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Online Digital Filters Applicable to Fast Pulse Wave Detection

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Abstract – **In an emergency, a proper real-time digital filtration is required to facilitate the pulse waveform interpretation and the correct recognition of presence of cardiac pulsations. Two types of digital filters are presented - for baseline drift reduction and waveform noise reduction (smoothing). The high-pass filter for real-time baseline drift reduction implements moving average of a number of signal samples at a predefined distance between them. We demonstrated the performance of a filter with a 0.5 Hz cut-off frequency on two segments of real PPG recordings, selected to contain strong baseline drift. A 20-point moving average low-pass filter was implemented to smooth the waveforms and produce the desired noise reduction. The simple implementation using minimal computing resources makes the proposed digital filters preferable in real-time applications and autonomous monitoring systems. The filters are considered applicable for the fast detection of presence of cardiac pulsations needed in emergency situations.**

Keywords – **Pulse wave detection, Real-time digital filters, Baseline drift, Average filter**

I. INTRODUCTION

In a series of resuscitation guidelines produced by International Liaison Committee on Resuscitation (ILCOR), European Resuscitation Council (ERC) and American Heart Association (AHA) is emphasized that checking the carotid pulse by palpation is an inaccurate method of confirming the presence or absence of circulation [1,2]. The time for a single pulse check is limited to no more than 10 seconds for healthcare providers. In relation to this, the design and usage of a specialized pulse wave detector in an emergency would be of great diagnostic significance.

Photoplethysmography (PPG) is a widespread optical technique for noninvasive monitoring of arterial pulsations. It is based on the detection of light reflected from or transmitted through tissue which intensity is modulated by the pulsating blood flow in the measurement site. The PPG waveform comprises a pulsatile ('AC') physiological waveform attributed to cardiac synchronous changes in the blood volume with each heart beat. It is superimposed on a slowly varying ('DC') baseline with various lower frequency components attributed to respiration, sympathetic nervous system activity and thermoregulation [3]. Intensive movement artifacts are common in an emergency too.

Digital filtering of the registered pulse wave is required to reject the baseline drift, along with other low-frequency signal components, and to smooth the pulse waveform. This will facilitate the subsequent waveform interpretation and the proper detection of the individual cardiac pulsations. Pulse wave detection in an emergency demands for fast computation methods for real-time digital filtration. Digital filters with integer coefficients are preferable in real-time operating systems with low power consumption and therefore limited computational resources [4,5].

The subject of the present work are two types of digital filters - for baseline drift reduction and waveform smoothing, applicable for fast detection of cardiac pulsations.

II. METHODS

A. High-Pass Filter

The proposed high-pass filter for real-time baseline drift reduction implements moving average of a number of signal samples at a predefined distance between them [4,5]. The filter, named *FilterDxN*, is designed according to equation (1):

$$y[i] = x[i] - \frac{1}{N} \sum_{j=-(N-1)/2}^{(N-1)/2} x[i + jD] \ , \qquad (1)$$

where *x* [ ] is the input signal, *y* [ ] is the output signal, *D* is the distance between the averaged samples (as a number of samples); *N* is the number of points in the average. An odd number N is required to avoid phase shift between the input and output signals.

The frequency response of *FilterDxN* resembles a comb filter – Fig.1. The zeros of the filter, f_0, occur at integer multiples of the ratio of sampling frequency F_s to *D.*

$$f_0 = k \frac{F_s}{D} \ , \qquad (2)$$

where k=0,1,2… The high-pass cut-off frequency f_c and the number of ripples in the pass-band are defined by the number of points in the average *N.* A frequency response with various cut-off and zero frequencies could be easily designed for a predefined F_s by choosing *D* and *N.* The frequency response in Fig.1 is calculated for sampling frequency Fs=250 Hz. Fig.2 shows the zoomed-in low frequency range. The three example combinations of D and N coefficients: Filter15x25, Filter 20x19 and Filter 10x17, produce low cut-off frequency of 0.5 Hz, 0.5 HZ and 1.1 Hz respectively.

Another important parameter is the time-interval for averaging $\frac{DN}{F_s}$, which defines the operational time-delay of the filter's output sample to the last input sample considered in the filter's equation.

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A particular benefit of the proposed *FilterDxN* is the simple implementation by means of a linear equation with integer coefficients. *FilterDxN* provides very fast filtering procedure at the price of minimal computing resources. That makes it preferable in real-time applications and autonomous monitoring systems. A disadvantage is the ripples in the pass-band.

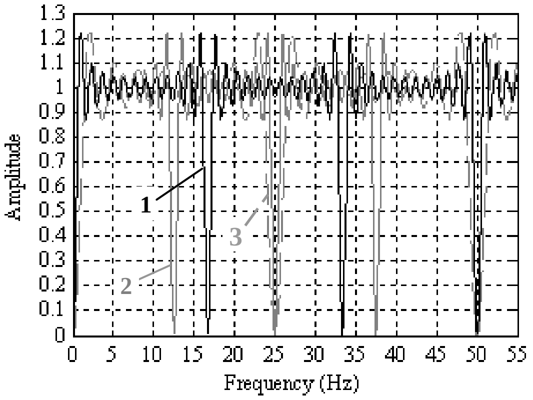

Fig.1. Frequency response of *FilrerDxN*, calculated for Fs=250 Hz: 1) Filter15x25 (fc=0.5Hz); 2) Filter 20x19 (fc=0.5Hz); 3) Filter 10x17 (fc=1.1Hz);

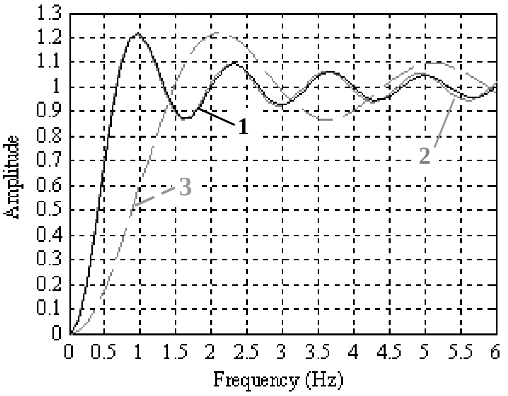

Fig.2. Frequency response – zoom in the low frequency range: 1) Filter15x25; 2) Filter 20x19; 3) Filter 10x17

B. Smoothing Filter

The moving average filter operates by averaging a number of points from the input signal to produce each point in the output signal [6]. When the points from the input signal are chosen symmetrically around the output point, and an odd number of samples N is used, in equation form this is written:

$$y[i]=\frac{1}{N}\sum_{j=-(N-1)/2}^{(N-1)/2}x[i+j] \quad , \qquad (3)$$

where $x[\ ]$ is the input signal and $y[\ ]$ is the output signal. This equation form is usually preferred since it produces no phase shift between the input and output signals. If such a phase shift is tolerable, an even number of samples N may be used too with the summation in equation (3) running from j=-N/2 to N/2. Yet another alternative for the index j is to run from 0 to (N-1). There is also possibility to use an even number of points N and to avoid the phase shifting. This may be accomplished when we smooth the smoothed values again with N=2. This leads to a little bit more complicated formula.

Multiple-pass moving average filters involve passing the input signal through a moving average filter two or more times. They have better frequency domain performance.

Figure 3 shows the frequency response of the moving average filter, calculated for F_s=250 Hz, as follows: 1) 15-point, two pass; 2) 20-point; 3) 15-point; 4) 10-point, two pass; 5) 10-point. As can be seen, the moving average is a very poor low-pass filter (the action in the frequency domain), due to its slow roll-off and poor stopband attenuation. In the time domain, however, the moving average is an exceptionally good smoothing filter. It is optimal for reducing random white noise while keeping the sharpest step response. The amount of noise reduction is equal to the square-root of the number of points in the average.

In addition, this digital filter is the fastest one available. Multiple passes of the moving average will be correspondingly slower, but still very quick.

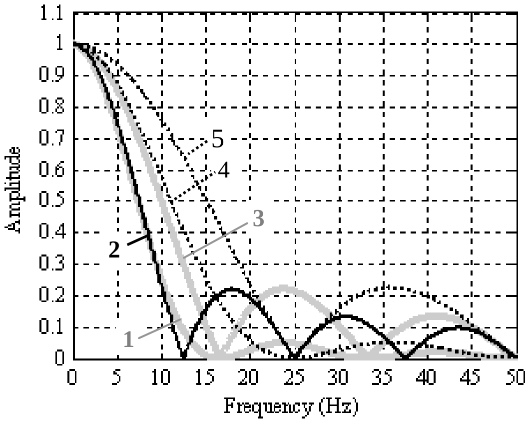

Fig.3. Frequency response of the moving average filter, calculated for Fs=250 Hz: 1) 15-point, two pass; 2) 20-point; 3) 15-point; 4) 10-point, two pass; 5) 10-point

III. RESULTS

The proposed digital filters are applied on real PPG waveforms (Fig.5, Fig.8), recorded from the region of the neck by an especially designed pulse wave detector [7]. A pulse wave detector must be able to recognize cardiac pulsations with a heart rate from 0.5 Hz (30 bpm (beats per minute)) to 4-5 Hz (240-300 bpm). Since the identification of presence of pulsations, not the shape of the waveform is important in an emergency, the signal was first filtered in

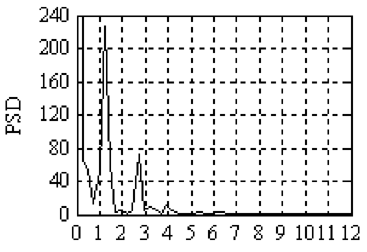

Fig.4. An example of a real PPG frequency spectrum, calculated for the recording in Fig.5

hardware using a first order low-pass filter with a quite low cut-off frequency – about 12 Hz. A hardware first order high-pass filter with a 0.5Hz cut-off frequency was also provided. The waveform was sampled at 250Hz, 8-bit. An example PPG frequency spectrum, calculated for the signal segment in Fig.5, is shown in Fig.4.

The signal processing is implemented in the software package MATLAB.7.0.

A. High-Pass Filter

A high-pass cut-off frequency of 0.5 Hz corresponds to the lowest heart rate of 30 bpm. A common approach is to design a comb filter with a zero at 50 Hz frequency, which ensures power-line interference rejection. For Fs=250 Hz, the possible values for D are 5, 10, 15 and 20, according to equation (2). For a fixed cut-off frequency, a greater value of D corresponds to a smaller N and less computations according to equation (1). The values of N that define a 0.5 Hz cut-off for D=15 and D=20 are N=25 and N=19 respectively. The frequency responses of *Filter15x25* and *Filter20x19* are shown in Figs. 1 and 2. Filter 15x25 is preferred due to the lower amplitude of the pass-band ripples in the range 6-12 Hz. Filter 15x25 has time for averaging of 1.5 seconds, which defines the operational time-delay of the filter's output. The performance of Filter15x25 was assessed by means of two segments of real PPG recordings, selected to contain strong baseline drift. The original waveforms with heart rates of 75 bpm (1.25Hz) and 101 bpm (1.68 Hz) are shown in Figs. 5 and 8 respectively. The corresponding filtered waveforms are presented in Figs. 6 and 9. As can be seen, the baseline drift was successfully removed.

B. Smoothing Filter

The smoothing filter must have a low-pass cut-off frequency of above 5 Hz, which corresponds to the highest heart rate of 300 bpm. A common approach is to design a comb filter with a zero at 50 Hz frequency, which ensures power-line interference rejection. Such filters, for example, are 15-point two pass, 20-point, 15-point, 10-point two pass and 10-point moving average filters. The frequency responses of these filters are shown in Fig.3. Data about the filters are summarized in Table1, namely the first zero frequency, the cut-off frequency and the amplitude at 5 Hz. Since the high-frequency interference and signal components are well suppressed by a hardware filter, a one-pass moving average filter is adequate for the present implementation. In addition, a phase difference between input and output signals is admissible, so a simple even-point moving average could be applied. We chose the 20-point moving average filter because of its best noise reduction. The filter has 0.08 sec time for averaging.

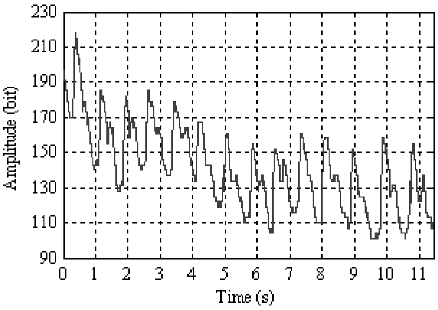

Fig.5. A segment of a real PPG recording, containing baseline drift, 75 bpm heart rate (1.25Hz)

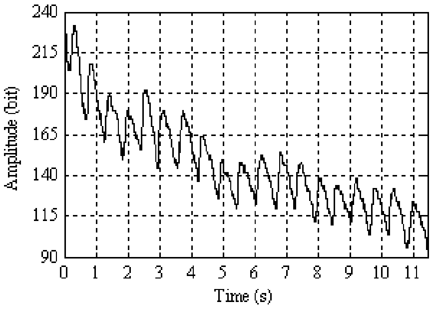

Fig.8. A segment of a real PPG recording, containing baseline drift, 101 bpm heart rate (1.68 Hz)

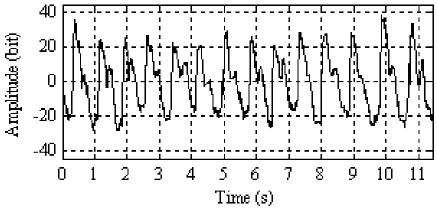

Fig.6. High-pass filter performance: the output of *Filrer15x25* for the input signal in Fig.5

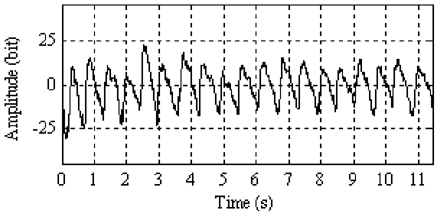

Fig.9. High-pass filter performance: the output of *Filrer15x25* for the input signal in Fig.8

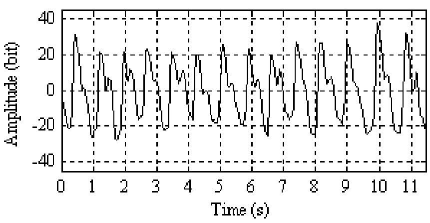

Fig.7. Smoothing filter performance: the output of a *20-point* moving average for the input signal in Fig.6

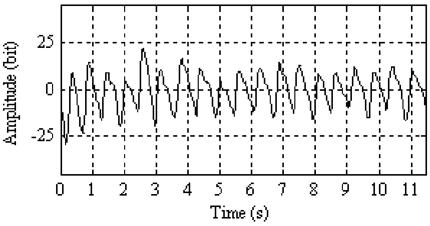

Fig.10. Smoothing filter performance: the output of a *20-point* moving average for the input signal in Fig.9

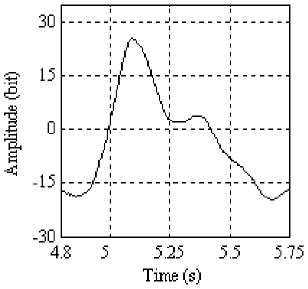

Fig.11. Smoothing filter performance: the output of a *20-point* moving average for the input signal in Fig.6 – a zoomed-in pulsation

The filter's performance was demonstrated using the waveforms with already removed baseline drift in Figs. 6 and 9 as input signals. The corresponding filtered waveforms are presented in Figs. 7 and 10. A zoomed-in single pulsation from the filtered record in Fig.7 is shown in Fig.11. As can be seen, the waveform was successfully smoothed.

III. DISCUSSION AND CONCLUSIONS

In an emergency, the monitoring devices operate under unfavorable environment and intensive movement artifacts. A proper real-time digital filtration is required to facilitate the waveform interpretation and the correct recognition of the individual cardiac pulsations. The identification of presence of pulsations, not the shape of the waveform is important in an emergency.

Two types of digital filters are presented in the present work: a high-pass filter for baseline drift reduction and a low-pass filter for PPG waveform noise reduction (smoothing).

The proposed high-pass filter for real-time baseline drift reduction, named *FilterDxN*, implements moving average of a number of signal samples at a predefined distance between them. In our implementation (sampling frequency of 250 Hz) we applied averaging over 25 samples distanced by 15 samples (*Filter15x25*), thus realizing a comb filter with a high-pass cut-off frequency of 0.5Hz (corresponding to the lowest heart rate of 30 bpm) and a zero at 50 Hz. We demonstrated the performance of *Filter15x25* on two selected segments of real PPG recordings with heart rates of 75 bpm (1.25Hz) and 101 bpm (1.68 Hz). The strong baseline drift in the original waveforms was successfully removed.

If signal segments disturbed by extremely high-frequency high-amplitude drift occur, it may be reasonable to temporarily switch over to a filter having a higher cut-off frequency (1.1 Hz for example). Such a compromise will provide better signal quality for the normal and high heart rates. At the very low heart rates, however, the waveform will be considerably distorted, since the fundamental frequency in the spectrum will be suppressed. Only the rising edge of the pulse wave may still remain discernible for the detection software, since it comprises higher frequency components.

The moving average low-pass filter operates by averaging a number of points from the input signal to produce each point in the output signal. In our implementation (sampling frequency of 250 Hz) we applied averaging over 20 consecutive samples to achieve a comb filter with a low-pass cut-off frequency of 5.5Hz (to accommodate the highest heart rate of 240-300 bpm) and a zero at 50 Hz.

TABLE1. MOVING AVERAGE FILTER

Filter	15-point two pass	20-point	15-point	10-point two pass	10-point
First zero (Hz)	16.7	12.5	16.7	25	25
fc (Hz)	5.4	5.5	7.5	8.1	11
Amplitude at 5Hz	0.74	0.76	0.86	0.88	0.94

The filter's noise reduction was demonstrated on the two test PPG signals with heart rates of 75 bpm (1.25Hz) and 101 bpm (1.68 Hz). The waveforms were successfully smoothed. With very high heart rates, due to the filter's cut-off frequency of 5.5 Hz, the high-frequency signal components will be suppressed and the shape of the waveform will begin to resemble a sine wave. The signal amplitude will also decrease (up to 76% at 5 Hz) due to the slope in the filter's frequency characteristic. These waveform distortions, however, may be considered tolerable, since they will probably not prevent the detection of presence of pulsations.

In conclusion, the proposed online digital filters provide real-time baseline drift and noise reduction using minimal computing resources. That makes them preferable in real-time applications and autonomous monitoring systems. The filters are considered applicable for the fast detection of presence of cardiac pulsations needed in emergency situations.

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