Recent Advances in Non-invasive Processing Schemes on Electrocardiogram (ECG): a Review

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Abstract

Non-invasive processing schemes on electrocardiogram (ECG) especially fetal ECG, represent technical advantages such as cohesive monitoring, explicit signaling and imaging, free of uterus infection comparing to traditional invasive methods. We concisely summarize the recent progress of methods in non-invasive detection and compression on ECG, then categorize the crucial sample datasets and major types of experimental design in the review sections. Algorithms and implementation of test platform on compression of ECG data and fetal health monitoring in practical systems design are simultaneously studied therein. Our study specifies that recent advances in this area lie in sparse representation, variable filtering techniques, multi-resolution feature extraction and a few other joint schemes. We also sketch a framework of portable system design on fetal ECG monitoring with specific choice on the elements of hardware configuration in the discussion section.

***Keywords*:** Non-invasive processing, detection, compression, electrocardiogram (ECG).

1. Introduction

Non-invasive processing on electrocardiogram (ECG) [1]-[8], [10]-[13], [16]-[21] display one of the most promising schemes in biomedical signal processing and medical imaging. In contrast to other conventional invasive methods, technical merits of non-invasive ECG detection [19] had been recognized as free of pain and infection, no time limits and hence easy, convenient and acceptable to patients, while the accuracy and stability urge great enhancement; meanwhile, cost of complicated devices and computational complexity on non-invasive detection are within the concern of practical realization. Several other schemes such as infrared detection, implantable monitoring, are also in parallel developments among recent investigations, which had been supporting the minimal invasive schemes on ECG processing, especially fetal ECG detection.

Keynote indices such as fetal ECG extracted from maternal ECG and fetal heart rate (FHR) [9], [14], [15], are critical for pregnancy diagnosis and biomedical research study. Classical non-invasive schemes [4], [19] such as adaptive noise cancellation, spatial filtering and independent component analysis (ICA), singular value decomposition (SVD), particle swarm optimization (PSO), illustrated both advantages and shortcomings in processing ECG data: those schemes and their combinations overcame challenging issues in replacing of invasive schemes, while typical weakness lies in the sensitivity of fetal locations and maternal movements, P/T wave extraction with baseline wandering and complete accuracy of ECG diagrams [19]. In the latest few years, several methods have been proposed by scholars within latest investigation [17], [19], which can be categorized as follows: the variations derived from extended Kalman filtering (EKF), sparse representation based schemes, and semi-blind anti-convolutional source separation applied in multi-channel data acquisition. These algorithms enriched the methodology on non-invasive detection and promoted theoretical progress on weak signal extraction in the related fields and their biomedical applications. Meanwhile, recent schemes on ECG monitoring and clinical diagnosis, are dedicated to balancing a specific system design with theoretically predicted technical advances in the sketched framework for practical use.

The remainder of this paper is structured as follows. In Section 2, we enumerate the published keynote schemes on non-invasive ECG processing in the latest five years. In Section 3, we concisely introduce typical design on ECG-based experiments in accordance with the involved datasets. Brief analysis on the results in accordance with technical advantages and their limitations are established in Section 4. The last Section 5 provides summary of our work and draws the conclusions.

2. Review of Recent Advances in Non-invasive ECG Processing Schemes

Significant achievements on non-invasive ECG detection and compression had been established over several decades, while a variety of the state-of-the-art techniques displayed respective merits in the past few years. In this section, we present a brief review of crucial non-invasive schemes on ECG processing (posterior to Year 2013 upon publishing), which are presented as follows:

An algorithm on automated fetal QRS detection [1] was derived with the Challenge 2013 database [2], where signals were

acquired from maternal abdominal ECGs and professional annotations on QRS locations. Free of measuring fetal QT intervals, this method was validated by participating in the events of fetal heart rate and fetal R-R interval measurements, where the former was annotated to generate FHR time series in contrast to their reference, and the latter was annotated to create the R-R interval time series in accordance with the FHR time series. This algorithm consists of steps such as subtracting averaged maternal ECG, detecting maternal QRS, fetal QRS and correcting their event series. It aimed to achieve better measurements on the quality of fetal QRS detection, while experiments present event-based work and predicted better results on sequence-based scheme.

Contemporary work on non-invasive fetal ECG with the focus of the same dataset (PhysioNet / Computing, Challenge 2013 [2]) included research concerns from multiple teams on efficient FECG extraction, which exploited non-invasive techniques towards decent removal of maternal component. The proposed schemes had extensive inclusions such as subspace decomposition or high-order data reconstruction, wavelet denoising and a few fusion schemes [3]. Meanwhile, collaborative work on fetal QRS detection indicated fast developments, i.e., entropy or R-S slope based scheme, combining source cancellation with expectation-weighted estimation, using echo state neural network (ESN) or merging fusion methods, where these schemes photographed progress in technical domain of weak signal detection. Similarly, besides a survey of prior approaches on non-invasive FECG extraction, Ref. [4] not only specified the benchmark of these methods with identical database and test set-up, but also displayed possible improvements combined with different schemes through quantitative evaluations, where the FUSE method (combining a subset of various source separation schemes) discussed in [4], had better performance comparing to all other individual methods using the same data on the training sets. Limitations on the Challenge set such as shortage of simultaneous signal acquisition and pathological cases, absence of chest ECG as well as error presence in some reference annotations, were also specified when concerning future supplements. In 2014, when Challenge 2013 had been issued with public access, the review study from Clifford *et al*. [6] summarized five steps in general process of FECG estimation: pre-processing, estimation and removal of maternal component, evaluation of FHR and *R-R* interval on time series, and the post-processing for noise reduction. Technical challenges called for the construction of larger database, annotated dataset with expected labeling for ST segments and QT intervals including normal and pathological cases, significant analogs on adult measures of abnormality in fetal population adjusted for gestational age [6]. Limitations on the difficulties in applying non-invasive FECG extraction algorithms to earlier stage of pregnancy [6], [7], had been referred in both Challenge set and other sets of clinical data.

The second focus on non-invasive FECG detection put emphasis on non-linear system modeling. A basic example was established as combining multi-variate wavelet tools with neuro-fuzzy systems, which was diagramed as generating two ECG signals with the aid of two leads. Inspired by similar understandings, comparison of single channel non-invasive FECG extraction scheme was performed in [5], where both qualitative and quantitative

analysis were displayed therein: after pre-processing for baseline wander and high-frequency removal, adaptive filters such as LMS, RLS and ESN were designed along with parameter optimization via exhaustive grid search on a training database [5], where the main contribution of this work comprises demonstration of mild superior performance on ESN compared to LMS, RLS and template subtraction techniques, performance improvement on FECG extraction schemes by adopting high baseline wander cut-off frequency, and excluding poor quality chest ECG from signal quality indices (SQI). The framework on performance assessment of the assembled algorithms on fetal QRS extraction and FHR, was also sketched by adopting the measures of F_1 (average F-score) and HR_{m} (extracted FHR to match the reference of FHR within ±5 heartbeats in the scale of percentage) [5]. Another supporting vector regression based approach [11] was realized by modeling non-linear transformation of ECG signals from abdominal to thoracic locations, which qualitatively displays stronger capabilities in both nonlinear analysis and FECG extraction effects in contrast to linear ICA-based models.

Besides the performance comparison of multiple non-invasive schemes, innovative study made significant progress on algorithmic modeling. A combination of signal processing techniques was proposed in [7], displaying kernel design of extended Kalman smoothing (EKS) and template adaption combined with a detection scheme in presence of evolutional computing. The detection process considered periodical and geometric features of fetal signal in time domain, while estimating kernel density and calibrating heart rates, were jointly used for signal channel detection in the final step of post-processing [7]. On the contrary, compensating systematic effects such as inter-channel deterministic time offsets in order to sustain the performance of spatial temporal filtering (STF) schemes for FECG signal enhancement, indicated contribution towards pre-processing [8], where the practical implementation was also suggested by using a portable multi-channel device on trans-abdominal FECG monitoring, which had been trialed for clinical promotions. Regarding to fetal heart detection, several Chinese scholars proposed an integrated scheme [9] by collaborating first-order difference operation, Hilbert transform and non-linear state-space projections to obtain the envelope of fetal heart beats after removing maternal components, which had been validated from trials on real mixed ECG data. Meanwhile, another single-channel based FECG extraction scheme proposed by Panigrahy and Sahu [10], adopted the extended state Kalman filtering and adaptive neuro-fuzzy inference system (ANFIS), verifying effectiveness of capturing FECG component at different noise levels. Most notably, the proposed model in [10] was tested for both real abdominal ECG recordings and synthetic dynamic ECG data in single-channel case. The proposed model in [10] claimed detection accuracy and viability on extension to further study related to multi-fetal ECG extraction.

In comparison to single-channel based ECG processing, several extraction techniques from multi-channel input system [12]-[14], [17] symbol for more complicated scenes. Ref. [12] presented a hybrid multi-stage adaptive filtering scheme with singular value decomposition (SVD) on cancelling maternal ECG and noises, which displayed more effectiveness on performance other than classical non-invasive detection schemes. The

theory of compressive sensing provided a strong mathematical tool on spare representation for two-dimensional signals, where the original framework as validated on two public datasets, had been introduced for joint detection / classification of mixed abdominal recordings and ECG compression [13], offering feasible plans for real-time weak FECG monitoring. Meanwhile, low-complexity schemes on detecting fetal movements had also been presented, which relies on variations in the amplitude of fetal QRS complex from abdominal recordings [14]. This scheme displays improvement comparing to a few state-of-the arts by tracking information changes of the fetal cardiac vector from calculating variations in the amplitude and shape of fetal QRS-wave, provides reliable registration of fetal movements from bipolar abdominal ECG leads, where the proposed algorithm reduced computational complexity and prospected feasibility on early detection of fetal motility variations and ambulatory detection of fetal movements [14]. Moreover, regarding to the fact that increasing the number of channels may significantly improve the correct rate of *R*- wave detection in condition of multi-channel abdominal ECG inputs, Ref. [17] derived a fusion method in contrast to two ICA-based maternal *R*-wave peak detection schemes, where the proposed algorithm showed promising results on the robustness and accuracy of *R*-wave detection for multi-channel maternal ECG. Another posterior work to [17] was the derivation of a method on separation of dual-channel maternal abdominal ECG via selecting diffusion-based channels [20], where the two-lead FECG algorithm (coined as SAVER) includes performing maternal ECG estimation via iterating the dsSTFT and non-local median method after noise suppression, followed by the FECG estimation via similar approaches of estimating maternal ECG after channel selection. As validated via two public datasets, the crucial part of this scheme lies in applying both lag map and diffusion map on the rough FECG signals then selecting their corresponding optimal linear combination [20].

Recent investigation towards non-invasive fetal health monitoring [15], [16], [18], [21] represents another branch of study in this research field, where major concerns are oriented in practical system implementations. A real-time FECG monitoring system with Android platform design was sketched in [15], where the proposed non-invasive algorithm relies on Seismo-cardiography to measure the mechanical activity of hearts, and quantitative results indicates applicability on real-time continuous unobtrusive cardiac, smartphone cardiography as well as wearable devices on medical applications [15]. Ref. [16] established the circuit design for a noise-reconfigurable resistive feedback amplifier, which enables tuning of the noise level and alternating power consumption in accordance with the characteristics of signals, then minimizing the consumption of total power, while the technique of current-reuse satisfies the requirements of viable applications [16]. A survey of the current standards in fetal monitoring was presented in [18], which specified that superior information was provided by fetal phonocardiography (FPCG) comparing to other techniques, where the developing schemes on data collection and data acquisition suggest promising trends on fetal health monitoring [18]. Considering possible fetal hypoxia urges detection and reliable diagnosis during labor and delivery, a

non-invasive medical instrumentation system on FECG extraction was configured in [21], where the utilization of 3D optimization graphs on cost functions of the LMS and RLS algorithms for multiple combinations of bio-electrode positions suggests safety and cost-efficiency. The developed scheme offers broader extensions to other non-linear processing systems on fetal health monitoring, while a major weakness was specified as dependence on the reference maternal ECG signals [21].

Due to the huge amount of data acquired in real-time of monitoring, compression of ECG data represents another aspect of research investigation. Regarding to the maternal ECG compression, a joint scheme of principle component analysis (PCA) with compressive sensing was presented in [22], where PCA played the role of de-correlating 12-channel ECG signals and obtain the clinical features in signals with lower dimensional eigenspace. This scheme utilized random projection on sparse eigenspace signals towards sparse binary sensing matrix to realize compressed measurements [22]. Quantitative evaluation on maternal ECG datasets with pathological, noisy and normal cases was displayed by means of the distortion measures in both clinical and non-clinical scales, where the proposed scheme exhibits higher compression efficiency at mild cost of increased computational complexity, and prospects applicability on maternal ECG telemonitoring with limited resources [22].

A set of comprehensive work in non-invasive detection and compression on FECG was performed in [19], which had investigated multiple algorithms for ECG separation in noisy cases. It specified that in single channel cases, the variations of nonlinear extended Kalman filters performed relatively well on both synthetic and real-life ECG data, while the extended Kalman smoother with ANFIS showed best overall results on the set of performance metrics in [19]. Other contributions lie in the twin-*R* correlative prediction by applying (4, 2) lifting wavelet transform (LWT) for sequential ECG data processing, parameter estimation via grey prediction GM(1, 1) model on ECG compression, a few examples on automatic FHR estimation with adaptive noise cancellation on synthetic ECG data, and a sample test on FHR recordings of fetal hypoxia on mature fetus either in physiological case or pathological case. Similar methods on adaptive noise cancellation or ECG denoising schemes were later reported in [23], [24] and [26], where the most recent work on real-time ECG extraction with three similar schemes using 12-lead ECG electrode configuration was experimented in [25].

Up to now, a set of typical methods on non-invasive ECG detection and compression in the latest five years have been briefly summarized in this section. Adaptive noise cancellation techniques are applicable when fetal ECG is separable from mixed noisy maternal ECG data, while the nonlinear transform in multi-channel system with combined algorithms with the focus on sparse representation, extended Kalman-filter typed schemes and other adaptive methods, offered feasible methodology in the recent advances of non-invasive ECG processing. Typical non-invasive ECG monitoring often adopts 8-lead or 12-lead electro-node placement with proper locations for fetal heartbeat detection, thoracic and abdominal ECG recordings, while a mini portable ECG recorder demands much higher integration of core elements in its

software platform. The following sections will provide the crucial datasets with general experimental study and our discussions on a possible system design.

3. Keynote Experimental Design with Sample Datasets

In this Section, we concisely introduce crucial types of ECG-based simulation trials in accordance with the sample datasets. The frequently used sample datasets are described as follows:

Physionet / Computing in Cardiology Challenge 2013 [1]-[3], [5]-[7], [9], [10], [12], [13], [17], [19], [20], [26]: The Challenge 2013 dataset comprises a sum of 447 records collected from five different sources: Ukraine non-invasive FECG has 340 records, taking up the major source of data; besides, 25 records of abdominal and direct FECG, 20 of artificially generated FECG, 14 of common non-invasive FECG and 48 of private scalp FECG, symbol for the rest four sources of FECG reference database, which include real data and simulated data. According to the degree of publicity of fetal QRS locations, the complete set of records on the Challenge 2013 had been partitioned into three set of groups: Set A (75 records of open information on both records and reference for fetal QRS locations), Set B (100 records of open information for only records), Set C (272 records that kept confidential for both records and reference for fetal QRS locations). The public Set A and Set B were often used for experiments by previous researchers. Experiments usually refer to part of the Challenge 2013 database in addition to one or two more ECG datasets.

MIT-BIT Arrhythmia database [11], [12], [19]: It includes 48 half-hour excerpts of two-channel in total, 24-hour ECG recordings selected from 47 subjects (25 men aged 32–89 years and 22 women aged 23–89 years, two records are collected from the same subject) as investigated by the BIH Arrhythmia Laboratory at MIT in 1975–1979. 23 recordings were randomly selected from a large set of ECG recordings collected from Boston's Beth Israel Hospital, where the population ratio of inpatients to outpatients in this complete set, got estimated as approximately 3:2.

Synthetic ECG data [19]: Two representative sets of synthetic ECG data were employed, one was used on maternal and fetal heart beat detection, where the data simulates maternal heart rate of 80–90 bpm with peak voltage 3.5 millivolts and fetal heart rate distributed from 120-160 bpm with peak voltage ~0.2 millivolts, the other data simulated maternal heart rate of 65–85 bpm, fetal heart rate of 110–150 bpm and T/QRS (range of 0.05–0.1) for both physiological and pathological cases in a 10-min time sequence. Other synthetic data referred to signals such as FPCG [18], [27] available at the PhysioBank intersecting the recordings and development status of a fetus.

PTB diagnostic ECG database and CSE database [22]: A total of 549 records from 290 subjects (209 mean and 81 women, ages ranged from 17 to 87 with mean 57.2) were included in this dataset. Each record contains 1-5 records where one of each comprises conventional 12 leads and 3 Frank leads on simultaneous ECG measurement. Common digital sampling rate of signals are 1 kHz with 16-bit resolution ranged from ±16.384 mV. It is a database provided by National Department of Metrology in Germany, aiming at research and teaching of the standards and performance of ECG algorithms. This PTB ECG database

was often associated with the CSE (Common Standards for Electrocardiography) database containing 1000 samples of short-time ECG records applying 12-lead or 15-lead electrodes. The CSE database was mainly developed to evaluate the performance of automatic ECG analyzers.

Other ECG databases [8], [11]-[13], [19]: *European database* and the *DaISy* (database for Identification of Systems) *database* were utilized by [12] on multi-channel ECG processing. The *Silesia dataset* stands for another abdominal and direct FECG Database [13], which has five multi-channel FECGs collected from five different pregnant women, each containing four abdominal FECG recordings in addition to a reference FECG recording directly acquired from a scalp electrode.

The majority of most recent experimental work on ECG processing, can be categorized as follows:

Performance comparison of non-invasive algorithms: the related research study was often viewed as comparing the performance of several algorithms on non-invasive ECG processing. For instance, nine algorithms on non-invasive FECG detection were investigated in [19], where the quantitative evaluations were based on single-channel abdominal ECG recordings using a single FECG database. Similar work was performed on those schemes with compression metrics (i.e., distortion measures) in multi-channel FECG recordings over datasets [22].

Proposal of combinative schemes or improvement of an algorithmic model: a few representative schemes either combining or improving existing non-invasive ECG schemes were established in [1], [4], [10], [12], [20], [26], where the proposed methodology shared common features as follows: the flowchart or block diagram on their techniques got presented in the steps of modeling, followed by the description of major steps on implementation of a specific algorithm on ECG processing, fetal heart estimation or fetal QRS detection, etc. Performance analysis on the proposed scheme with reference to a few other schemes was tabulated on the section of results and discussions. Single or multiple databases as mentioned above served as the experimental data.

Recordings of ECG output via non-invasive techniques in a time sequence: one typical example was displayed in [13], where the kernel contribution was to testify different records of ECG signals on a proposed framework, which jointly performed compression, detection and classification based on compressive sensing theory. Evaluation parameters from information metrics on detection and those on data compression were presented to measure five recordings as duration and dataset varied.

Design of a fetal ECG monitoring system on either software devices or hardware platforms: The arrangements of ECG electrodes were taken respective concern in each system design in [15], [16], [25]: [15] focused on an adaptive algorithm, which displayed its merits on heart rate monitoring via validating an Android-based smartphone, [16] showed specific parameters on a noise-reconfigurable amplifier by employing a few techniques on enhancing power efficiency via the current-reuse, a capacitive feedback, the input resistor and bias current, while [25] considered optimal configuration on 12-lead ECG electrode positioning to ensure better quality of fetal ECG signals.

4. Discussions of Our Study

Among the non-invasive fetal ECG filtering techniques, it had been recognized that adaptive noise cancellation based schemes were well performed, where their principles were to extract thoracic and abdominal records from two symmetric input channels on the maternal body, and the difference of abdominal recording (containing fetal ECG and maternal ECG, after pre-processing) from thoracic signals (as reference) after enhancing the output, became relatively pure fetal ECG.

With respect to the studies as described above, technical schemes with advantages and limitations on non-invasive ECG processing have been established. In this section, discussions of our theoretic investigation are presented, which follows by a sketched diagram in fetal ECG monitoring systems along with the required hardware elements. We aim to adapt the research study towards prospective practical portable devices of real-time ECG data processing, FHR estimation, prediction and fetal QRS detection to multi-channel input-output systems.

The frequently used algorithms such as LMS and RLS [21] require more reasonable design on the functional relationship of convergence curve and iteration step on its dual-variable function in order to improve their convergence behavior. Meanwhile, the optimum filters such as complement Wiener filtering, can be adopted on non-random signals after adaptive processing, where vector recursive Kalman filtering was selected to obtain the estimates on a few signals after sampling discretization. Other variations of solutions to performance improvement on non-invasive ECG processing, include vector decomposition of ECG in *n*-dimensional projection space to proceed with adaptive processing, and consider sequential adaptive cancellation or combining inverse wavelet transform with adaptively updated multiple references in condition of different noise scenarios.

A predictive FECG monitoring system on the basis of grey system theory was addressed in [19], where the framework can be sketched using ideas as follows: the thoracic and abdominal areas of a pregnant woman on testing can be regarded as a grey system, where its input signals exhibit typical grey features such as short sequence of time series, less prior information, and ambiguous statistical data. The approximation of grey prediction is to find a substitute for the discrete approximation model of a continuous system, while the signal residual is discretized to establish a whitened differential equation [19]. Hence, "whitening signals" are regarded as the common goal of designing a FECG monitoring system based on semi-blind grey prediction, where the equipment is composed of three major parts: transducer, instrumental host and record screening. A test bench will be programmed to realize grey prediction with various functions. A software package of GMZK grey system will be adopted for practical use, associated with an interface handled by the Microcontroller Unit (MCU). A block diagram of the FECG monitoring system modules is depicted in Figure 1.

Major work flow of grey prediction on multi-channel non-invasive FECG processing is described as follows: first, an AGO accumulator accumulates the received sampling data points, then exploits the residual variables to calculate independent variables of the whitening differential equations, the third step is to perform grey correlation analysis by curve fitting and comparing the goodness of fit,

while displaying the predictor outputs on screening indicates the last step, where the predictive function variables are dependent of manual / automatic settings.

The workflow of amplifying fetal ECG input signals is concisely described as follows: when a signal got collected by the transducer (detection probe) from maternal body surface, it was sent to the subsequent circuit after amplification. Due to the special feature of biological signals (high output impedance, low frequency, weak amplitude and surrounded by severe background noise), amplifiers must satisfy a few fundamental requirements as follows: a) high input impedance, high gain; b) high common-mode rejection ratio (CMRR); c) low noise, low drift. The AD627 instrumental amplifier stands for a relatively good choice with superior performance among the biomedical instruments.

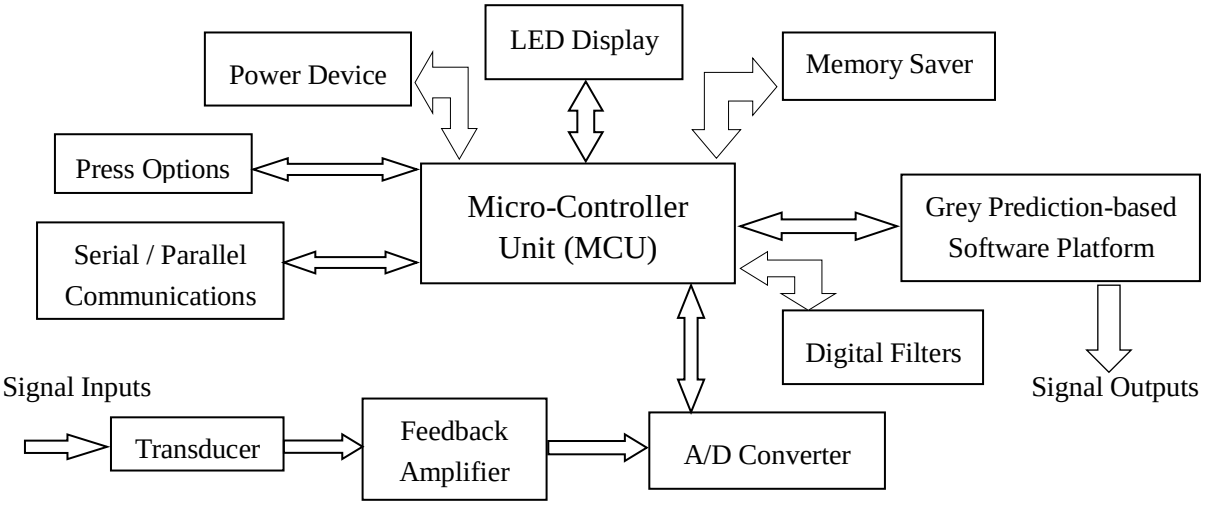

Figure 1. Block diagram on real-time FECG monitoring system modules

The hardware system and peripheral circuits are described in the following scenarios: a micro-control unit (MCU) will be used as the central processor, where its periphery is connected with A/D conversion, power supply, serial / parallel communication, flash memory, liquid crystal module (LCM) and key circuit. The MCU is implemented by the 8-bit processor 89C51 from ATMEL with selected specific devices as below:

Flash: 1Mx8-bit Flash Memory AT29C080 from ATMEL;

LCM: 128-bit graphic LCD module MCG12864A from Truly;

A/D conversion: 8-channel synchronous 8-bit sampling MAX155 from MAXIM;

Serial Communications: CMOS and RS-232 voltage conversion device MAX232 from MAXIM, Parallel Communication Port is reserved for further updates;

Power Devices: pump-powered MAX619 from MAXIM, with two dry-cell supplies up to 5V.

Since high-density field programmable logic devices (PLDs), including CPLDs and FPGAs integrate a large number of logic functions into a single IC. We selected Cypress's 128 Macro-cell CPLD (CY37128) [28], and will exploit Warp2-VHDL as the hardware platform on design. The entire CPLD contains three modules: RAM expansion, digital filters and combinational logics. Very high-speed

integrated circuit Hardware Description Language (VHDL) was used to design the low-pass digital filter with variable cut-off frequency, passing the signal to MCU after filtering.

The comprehensive design process of VHDL can be divided into the following steps:

a) define the design demands; b) system description and code design using VHDL language; c) simulation of original VHDL codes; d) integrating design and optimizing the layout and wiring; e) simulating module design after layout and wiring; f) device programming. The combinational logics required in the entire system were integrated in the CPLD to make full use of resources on macro cells, which effectively saved the area of the circuit board, and enhanced the reliability of system.

The sketched real-time FECG monitoring system can make surveillance on signal outputs (i.e., fetal heart beats, fetal QRS waves, and other FECG irregularities) by the micro-processor via LED screen, then compare the results from grey prediction output. This design suggests a suitable match for real-time monitoring on pregnant women in the family wards, which also matches expectations on portable monitoring in convenience with outdoor activities or short trips on travel.

5. Summary and Conclusions

In this paper, recent advances in non-invasive ECG detection, compression and a few other related topics such as fetal heart rate estimation and QRS detection along with fetal health monitoring systems, were investigated in chronological order. Representative schemes contributed on non-invasive ECG processing in the latest five years were sorted in accordance with sample databases and common flowchart of typical research study. It is specified from our review that adaptive noise cancellation, sparse representation in the compressive sensing scenario, and combining non-linear filtering with multi-scale feature extraction, displayed technical merits in this field. A framework of portable system design on possible options of selecting elements for each module, is also sketched along with discussion towards practical realization of real-time fetal ECG monitoring.

Algorithmic models on non-invasive ECG processing still call for further efforts on reducing computational cost. While a combined scheme such as extended Kalman smoothing with variations along with non-linear transform achieved nearly perfect quantitative results, common standards on the compatibility of a universal algorithm to portable multi-lead ECG monitoring system, will also demand future promotion. We aim to improve the software platform with reference to the wavelet toolbox, which upgrades our experimental design when applying both real and synthetic ECG data to the practical software platform in connection with the 8-lead or 12-lead ECG electrode system.

References

1. Kropfl M, Modre-Osprian R, Schreier G, Hayn D. A robust algorithm for fetal QRS detection using non-invasive maternal abdominal ECGs. *Comput. in Cardiology*. 2013; 40: 313-316.
2. Silva I, Behar J, Sameni R, Zhu TT, Oster J, Clifford GD, Moody GB. Noninvasive fetal ECG: the PhysioNet/computing in cardiology challenge 2013. *IEEE Conf. Comput. Cardiology (CinC)*. 2013; 149-152.
3. Behar J, Oster J, Clifford GD. Non-invasive FECG extraction from a set of abdominal sensors. *IEEE Conf. Comput. Cardiology (CinC)*. 2013; 197-200.
4. Kumar P, Sharma PK, Prasad S. Detection of FECG from multivariate abdominal recordings using wavelets and neuro-fuzzy systems. *Int'l J. Eng. Adv. Technol. Studies*, 2013; 2(1): 45-51.
5. Behar J, Johnson A, Clifford GD. Oster J. A comparison of single channel fetal ECG extraction methods. *Annals Biomed. Eng.* 2014; 42(6): 1340-1353.
6. Clifford GD, Silva I, Behar J, Moody GB. Non-invasive fetal ECG analysis. *Physio. Measure.* 2014; 35(8): 1521-1536.
7. Andreotti F, Riedl M, Himmelsbach T, Wedekind D, Wessel N, Stepan H, Schmieder C, Jank A, Malberg H, Zaunseder S. Robust fetal ECG extraction and detection from abdominal leads. *Physio. Measure.* 2014; 35(8): 1551-1568.
8. Melillo P, Santoro D, Vadursi M. Detection and compensation of inter-channel time offsets in indirect fetal ECG sensing. *IEEE Sen. J.* 2014; 14(7): 2327-2334.
9. Zheng W, Wei XY, Zhong JJ, Liu HX. Fetal heart beat detection by Hilbert transform and non-linear state-space projections. *IET Sci., Measure. Technol.* 2015; 9(1): 85-92.
10. Panigrahy D, Sahu PK. Extraction of fetal electrocardiogram (ECG) by extended state Kalman filtering and adaptive neuro-fuzzy inference system (ANFIS) based on single channel abdominal recording. *Sadhana*, 2015; 40(4): 1091-1104.
11. Zheng W, Li XL, Wei XY, Liu HX. Foetal ECG extraction by support vector regression. *Electron. Lett.* 2016; 52(7): 506-507.
12. Selvaraj R, Kanagaraj B. A multi-stage adaptive singular value decomposition approach for fetal ECG signal extraction in multichannel input system for prenatal health monitoring. *Asian J. Inf. Technol*. 2016; 15(6): 1049-1055.
13. Poian GD, Bernardini R, Rinaldo R. Separation and analysis of fetal-ECG signals from compressed sensed abdominal ECG recordings. *IEEE Trans. Biomed. Eng.* 2016; 63(6): 1269-1279.
14. Rooijakkers MJ, Rabotti C, de Lau H, Oei SG, Bergmans JWM, Mischi M. Feasibility study of a new method for low-complexity fetal movement detection from abdominal ECG recordings. *IEEE J. Biomed. Health Informatics*, 2016; 20(5): 1361-1368.
15. Tadi MJ, Lehtonen E, Hurnanen T, Koskinen J, Eriksson J, Pänkäälä M, Teräs M, Koivisto T. A real-time approach for heart rate monitoring using a Hilbert transform in seismocardiograms. *Physio. Measure.* 2016; 37(11): 1885-1909.
16. Song S, Rooijakkers MJ, Harpe P, Rabotti C, Mischi M, van Roermund AHM, Cantatore E. A noise reconfigurable current-reuse resistive feedback amplifier with signal-dependent power consumption for fetal ECG monitoring. *IEEE Sen. J.* 2016; 16(23): 8304-8313.
17. Yu Q, Guan Q, Li P, Liu TB, Huang XL, Zhao Y, Liu HX, Wang YQ. Fusion of detected multi-channel maternal

electrocardiogram (ECG) *R*-wave peak locations. *BioMed. Eng.* 2016; 15(4): 1-16.

18. Adithya PC, Sankar R, Moreno WA, Hart S. Trends in fetal monitoring through phonocardiography: challenges and future directions. *Biomed. Signal Process. Control*, 2017; 33: 289-305.
19. Gao X. Non-invasive detection and compression of fetal electrocardiogram. *Interpreting Cardiac Electrograms - From Skin to Endocardium*, *InTechOpen*. 2017: 53-74; Print ISBN 978-953-51-3571-5.
20. Li RL, Frasch MG, Wu HT. Efficient fetal-maternal ECG signal separation from two channel maternal abdominal ECG via diffusion-based channel selection. *Frontiers in Physiology*, 2017; 8: 1-12.
21. Martinek R, Kahankova R, Nazeran H, Konecny J, Jezewski J, Janku P, Bilik P, Zidek J, Nedoma J, Fajkus M. Non-invasive fetal monitoring: a maternal surface ECG electrode placement-based novel approach for optimization of adaptive filter control parameters using the LMS and RLS algorithms. *Sens.* 2017; 17(5): 1154; http://www.mdpi.com/1424-8220/17/5/1154.
22. Singh A, Sharma LN, Dandapat S. Multi-channel ECG data compression using compressed sensing in eigenspace. *Comput. Biology Med.* 2016; 73: 24-37.
23. Ma YP, Xiao YG, Wei G, Sun JW. Foetal ECG extraction using non-linear adaptive noise canceller with multiple primary channels. *IET Signal Process.* 2017: 1-10; DOI: 10.1049/iet-spr.2016.0605.
24. Escalona OJ, Lynn WD, Perpiñan G, McFrederick L, McEneaney DJ. Data-driven ECG denoising techniques for characterizing bipolar lead sets along the left arm in wearable long-term heart rhythm monitoring. *Electronics*. 2017; 84(6): 1-18; doi:10.3390/electronics6040084.
25. Marchon N, Naik G, Pai R. ECG electrode configuration to extract real time ECG signals. *Procedia Comput. Sci.* 2018; 125: 501–508.
26. Sutha P, Jayanthi VE. Fetal electrocardiogram extraction and analysis using adaptive noise cancellation and wavelet transformation techniques. *J. Med. Syst.*, 2017; 42(21): 1-18; [Online] Available: https://doi.org/10.1007/s10916-017-0868-3.
27. Koutsiana E, Hadjileontiadis LJ, Chouvarda I, Khandoker AH. Fetal heart sounds detection using wavelet transform and fractal dimension. *Frontiers in Physiology*. 2017; 5: 1-9. http://www.digikey.cn/number/en/cypress-semiconductor-corp/428/CY37128/18327.