AECG shows that the model can extract both maternal and fetal heart rates utilizing a single-lead configuration. The single-lead feature is desirable from the comfort point of view of the patient especially when the duration of monitoring is long.

Table 3: Visual C++ versus VHDL Results for Fetal RR Interval

No	RR Interval (Number of Samples)		% Diff.
	VC++	VHDL	
1	194	194	0%
2	197	197	0%
3	195	195	0%
4	197	198	0.5%
5	197	196	-0.5%
6	198	199	0.5%
7	196	195	-0.5%
8	201	201	0%
9	197	197	0%
10	312	323	3.5%
11	290	279	-3.8%
12	212	213	0.5%
13	190	189	-0.5%
14	201	201	0%
15	188	189	0.5%

Some improvements to the R peak detection capability of the algorithm would be expected with enhanced procedures such as the normalization of the cross-correlation outputs and variable MECG complex duration to take into account for cases when the MHR exceeds 125 BPM. The sensitivity of the algorithm to motion artifacts and muscle noise may also be reduced with the incorporation of more rules in its RR interval validation schemes. As expected, a favorable FECG’s signal-to-noise ratio is a definitive enhancement in future research. An interesting direction for future research is to compare the outcome of clinical diagnosis based on FHR/MHR determination using our system to FHR determination by ultrasound. Another area for further investigation could be the case of twins’ resolution by AECG. When fully developed, such a system will be a useful tool in the assessment of the fetal condition and its relationship to that of the mother’s.

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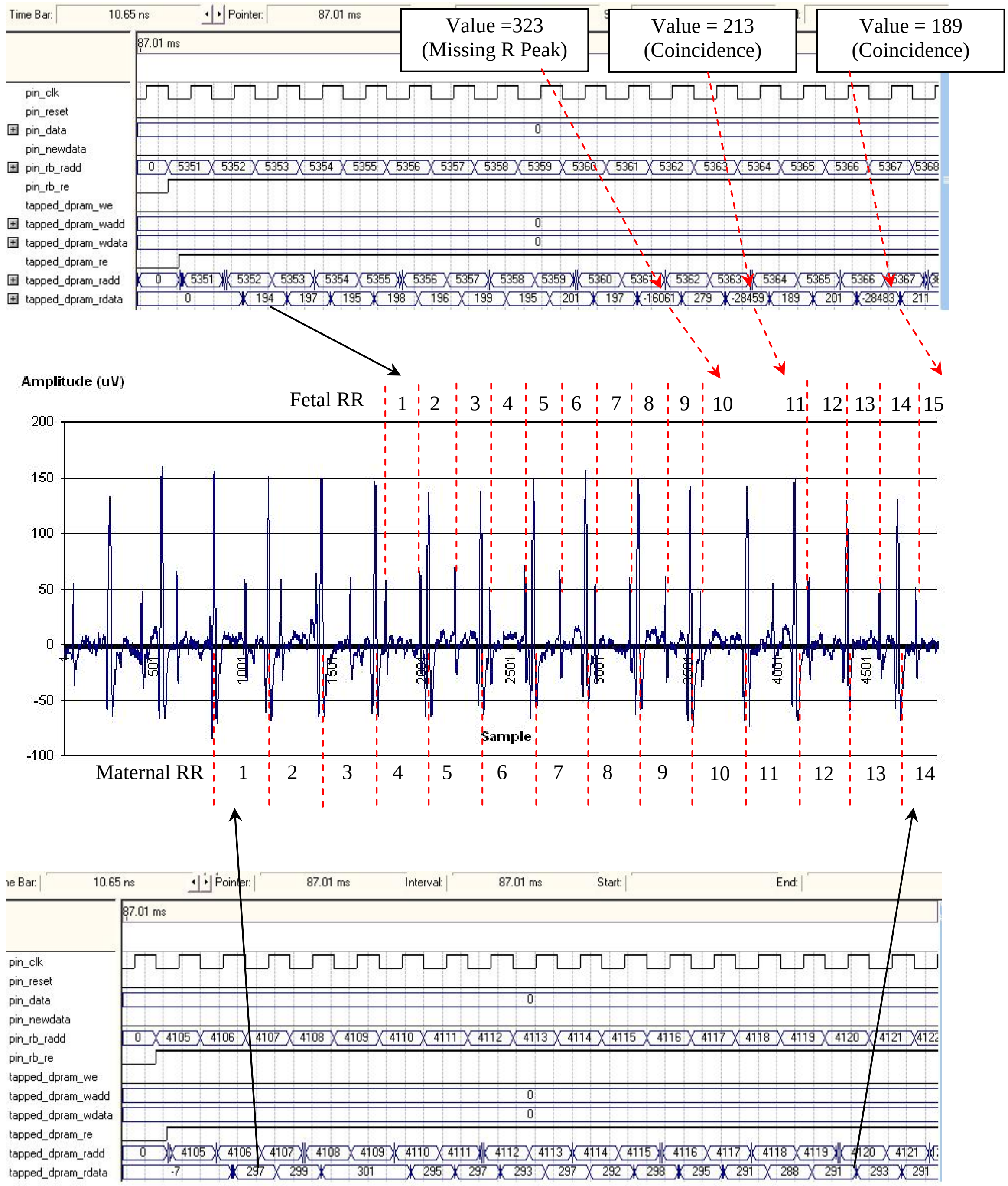

Fig. 2: A Sample Result of Maternal and Fetal R-peaks Detection (data: 1-4900).

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