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Comparative Study of Event-Synchronous Interference Cancelling Methods

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***Abstract*— In case of a periodic disturbing signal as "noise", special solutions for noise reduction can be applied. In literature, an Adaptive Noise Canceller modification was proposed for this case by Strobach et al. [5] and applied by several other researchers. It uses an artificial reference signal, based on event triggered averaging of segments of the recorded wanted (but disturbed) signal in order to obtain a template for the repetitive distortion sequence which is used to construct the artificial reference signal. The simple subtraction and the adaptively modified template subtraction are also used, with better performance, to remove the repetitive noise component. Methods are basically introduced in simulations, and then demonstrated in real biosignal processing, considering the case of removing the disturbing maternal ECG from abdominal signals of pregnant women in order to get the fetal ECG for diagnosis purposes.**

I. Introduction

THE Adaptive Noise Canceller (ANC) is a classical linear method [1]-[2] to clean a disturbed signal (Fig. 1); the ANC can be applied when the noise source $v(n)$ is (i) not correlated with the signal of interest $s(n)$, and (ii) separately accessible by a second recording channel $v_1(n)$. A typical application example is the hands-free speaking usage of a mobile phone in the car with one microphone in front of the driver focused to him and another general microphone to record the 'noise' present in the car. The main idea is that a noise component $v_0(n)$ contained in a signal $d(n)$ can be removed by subtraction when an isolated version of the noise itself is available in addition to the compound signal recording. Fig. 1 illustrates the scheme with a linearly processed version of the noise channel

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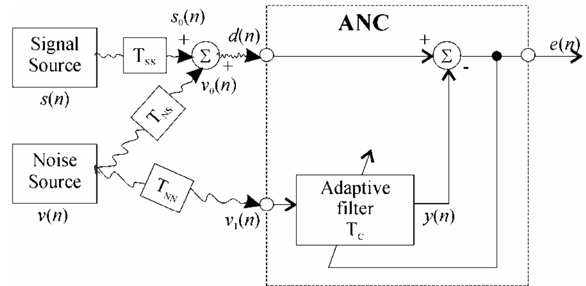

Fig. 1. Classical structure of the Adaptive Noise Canceller (ANC). For denoising, a copy $y(n)$ of the noise component $v_0(n)$ is estimated from the reference signal $v_1(n)$ by an adaptive filter algorithm and subtracted

(adaptive filter with transfer function $T_C = T_{NS} / T_{NN}$), which cancels the noise component in the signal. Signal propagation of $s(n)$ to the recording site is formally described by transfer function T_{SS}.

Mathematically, the basic problem is to find the coefficients of the adaptive filter, $\hat{\mathbf{w}}$, of order M, such that the mean square error ES at the output is minimized according to

$$\begin{aligned} ES &= \mathrm{E}\left(e^2(n)\right) \Rightarrow \min, \\ e(n) &= d(n) - y(n) = s_0(n) + v_0(n) - y(n), \end{aligned} \tag{1}$$

with E indicating estimation and assuming that the signal of interest, $s(n)$, and the reference signal, $v_1(n)$, are not correlated, but $v_0(n)$ and $v_1(n)$ are correlated.

A special case is the disturbance of a signal $s(n)$ by a periodic 'noise' source like a sinusoidal signal (e.g. crosstalk from power line), which was originally discussed in [3]. In this case, the (time invariant) a priori information about the disturbing component $v_1(n)$ can be used in order to avoid the necessity for a reference signal recording. It can be substituted by an internal signal source with the periodic signal profile, amplitude and frequency being adapted such to fulfill (1). In biosignal processing, such a repetitive signal is the electrocardiogram (ECG) which shows up in several other electrophysiological recordings as "noise". E.g. the maternal ECG component (mECG) appears in the abdominal fetal ECG (fECG) recording and must be removed to allow fECG monitoring. Cerutti *et al.* [4] suggested a mECG triggered averaging of the fECG signal to obtain a mECG template which is then subtracted from the fECG to denoise it – in principle an ANC approach. More recently, the Event-Synchronous Adaptive Interference Canceller (ESAIC) [5] again addressed this specific application of ANC by reporting about the problem to cancel ECG cross talk components in the magnetoencephalogram (MEG).

This study will now elucidate some characteristic features of these methods, in particular their inherent performance limits, which are important for the decision to apply the method. For demonstration, the ECG removal in simulated data and the mECG removal in the fECG are considered.

II. Event Synchronous Adaptive Interference Canceller - EASIC

ESAIC was proposed by Strobach et al [5] to consider the problem that (i) the periodic disturbance was not really periodic but only repetitive (i.e. the period shows some trailing noise segment whose length varies from repetition to repetition), and (ii) the transfer function T_{NS} can contain some nonlinear characteristic, which is incompatible with the basic linear ANC principle. The concept of ESIC is depicted in Fig. 2; it shows that the reference signal is now derived from the measurement channel $d(n)$ itself by event triggered averaging in the block *Reference*. Thus, any nonlinear distortion of the repetitive disturbance signal during the propagation from the noise source to the recording sensor of the measurement channel is considered. Since the repetition of the disturbing noise sequence is not strictly periodic, the timing must be determined from the reference input by event detection (event trigger).

The ESAIC is a two pass algorithm. First, a template of the disturbance segments is obtained by coherent averaging [6] of the individual segments of $d(n)$. For this purpose, an event trigger strobe signals the onset detection of every repetition of the disturbance sequence, and, accordingly, the signal $d(n)$ is structured into segments; all these segments aligned to their beginning were averaged. Finally, the template sequence is cut to the shortest interval length ever found between trigger events during this process; i.e. to the shortest segment considered by the averaging procedure. Secondly, the noise compensation pass follows starting again at the beginning of the recording. Each time an event trigger strobe appears, the mixer will send the average ECG segment to its output; the gap between the end of the actual template and the beginning of the next template (due to different event intervals) is filled with some indifferent noise-like signal with length N_{AN}. N_{AN} can vary from repetition to repetition. This artificial reference signal $x(n) = v_2(n)$ is passed together with the corrupted signal of interest $y(n) = d(n)$ to the adaptive filter based on a lattice structure [5]. For recurrent computation of the coefficients of the M^{th} order adaptive filter, the Schur RLS algorithm was used [7]. The cleaned output signal $e(n)$ is computed based on this adaptive algorithm. The output mean square error ε normalized to the signal energy of s_0 is for the Strobach et al method [5]:

$$\varepsilon = \frac{\sum_n \left(v_0(n) - \left(w_n(n) * v_2(n)\right)\right)^2}{\sum_n s_0^2(n)\cdot} \tag{2}$$

with * indicating convolution and $\boldsymbol{w_n}$ representing the impulse response of the adaptive lattice filter.

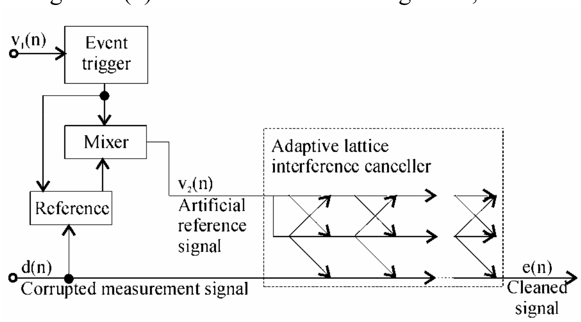

Fig. 2. Block diagram of processing steps of the event-synchronous canceller (according to [5]).

III. Event Synchronous Interference Noise Canceller – ESC

Let us consider the block diagram of the averaging depicted in Fig. 3 with assuming the transfer function $T_C = 1$ for the first instance (i.e. $\mathbf{w}_n = \{1 \quad 0 \quad 0 \quad \ldots\}$) thus $y(n) = v_2(n)$; this is the general form of an Event Synchronous Interference Canceller (ESIC) which simply subtracts the artificial reference from the input signal for denoising. Variations of amplitude and jitter will cause a significantly larger error, which depends on the signal-to-noise ratio. However, the method can be improved by cascading a block 'Compensation' (Fig. 4) which performs

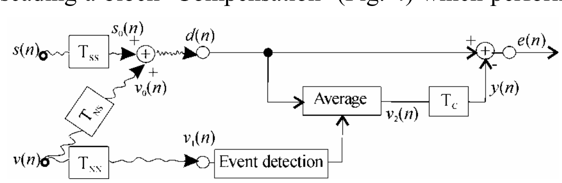

Fig. 3. Averaging scheme to obtain the artificial reference signal. For the general ESIC approach, referred also as "simple subtraction method", a template segment of the repetitive disturbing component is constructed from the signal channel by event triggered averaging, and, in case of $T_c = 1$, it is directly subtracted from the signal channel.

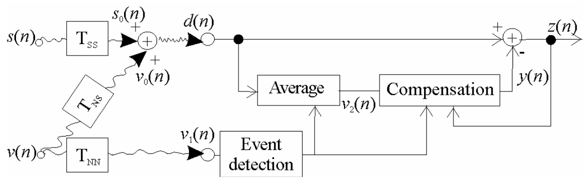

Fig. 4. The ESC scheme which introduces an individual compensation for amplitude variations and jitter

a gain adaptation and jitter compensation for the individual waves. The gain adaptation was already realized [8], [9], [10] and proved to reduce the error further; the jitter compensation, however, requires a more sophisticated approach, which must be designed by future investigations.

The reference input is an artificial reference signal and the primary input is the contaminated signal. The removing of the noise signal is performed now by direct subtraction of the reference input from the primary input when a segment of the periodic noise is detected. That subtraction includes the linear and non-linear distortions of the noise signal associated with the signal path and the recording techniques. The artificial reference signal is the template $\overline{n}_0$. In order to preserve the amplitude variations in the real periodic noise signals the adaptive amplitude gain, a^*, is used in block 'Compensation'. The amplitude gain is that value which minimizes an error function over $[a_1;a_2]$.

If the error function is defined as:

$$Func(a_i) = \sum_n \left[d(n+iT) - a_i \cdot \overline{n}_0(n+iT)\right]^2 \qquad (3)$$

then we can find

$$a_i^* = \min_{a \in [a_1, a_2]} Func(a_i). \qquad (4)$$

The interval of minimization is chosen $[0.9,1.1]$ to avoid local instability when signal artefact occurred in the repetitive noise signal.

IV. Demonstrations of Event Synchronous Interference Cancelling Methods

In order to analyze the performance of the event synchronous interference cancelling methods, the resulting output error (normalized to the signal energy of $s_0(n)$) due to the reference signal estimation by averaging is defined by:

$$\varepsilon = \frac{\sum_n (s_0(n) - z(n))^2}{\sum_n s_0^2(n)} = \frac{\sum_n (v_0(n) - v_2(n))^2}{\sum_n s_0^2(n)} \qquad (5)$$

TABLE I
Comparison between the different noise cancelling methods

Output error - ESAIC	Output error - ESC	Output error ε – ESIC
0.0493	0.0341	0.0401
0.0667	0.0396	0.0402

Table I depicts the error ε for the three different methods (ESAIC, ESC, ESIC) for two data series of about 100 ECG segments which includes amplitude among segments of the repetitive signal. Evidently, the ESAIC produces the largest error ε, whereas the ESC shows the smallest ε.

The basic "averaged template subtractions" (ESIC)-method was sometimes applied to different physiological signals, e.g. abdominal signals [4], MEG signals [5], EMGdi signals [8], [11] and EEG signals [12]. This study originally shows the benefits of using an adaptive gain, like in the ESC method [8], when the periodic disturbing "noise" exhibits amplitude variations among periods. The "noise" cancellation of ECG by ESC, ESIC and ESAIC in real biosignals is now demonstrated.

The application of the methods on real signals concerns the removal of the maternal ECG (mECG) from an abdominal recording on a pregnant woman in order to extract the fetal ECG (fECG). Like in the previous application example, the removing cannot be addressed by ordinary filtering due to the spectral overlapping of both signals. Most of the power density of the R wave of an adult covers the range 10-30 Hz, whereas that of the fetal R wave is between 15 Hz and 40 Hz [13]. The original abdominal recording is shown in Fig. 5.a, having a sampling frequency of 250 Hz; note that the fECG components are of smaller amplitude but higher beat rate.

The "cleaned" signal after mECG removal by ESC is depicted in Fig. 5.b. A similar result is obtained by applying the ESIC method (Fig. 5.c), as the mECG shows no strong variation from beat to beat. In Fig. 5.d. the cleaned fECG by ESAIC method is shown. Note that there is still some remaining mECG in the fECG for this method, even when the mECG is not varying a lot, as for example in the case when uterine contractions appear. Again, success of the ESC application is obvious, as the fECG is extracted such that fetal heart rate can be simply determined for diagnosis purposes.

V. Conclusion

The paper demonstrates the performance of different event synchronous interference cancelling methods, on simulated and real biosignals, revealing the benefit of using the simple template subtraction method (ESIC method) and of the adaptive gain in template subtraction (ESC method).

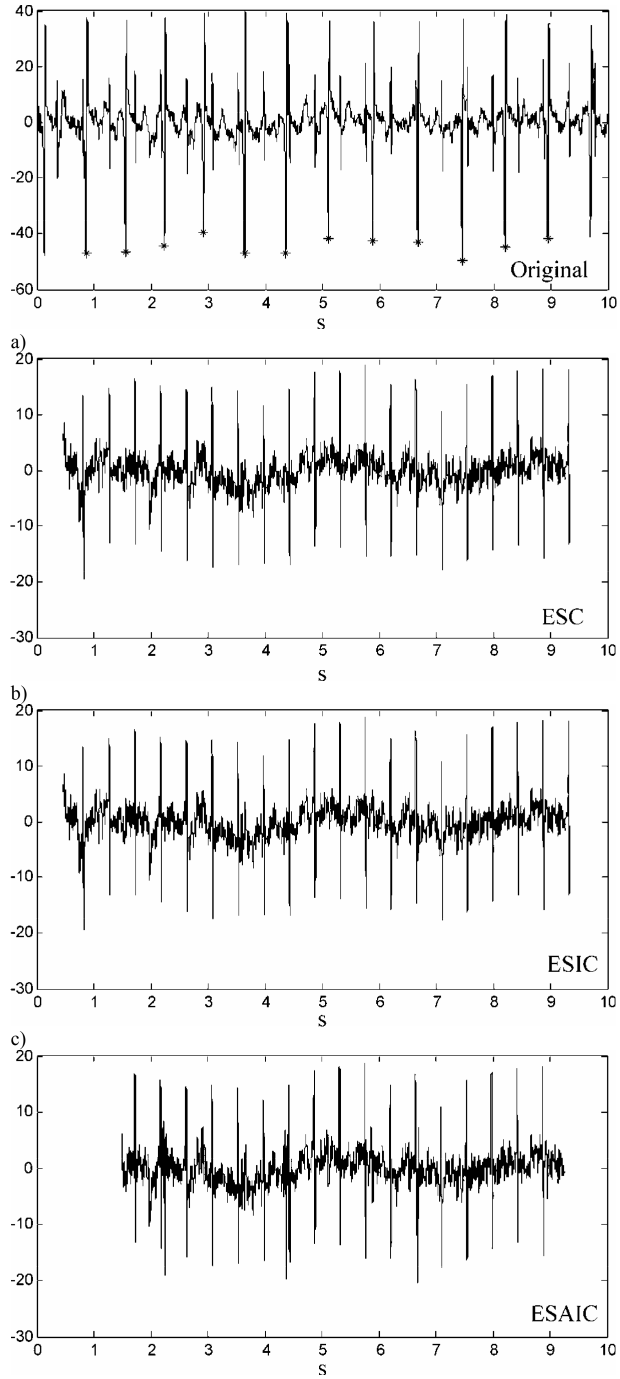

Fig. 5. Removal of the mECG from an abdominal fECG recording. a) original abdominal signal with the QRS complexes of the mECG marked by *; b) fECG extracted by ESC method; c) fECG extracted by ESIC method; d) fECG extracted by ESAIC. Again, appropriate mECG removal can be seen, with best performance of the ESC method.

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