A DSP Algorithm and System for Real-Time Fetal ECG Extraction

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Abstract

Fetal ECG (FECG) extraction from maternal abdominal potential recordings is a task of paramount importance for pediatric cardiologists, but there is a lack of established solutions for it. In this paper the real-time implementation of a block-on-line Independent Component Analysis (ICA) algorithm for FECG extraction is presented and evaluated over real long lasting recordings. The problem of the signals permutation, typical of ICA algorithms and particularly severe for block-on-line ones, is analyzed in detail. The comparison with batch approaches applied to different segments of the signals demonstrates the quality of the proposed solution. The performances of the real-time implementation enable further developments of the system to automatically provide other interesting clinical parameters.

1. Introduction

Non-invasive FECG aims to provide ECG traces representing the fetal heart activity in early and late pregnancy comparable with those achievable on adult subjects. Even with all the limitations posed by the indirect recording [1], a morphological analysis can be carried out to identify fetal pathologies and set up a therapeutic intervention in time. In transabdominal potential recordings, the low-power FECG is hidden in a mixture of several high-power sources, mainly ascribable to the maternal physiological interferences (ECG, EMG, respiration) and to the instrumental noises. It is well known that the original sources cannot be separated using traditional frequency domain filters due to the spectral overlap between the different sources [2]. The only methods giving recognized good results are based on adaptive filtering or Blind Source Separation (BSS) algorithms, the latter usually providing better results than the former at the expenses of an increased complexity [3].

To cope with the lack of real-time ICA algorithms able to provide results with a quality comparable with the batch ones, we developed a block-on-line algorithm, OL-JADE, based on the famous JADE algorithm [4], able to give the same quality of the original batch algorithm joined with the tracking ability of an on-line one. Since this kind of processing is targeted for real-time clinic examinations, we also proposed a real-time implementation on a floating point DSP [5]. The critical issue of the algorithm is the permutation ambiguity (due to the mathematical formulation of the problem) since it may lead to a block-by-block scrambling of the separated sources. In this paper this problem, partially addressed in the formulation of the on-line algorithm, is studied on real mixtures, providing further information and possible solutions, along with comparisons with the original batch approach.

2. Methods

ICA aims to find a linear transformation that minimizes the statistical dependence between the components of a random vector. When it represents the mixture of more unknown independent source signals, and the mixing process is also unknown, ICA can be used to find a good estimate of the sources, thus acting as a BSS algorithm.

OL-JADE is a block-on-line version of the famous JADE [4] algorithm, which consists of a Second Order Statistics (SOS) stage providing centering and whitening of the original signal mixtures, followed by a Higher Order Statistics (HOS) stage. Whitening decorrelates and orthogonalizes the original mixtures, reducing the number of parameters to estimate, so that only a rotation, provided by the HOS stage, is then required to identify the independent sources [6]. JADE is a batch algorithm, working on a segment of data of interest containing enough statistical information on the independent components to perform the separation. This means that both the SOS and HOS stages are performed off-line. The HOS stage obtains higher-order independence by multiplying decorrelated mixtures by an orthogonal rotation matrix $\mathbf{G}$, computed by the Jacobi method, which minimizes the sum of squared fourth order cross cumulants of the whitened signals. A direct block-by-block application of JADE would result in segments of sources placed in different orders in adjacent blocks (permutation ambiguity), leading to a useless output for a real-time clinic device.

OL-JADE [5] presents several expedients to reduce inter-block permutations:
1. Since the off-line SOS stage can introduce permutations, it is replaced with an on-line sample-by-sample one: a running average over L samples for centering followed by an on-line whitening performed adapting the whitening approach presented in [7]. This way the inputs for the SOS stage vary without abrupt changes and the continuous whitening matrix update allows tracking while avoiding permutations. A T-wide frame is formed at the end of the SOS stage.
2. The whitened mixtures are then passed to the HOS stage exploiting a sliding window approach with a wide overlap to preserve the information of the previous blocks of samples. The SOS-preprocessed frame is inserted in a L-wide sliding window with an overlap of $L - T$. This gives to the HOS stage the possibility to work with larger frames but providing an adequate throughput.
3. Permutations can be introduced in the HOS stage if for every block the rotation angle is evaluated from scratch, due to some ambiguities in the evaluation of the rotation angle in JADE we will highlight in the following. A solution in this case is to give the HOS stage the possibility to work introducing only small corrections on the result of the preceding separation, reducing the influence of such estimation ambiguities. To this aim the Jacobi method is preceded by a preliminary coarse separation performed using the rotation matrix obtained on the previous block. After this preconditioning, the Jacobi method in the HOS stage is applied as in the original JADE providing a L-wide block of samples of the estimated sources, where only the oldest T samples are taken into account to provide the output. A detailed explanation of the algorithm can be found in [5].

The algorithm has been coded in C for DSP, and can run both with file I/O on a PC platform or in real-time on a DSP. The latter result opens to the realization of a real diagnostic equipment for fetal ECG extraction in real-time. The DSP porting has been targeted for the 300MHz floating point TMS320C6713 DSP by Texas Instruments. Having to rely on pre-recorded signals, the system was simulated using a Device Cycle Accurate Simulator under Code Composer Studio v3.1 including all the peripherals involved in a real implementation (EDMA, McBSP).

To test the algorithm, two databases were used. Both of them are composed of 8 real potential recordings from a pregnant (5 abdominal, 3 thoracic) with 12-bit resolution. The main differences are in sampling rate and duration. The first one (publicly available [8]) lasts 10 seconds and the sampling rate is 250Hz. The second one (by courtesy of Prof. L. De Lathauwer) lasts 1 minute and the sampling rate is 500Hz. After some trials we found that the higher sampling rate is not useful for a better separation and then, since it affects both the processing time and the buffers size, we choose to resample the second database at 250Hz. With this sampling rate the parameters L and T were chosen equal to 1024 and 256 respectively so that the algorithm produces almost one second of processed signals every second, with a delay of 4 seconds. In the following all the described experiments refer to the application of the algorithm to the longest database.

3. Results

The estimated sources achieved with the on-line algorithm are shown in Fig. 1. The FECG traces are clearly present in the 2^{nd} and 3^{rd} traces, whereas the maternal ECG are in 1^{st}, 6^{th} and 7^{th} traces. As can be seen there are permutations only on the noise channels, on blocks 14 and 48. Such permutations are anticipated by an evident signal distortion.

To test the proposed algorithm, we compare it against two algorithms:

- BB-JADE, which is a block-by-block application of JADE over short-length segments with manual reordering of the sources, differing from OL-JADE only in the SOS stage: from a comparison with it, it is possible to evaluate the effect of the different strategies at this level;
- JADE, over the whole signal at the same time, to verify if it is possible to identify a time-variance in the mixing process or errors in block-by-block processing.

To find an explanation to the permutation problem we have to analyze the HOS of JADE in more details. The reason of permutations can be found in the way the angles of the rotation matrix are estimated, after the SOS stage. The process is carried out by the Jacobi method, which consists of successive planar rotations of couples (i, j) of signals. At every iteration, the optimization problem consists in the identification of this only angle θ_{ij} for the construction of an elementary Givens matrix. It can be computed in closed form by (1), argued for real signals from [9]:

$$\theta_{ij} = \frac{1}{2}\arctan\left[\frac{2a_{ij}}{(a_{ii}-a_{jj})+\sqrt{((2a_{ij}-a_{jj})^2+4a_{ij}^2)}}\right] \quad (1)$$

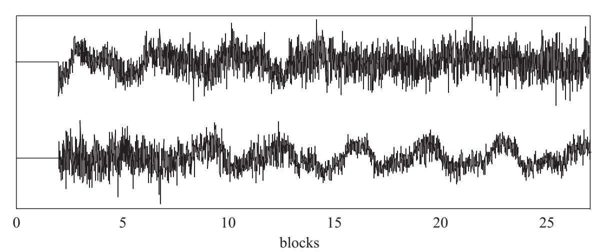

Figure 2. Detail of the estimated noise sources 4 and 5 at the beginnning of the record.

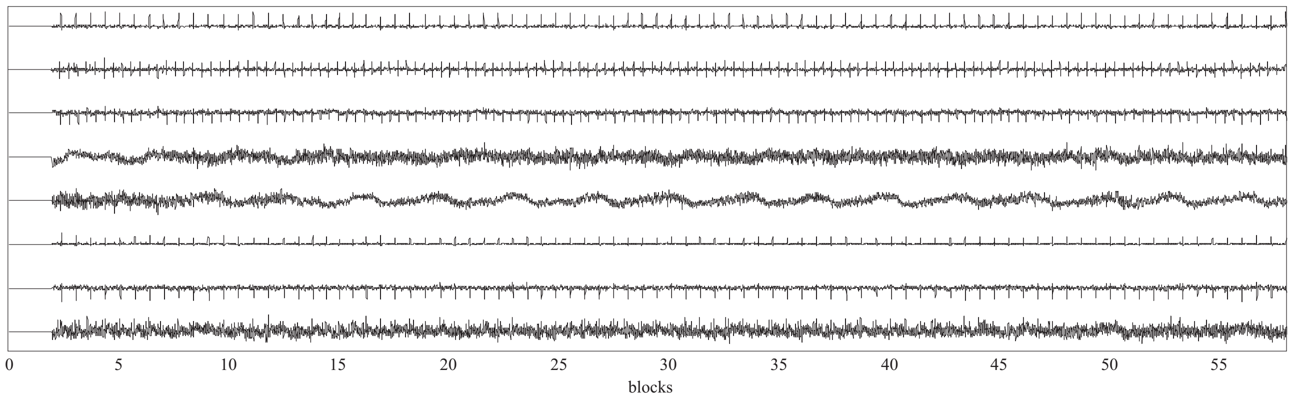

Figure 1. Estimated sources with the proposed algorithm. One block consists of 256 samples at 250Hz. The amplitude of the estimated sources, being scaling an ICA ambiguity, is not relevant and has been omitted.

Since numerator and denominator are not representative of the sin and cos of the angle to estimate, there is an ambiguity in the determination of the value to assign to θ_{ij}, with $-\frac{\pi}{4} < \theta_{ij} < \frac{\pi}{4}$. So the angle is evaluated as $\theta_{ij} \pm \frac{\pi}{2}$ respectively for $\theta_{ij} < -\frac{\pi}{4}$ and $\theta_{ij} > \frac{\pi}{4}$. This way, the only effect is a swap of the two sources without degradation in the signal quality. The aforementioned preconditioning strategy was introduced in the OL-JADE just to avoid to deal with elementary rotations where the estimated angle is larger than $\frac{\pi}{4}$, thus proceeding by small rotations. Nevertheless, permutations are still present and clearly visible in Fig. 1. In this case, the sources swap is preceded by a transient stage where each trace is gradually transformed into the other (Fig. 2). We can analyze the rotation angles applied to the whitened mixtures in the HOS stage for every block, thus taking into account the rotation induced by preconditioning too. Such angles, for the two permutating traces 4 and 5 at the beginning of the separation process (Fig. 2), are depicted in Fig. 3. In the blocks preceding the 15^{th} one there is a trend of the rotation angles leading to an overall rotation of more than $\frac{\pi}{2}$ with respect to the average estimate in the preceding blocks. It can be seen that the HOS stage of JADE produces several wrong estimates of the angles biasing the separation process to points far from the correct solution so that at last a rotation greater than $\frac{\pi}{4}$ is required.

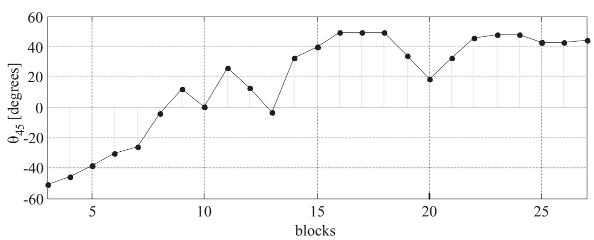

Figure 3. Overall rotation angles applied at every block between the sources in Fig. 2.

The effect of these wrong estimates on the noise traces is visible (permutation) and does not require further analyses. The same does not apply to the FECG traces, where no permutations are present but we are interested in evaluating possible consequences on the signal quality. To this aim, we performed a comparison between JADE and both OL-JADE and BB-JADE in terms of root-mean-square (rms) errors between the homologous FECG estimated sources within T-wide segments:

$$rms_{err} = \frac{\|FECG^{(i)}_{JADE} - FECG^{(i)}_{alg}\|_2}{\sqrt{T}} \qquad (2)$$

The results are depicted in Fig. 4, where it is possible to note that at the begging and at the end of the records the rms_{err} are largely over the average error. It should be also noted that the average errors are almost the same with both OL-JADE and BB-JADE (around 0.20) but the maximum errors are greater for OL-JADE. From other trials with synthetic mixtures originated by a time-invariant mixing process, we found that the errors (with respect to the real sources) for OL-JADE and BB-JADE are similar, the one of OL-JADE being always greater than the other. Since the two algorithms differ only for the SOS stage and preconditioning, which does not alter the HOS stage behavior, this can be due only to the SOS stage, which is less precise in OL-JADE, while it seems not due to a time-variance in the mixing process. At the same time it reveals also that the information available for the algorithm to process the noise is somehow too poor when $L = 1024$. The estimation of the noise sources is not improved by window enlargements, being JADE highly sensitive to noise. Since the segments where these errors are present are of short-length, it is better to keep the windows short and to identify automatically those segments to produce a quality index useful for the evaluation of the achieved sources. The same considerations apply also the second permutation, only slightly visible in Fig. 1, between sources 4 and

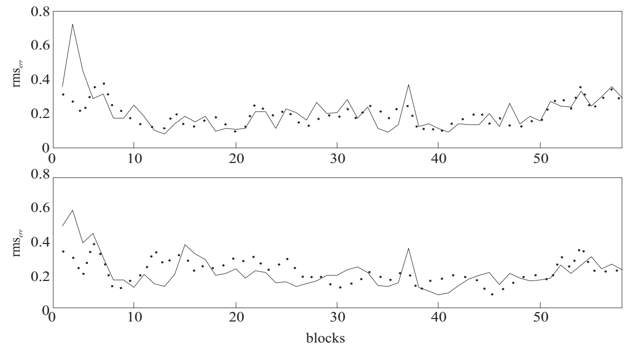

Figure 4. rms_{err} for OL-JADE (solid) and BB-JADE (dotted) with respect to JADE.

8 at block 48. However it should be noted that the errors affecting the FECG sources are too small to induce permutations on them, but only slight distortions not perceivable by the user.

The DSP implementation of the FECG extractor was profiled to evaluate the CPU load without any procedure to prevent permutations, since this aspect deserves further investigations on larger databases we are currently recording. The algorithm requires a number of clock cycles that varies according with the number of sweeps needed for the Jacobi method, where each sweep requires a number of elementary Givens rotations variable from 1 to 28 ($n(n-1)/2$ with $n = 8$ signals). The number of sweeps is unpredictable since it is controlled by a threshold on the rotation angle: if the elementary Givens rotation is below a threshold angle such a rotation will not be performed. In our implementation this angle was fixed to $3.125 \cdot 10^{-4}$. For this reason, the application profiling is not straightforward and requires the evaluation of the worst case. With the given signals, the maximum number of required sweeps was 16, with 169 elementary Givens rotations. In this worst case, the number of required clock cycles is 25,621,064 that represents only 8.34% of the available computational clock cycles, taking into account the clock frequency, the sampling frequency and the size of the blocks.

4. Discussion and conclusions

In this paper a novel on-line algorithm for FECG extraction from transabdominal potential recordings was evaluated over long real recordings to assess the separation results and the robustness against permutations. The algorithm shows permutations on the noise channels due to a not-perfect on-line sample-by-sample SOS stage and to a characteristic poor robustness to the noise of JADE. However, the effect on the estimated FECG is negligible and all the useful signal sources seem to be not affected by permutations. A possible solution to recover permutations is to force the output of the HOS stage with a permutation matrix when a permutation is identified in a block exploiting the approach presented in Section 3 based on the overall rotation angle. For a deeper investigation on a larger set of signals, there is an active cooperation with the Division of Pediatric Cardiology of the Hospital "G. Brotzu" of Cagliari (Italy).

The proposed hardware implementation feces the problems of an embedded medical system, such as the currently used electrocardiographs for adults and children, with all the limitations imposed by such implementations. The proposed solution opens to the realization of a real equipment, and the whole system is continuously in progress to add extra processing such as QRS detection, average fetal heartbeat extraction and delineation, and so on.

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