REMOVAL OF FREQUENCY FLUCTUATING POWER-LINE INTERFERENCE FROM ECG

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Abstract: The ECG signals are very often contaminated by residual power-line (PL) interference. Traditional filters suppress the ECG components around the rated PL frequency. A subtraction procedure has been developed two decades ago. It eliminates almost totally the interference without affecting the signal spectrum. PL frequency variations are compensated by continuous hardware measurement resulting in small deviations from the rated sample interval. Later on, software measurement has been proposed. However, the ongoing sampling rate (SR) adaptation of the analogue–to–digital conversion (ADC) is still impeding. This paper deals with an algorithm developed for interference removal without ADC SR modification. It consists of the following steps: i) each input ADC sample is recalculated after irregular shifting of its position according to the last detected PL frequency; ii) the ongoing PL interval is software measured thus defining the next location for signal re-sampling; iii) a moving window of already irregularly spaced samples is subjected to the subtraction procedure; iv) the samples free of interference are re-sampled back, so that the output signal is again a sequence with regular rated SR.

Introduction

The ECG signals are very often contaminated by residual power-line (PL) interference. It is due to the parasitic currents, which flow through the cables and the patient body raising a false differential voltage [1].

Traditional filters suppress the ECG components around the rated PL frequency. Digital notch filters with narrow band may reduce to some extent this phenomenon but they cannot follow the larger PL frequency deviations allowed by the standard. The transient time response of such filters is unacceptably long [2], either for adaptive and non-adaptive notch filters [3, 4]. YOO *et al.* [5] proposed a hardware notch filter, which varies its centre frequency with the PL frequency changes. However, the filter Q factor determines inadmissible wide rejection bandwidth of the signal spectrum. A software implementation of the idea has been studied [6]. The results show that acceptable distortions may be obtained by narrower than 49.9÷50.1 Hz band-pass filter, but with an exclusively long tail, which appears every time the centre filter frequency is corrected by very small steps to follow gradually the PL frequency change.

A subtraction procedure has been developed two decades ago [7-9]. It eliminates almost totally the interference without affecting the signal spectrum:

- moving averaging (comb filter) is applied on linear segments (with frequency band near to zero) to remove the interference components;
- they are stored and further subtracted from the signal wherever non-linear segments are encountered.

PL frequency variations are compensated by continuous hardware measurement resulting in small deviations from the rated sample interval. Later on, software measurement has been proposed [6]. However, the ongoing sampling rate (SR) adaptation of the analogue–to–digital conversion (ADC) is still impeding. This paper deals with an algorithm developed for interference removal without ADC SR modification.

Materials and Methods

The study was carried out in a MATLAB environment. Real ECG recordings were taken from universally acknowledged databases. Sinusoidal interferences were synthesised and the mixed signals were subjected to the developed algorithm and program, which have a structure that simulates real-time going procedure.

The algorithm consists of software PL frequency measurement and two–way signal re-sampling. The first one–way re-sampling substitutes the hardware ADC interval adjustment.

The contaminated signal is processed by band-pass filter from 13 through 20 Hz at –3 dB. The amplitudes of two adjacent samples on a positive-going slope of the interference signal, located below and above the zero line, are measured [6]. Then the crossing point of the interference with the zero line is determined by interpolation. It is used to calculate the ongoing fluctuation of the interference period of repetition, which results in update of the irregular sample intervals and interpolation of the corresponding amplitudes.

The next diagram illustrates rated sample intervals marked by | and sequence of interference intervals, which are indicated by increasing numbers.

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|     |     |     |     |     |     |
   1    2  3     4      5      6
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The amplitudes corresponding to the irregular positions 1, 2 ... are calculated by linear interpolation as

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well as by using the Lagrange's interpolating polynomial

$$y(x)=y_0\frac{(x-x_1)(x-x_2)...(x-x_n)}{(x_0-x_1)(x_0-x_2)...(x_0-x_n)}+y_1\frac{(x-x_0)(x-x_2)...(x-x_n)}{(x_1-x_0)(x_1-x_2)...(x_1-x_n)}+...$$
$$+y_n\frac{(x-x_0)(x-x_1)...(x-x_{n-1})}{(x_n-x_0)(x_n-x_1)...(x_n-x_{n-1})} \qquad (1)$$

applied for n=4 and n=8. In case of linear interpolation, two neighbouring rated samples only are taken in consideration to calculate the inside amplitude at irregular position. Two or four symmetrically located rated samples are included additionally when Lagrange's interpolating polynomial is used with n=4 or n=8, respectively.

In fact, the contaminated signal processed by the band-pass filter is the interpolated one. The study of the problem, supported by the results obtained, shows that this way the accuracy of following the interference frequency fluctuations increases considerably. Nevertheless, high QRS complexes combined with low but not negligible interference may modulate the band-pass filtered signal, thus intolerably shifting the crossing points on the zero line. Therefore, the influence of such QRS complexes is reduced by clipping abrupt high frequency deviations beyond a level corresponding to the reasonably possible rate. In this study, it is assumed to be no more than 0.5 Hz per 8 s, having in mind the inertia accompanying under normal circumstances the load fluctuations of electric power stations.

The second one–way re-sampling restores the signal time scale. The diagram is reciprocal to the previous one.

1 2 3 4 5 6
| | | | |

Results

For correct comparison of the results and assessment of the studied algorithm versions, one and the same AHA 7009 recording is used. It represents a case of trigeminy with steep normal QRS complexes and larger ventricular ectopic beats.

Fig. 1 shows the efficiency of the algorithm. The input 'clean' signal may be seen in the first subplot. The next traces represent: input signal superimposed by interference, which is frequency modulated from 50 through 49.5 Hz; result of applying the algorithm; zoomed difference between the 'clean' and the processed signal. The 'error' remains below ±20 µV, except for some peaks within the normal QRS complexes, which slightly exceed these limits. Besides the very small signal distortions, it contains negligible residual interference as well as eliminated muscle disturbances and other noise belonging to the 'clean' signal. This was proved by synthesized ECG signal without any noise [6]. It was subjected to the procedure but the resultant signal was found identical with the synthesized.

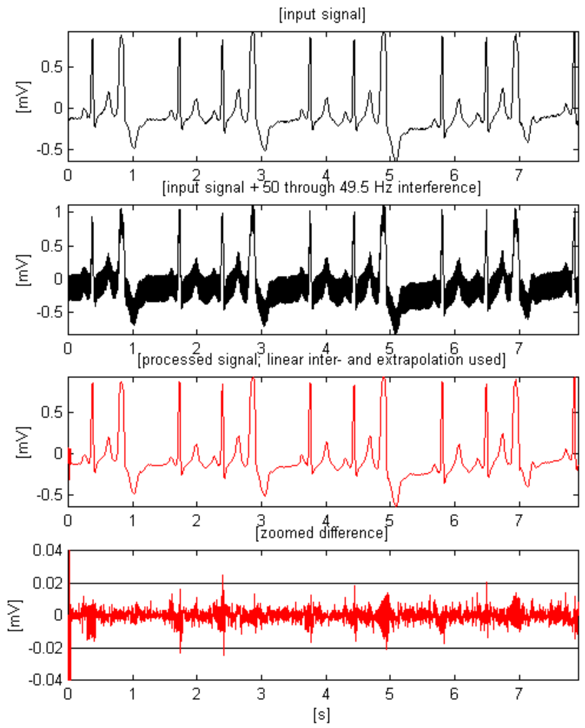

Figure 1: First trace – 'clean' AHA 7009 recording; second trace – the same signal contaminated by interference modulated from 50 through 49.5 Hz; third trace – processed signal; forth trace – zoomed difference

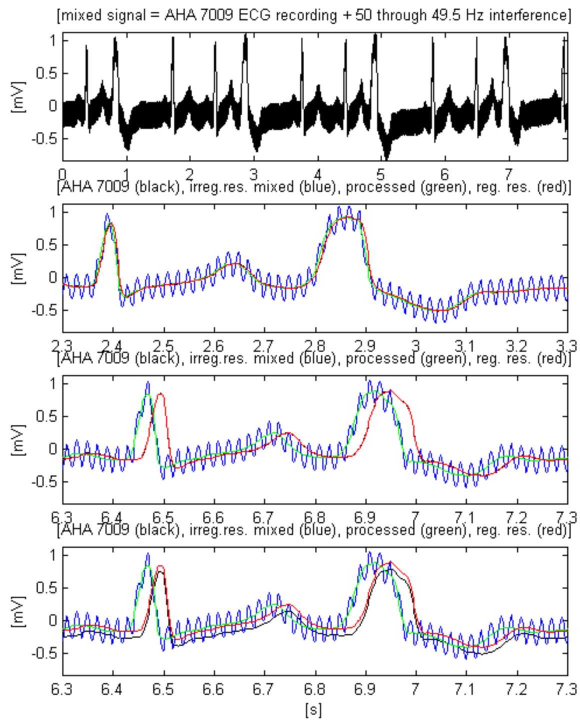

Figure 2: Irregularly re–sampled, processed and regularly back re–sampled contaminated by interference ECG signal

Fig. 2 illustrates the two re-samplings including the intermediate interference cancellation. The first subplot shows the AHA 7009 recording superimposed by the same interference. The next subplots use black colour for the input 'clean' recording, blue for the irregularly

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re-sampled contaminated signal, green for the result of applying the subtraction procedure and red for the regularly back re–sampled signal. The second subplot presents a time-axis zoomed initial part of the recording where the left shifting of the first re–sampled ECG signal may be detected with difficulty because of the small difference in frequency. This is better observed in the final part of the recording (third subplot) except for the input 'clean' signal, which is overlapped by the back re–sampled one. Therefore, the black trace is shifted down in the last subplot.

Fig. 3 shows the case when the frequency modulation of the interference is inverted – from 50 through 50.5 Hz. No significant divergence from the zoomed difference shown in Fig. 1 may be observed. Once more, peaks arise within the QRS complexes.

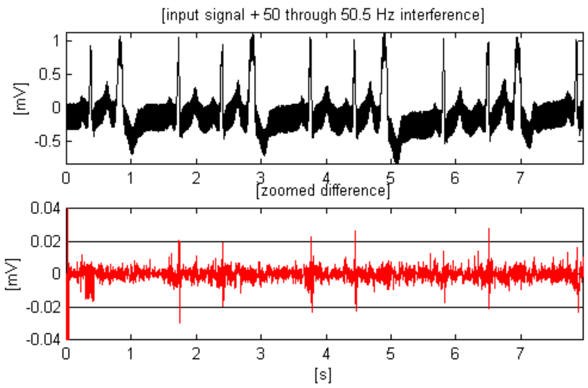

Figure 3: First trace – AHA 7009 recording contaminated by interference modulated from 50 through 50.5 Hz; second trace – zoomed difference between input and processed signal

The next two Figures assess the higher features of the 4 and 8 points Lagrange's re–sampling. As expected, they have smaller errors compared to these obtained with linear interpolation, but the differences are not significant. Besides, the advantage of the 8 points polynomial before the 4 points one is negligible. Therefore, the Lagrange's re–sampling is further abandoned, although its higher complexity does not reflect apparently on the algorithm running time of the modern microcontrollers.

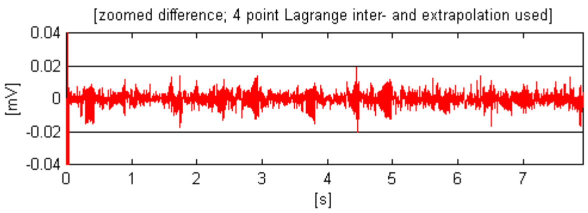

Figure 4: Accuracy obtained with 4 points Lagrange's re–sampling; the errors within the re–sampled QRS complexes are below ±20 μV

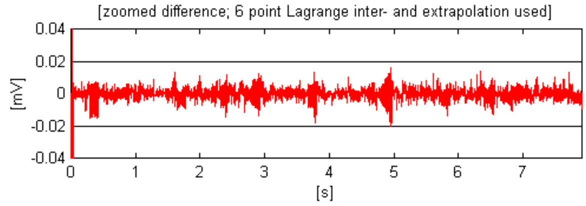

Figure 5: Accuracy obtained with 8 points Lagrange's re–sampling; no meaningful differences compared to the 4 points Lagrange's re–sampling can be seen

As the presented algorithm is a typical process with feedback, the different components of the error cannot be easily assessed. From the other hand, the software measurement of the PL frequency fluctuation is theoretically assumed to give dominant influence on the error. Therefore, the algorithm accuracy is checked first with preliminary calculated frequency course of the used interference instead of measured one. As can be seen in Fig. 6, the software measurement is correct since the zoomed difference is similar to that in Fig. 1.

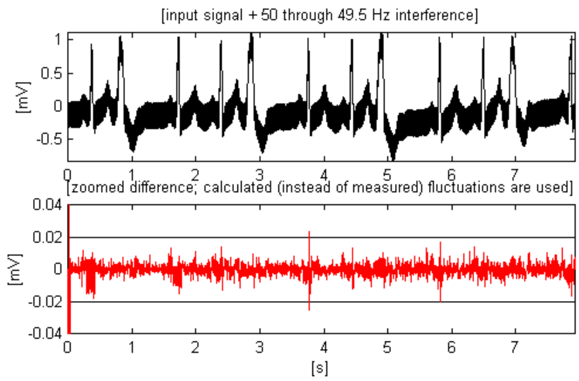

Figure 6: Result of processing the signal with preliminary calculated instead of measured frequency fluctuations; no significant error decrease can be observed

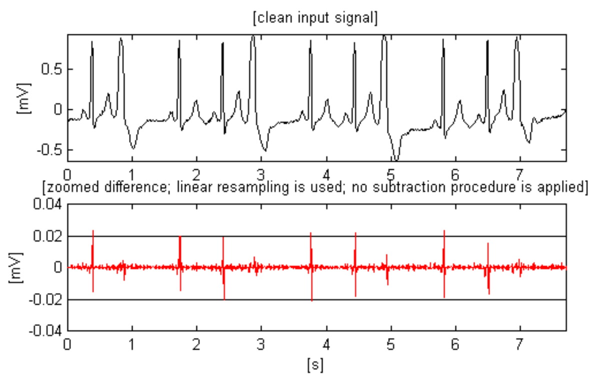

Figure 7: Result obtained on 'clean' input signal; linear re–sampling is used; no subtraction procedure is applied

The error proper to both regular and irregular re-sampling is assessed and shown in Fig. 7. Linear interpolation is applied on 'clean' input signal, which is not subjected to the subtraction procedure. The peaks observed in the second trace are related to the steep and sharp QRS complexes.

The eliminated by the subtraction procedure signal components can be seen in Fig. 8. As mentioned above, negligible part of them is due to the procedure itself. On our case the third trace consists of muscle disturbances that may be found in the input signal.

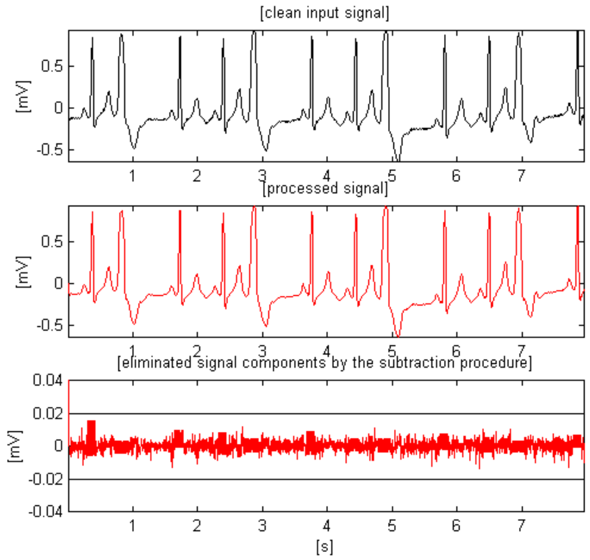

Figure 8: Result obtained on 'clean' input signal. The eliminated signal components are predominantly muscle disturbances, negligible residual interference and extremely small distortions introduced by the procedure

Discussion

The subtraction procedure manifests incontestable advantages when the residual PL interference has to be eliminated without affecting the signal components around the rated PL frequency.

The usually applied hardware synchronized ADC is difficult for implementation in battery–powered instruments and computer aided systems for ECG recording and analysis.

The improved procedure includes additionally developed: i) software measurement of the PL frequency and ii) two–way re–sampling. The assessment of the added errors shows that the part belonging to the first technique is extremely small, while the second one is insignificant for the analysis, even if linear interpolation is used. A reasonable requirement for residual noise of ±20 μV is slightly exceeded within high and sharp QRS complexes only.

The software PL frequency measurement over the irregularly re-sampled signal was found to be the key solution for accurate results. Still, the clipping of unrealistic fast frequency changes due to high and large QRS complexes remains quite necessary.

The algorithm combining the processes illustrated by both diagrams seems to be simple for implementation. However, the real time going sequence of consecutive signal interpolations requires more sophisticated coordination of steps, which are non-alternatively associated with the diagrams.

Conclusions

The developed algorithm for removal of frequency fluctuating PL interference from ECG signals represents a complete procedure regardless of the specific hardware circuits and their accompanying software.

The procedure may become independent of the rated PL frequency by incorporating the presented in [9] algorithm for automatic switching between branches for 50 and 60 Hz, taking in consideration the cases of non-multiple sampling.

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