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Evaluation of the Effect of Step Size on Delta Modulation for Photoplethysmogram Compression

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Abstract

In this paper, delta modulation (DM) is employed as a compression technique for a high-resolution photoplethysmogram (PPG) signal. To accommodate both clean PPG and signals affected by motion artifacts, the effect of step size is evaluated on the performance of DM in order to optimize this technique before it can be deployed in a wireless data acquisition system. To this end, the PPG was recorded using 16-bit analog-to-digital converter (ADC) at a 1000 Hz sampling rate. In order to take into consideration the effect of the DC and AC of the PPG during the performance evaluation, both the $PRMS_{AC+DC}$ (with DC component) and $PRMS_{AC}$ (without DC component) were estimated. As expected, results show that the $PRMS_{AC+DC}$ was lower than $PRMS_{AC}$ at all step sizes. Simulation results show that for clean PPG free of motion artifact the optimum step size required to decompress the PPG is $V/(2^{-15}-1)$ with a $PRMS_{AC} = 4.7\%$; $PRMS_{AC+DC} = 0.1\%$, where V is the dynamic range of the ADC. For PPG affected by motion artifact, the optimum step size required to decompress the PPG is $V/(2^{-14}-1)$ with a $PRMS_{AC} = 4.9\%$ and $PRMS_{AC+DC} = 0.12\%$. The closeness of these values to the finest possible step size $V/(2^{-16}-1)$ can be explained by the relatively high sampling rate compared to the Nyquist frequency of the PPG.

Keywords: Data compression; Photoplethysmogram; Motion Artifact; Delta Modulation

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1. Introduction

Photoplethysmography is a non-invasive optical technique used to measure the blood volume changes in the microvascular bed of tissue. The photoplethysmogram (PPG) signal contains AC and DC component. The DC component signal is due mainly to absorption of light by non-pulsating arterial blood, venous blood and bone while the AC component is due to absorption of light by pulsating arterial blood [1, 3]. An AC component of the PPG signal provides valuable information related to the vascular and hemodynamic properties of human subjects [1, 2, 9]. Multi-channel PPG recording systems [1, 3, 9, 10] have been developed by various researchers to study the relationship between pulse wave velocity and cardiovascular diseases [3].

The development of portable instruments would increase the patient comfort level and ease for real time data acquisition [4]. The design and development of wireless data acquisition system are always limited by power consumption, storage capacity, computational and hardware capability [5]. Storage capacity and communication bandwidth could be addressed by introducing the data compression algorithm in the wireless data acquisition system.

Data compression algorithms have been deployed which are suitable for electrocardiograms (ECG) and electroencephalograms (EEG) in order to store and transmit the signals to the system host for analysis [6-8]. High resolution, real-time and wireless data acquisition systems may require data compression in order to reduce data size. Delta Modulation (DM) compression has been extensively utilized for audio signals, and algorithms for PPG signals have been developed where pulse code modulation (PCM) was the reference [11]. The compression ratio of the DM compression algorithm in this case was around 16. The DM compression algorithm uses direct data compression where a ‘1’ and ‘0’ represent a greater than or less than condition, respectively compared to the previous sample. An integer and step size is used to convert the stored bit stream into an analog signal later.

But PPG signals are often affected with motion artifact, which affects the quality of the PPG signal [12]. Motion artifact will deform PPG signal and affect the decompressed PPG signal. Therefore, choosing the suitable step size for DM is critical as it may affect the PPG signals for both conditions of with and without motion artifact. The objective of this paper is to determine the effect of the step size using the DM algorithm on the PPG waveform under two different conditions: with and without motion artifact. Even though the compression ratios (CR) are similar, the performances in terms of signal reconstruction are different.

2. Methodology

2.1. Data acquisition

The PPG signal was recorded from a 25 year old healthy male for 4 seconds by using a transmission PPG probe (NELLCOR DS-100A). Two types of PPG signals were recorded: a clean PPG signal (Fig. 1) and a PPG signal with motion artifact (Fig. 2). The analog PPG signal was sampled at 1000 samples per second using a 16-bit analog to digital converter, ADS 1198 (Texas Instruments, Inc). The digitized PPG signal was sent to a personal computer (PC) via USB and saved as an ASCII file. MATLAB (The MathWorks, Inc.) software is used to implement the DM algorithm with various step sizes.

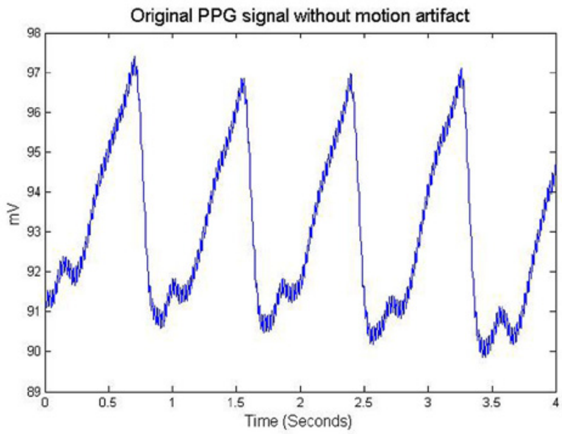

Fig. 1. Four second sample trace of a clean section of a photoplethysmogram sampled at 16-bits, 1000 Hz

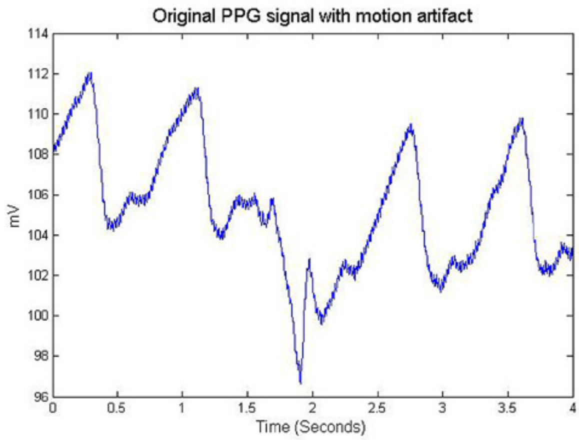

Fig. 2. Four second sample trace photoplethysmogram with motion artifact sampled at 16-bits, 1000 Hz

2.2. Delta modulation (DM) with variable step sizes

Various step sizes have been used to evaluate the quality of the compressed PPG signal with and without motion artifact. Step size is defined in Eq. 1. The data compression ratio (Eq. 2) and percentile root mean square error (PRMS) (Eq. 3 and Eq. 4) were used as performance indices.

$$\text{Step size} = \frac{\text{Vmax} - \text{Vmin}}{2^{\alpha} - 1} \tag{1}$$

$$\text{Compression Ratio (CR)} = \frac{\text{Uncompressed data size}}{\text{Compressed data size}} \tag{2}$$

$$PRMS_{AC} = \sqrt{\frac{\sum_{i=1}^{n}((x_i-\Delta)-x'_i)^2}{\sum_{i=1}^{n}(x_i-\Delta)^2}} .100\% \quad (3)$$

$$PRMS_{AC+DC} = \sqrt{\frac{\sum_{i=1}^{n}(x_i-x'_i)^2}{\sum_{i=1}^{n}x_i^2}} .100\% \quad (4)$$

Where α is the number of bits, x_i is the original signal, x'_i is the reconstructed signal, n is the total number of samples, Δ is the mean of the original signal (DC component of PPG signal), Vmin is the ground reference and Vmax is the reference voltage for the ADC. In this work, Vmin == 0, Vmax = 2.4 V.

To better reflect the ability of the DM in reconstructing the pulsatile part of the PPG, Eq. 3 is used to calculate the PRMSAC of PPG signal with an AC component by eliminating the DC component in the photoplethysmogram. Eq. (4) is used to calculate the PRMSAC+DC of PPG with AC and DC component. Table 1 shows the calculated step sizes in Volt and its number of bits using Eq. 1. When the number of bit increases, the step size (Volt) decreases. The maximum value for α is 16 which corresponds to the full 16-bit ADC resolution. To better reflect the results, the value of α has been limited from 11 to 16.

Table 1. Calculated step sizes.

Number of bits, α	Step Size (μV)
12	1170
12	590
13	290
14	150
15	70
16	40

3. Results

Fig. 3 and 4 show the decompressed PPG signal for an artifact-free PPG with α = 15 and 16. The decompressed signal characteristic is closer to the original signal when α = 15. A smaller step size is obtained for a larger α = 16 vs. α = 15. When the number of bits increases (a smaller step size being employed), the decompressed PPG signal deviates from the original PPG signal. This phenomenon is known as slope overload.

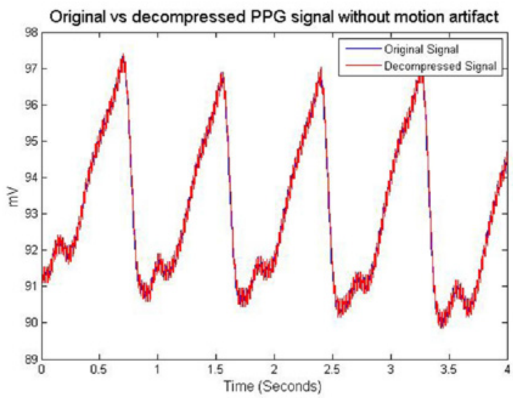

Fig. 3. Original 16 bits PPG signal (blue); Decompressed PPG (red) signal with α =15.

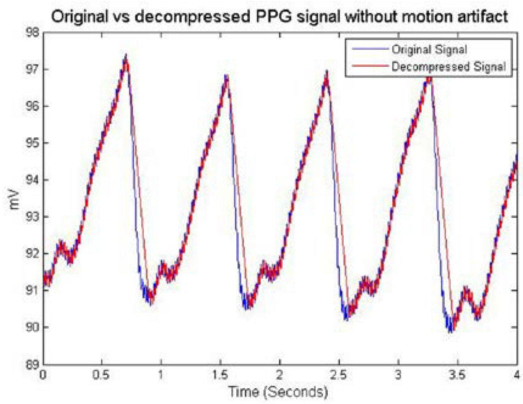

Fig. 4. Original 16 bits PPG signal (blue); Decompressed PPG signal (red) with α =16.

Fig. 5 and 6 show the decompressed signal with motion artifact effect for α = 15 and 16. Similar to Fig. 3 and 4, when the number of bits increases, the decompressed signal deviates from the original PPG signal characteristic due to the slope overload effect.

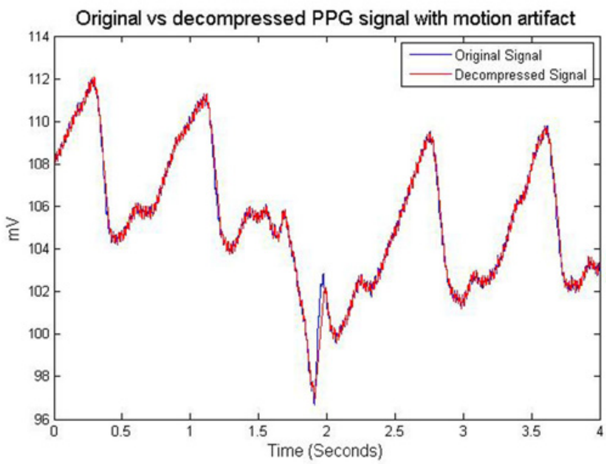

Fig. 5.Original signal PPG signal with artifact (blue); Decompressed PPG signal with artifact (red) with α =15

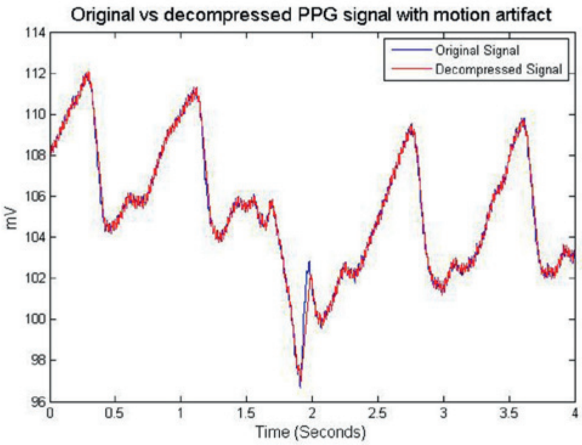

Fig. 6. Original signal PPG signal with artifact (blue); Decompressed PPG signal with artifact (red) with α =16.

It is noteworthy to mention that under all simulation cases, the CR is very close to 16. Fig. 7 shows the $PRMS_{AC+DC}$ of PPG signal with motion artifact and without motion artifact under different step sizes. From Fig. 7, the least $PRMS_{AC+DC}$ value was 0.1% (step size = 70 μV) with motion artifact and 0.12% (step size = 150 μV) without motion artifact. This is due to the fact that the reconstructed signal with motion artifact requires smaller step size to track back the signal when there is a large change of signal amplitude. The least $PRMS_{AC+DC}$ value for reconstructed PPG signal without motion artifact occurred when α=15. This is because the maximum signal to noise ratio (SNR) of the signal occurred when α equal to 15. When α increases to 16, the largest step size will capture the noise into the reconstructed signal. As such, the $PRMS_{AC+DC}$ value for α=16 is higher than α=15.

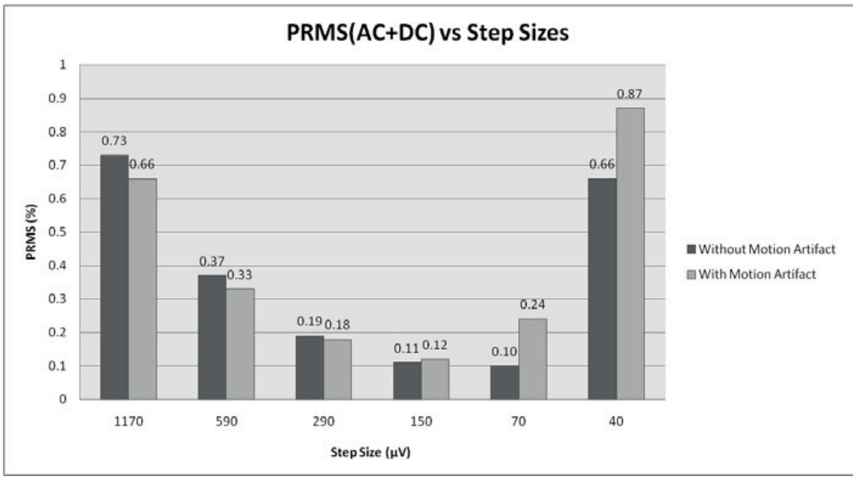

Fig. 7. Comparison between $PRMS_{AC+DC}$ versus step sizes (μV).

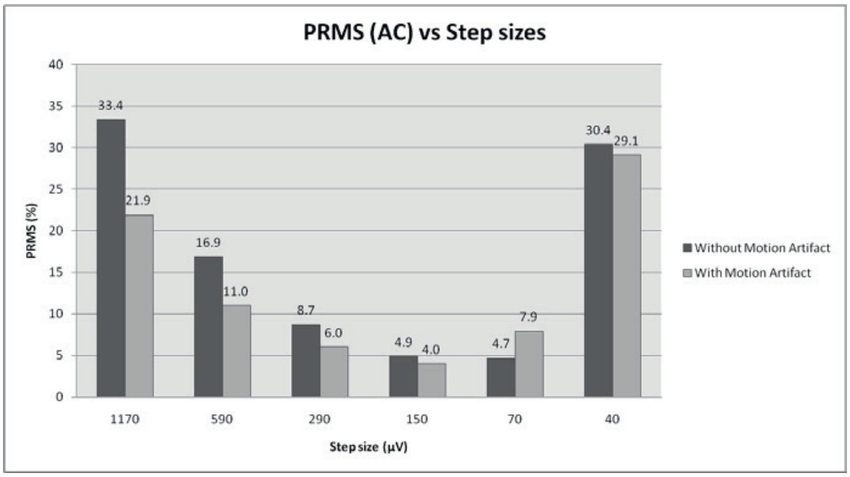

Fig. 8. Comparison between $PRMS_{AC}$ versus step sizes (μV).

Fig. 8 shows the $PRMS_{AC}$ of PPG signal with motion artifact and without motion artifact with various step sizes. Noticed that the $PRMS_{AC}$ value (Fig. 8) is higher than $PRMS_{AC+DC}$ value (Fig. 7). Normally, the DC component of the PPG signal is higher than the AC component. Any disturbance on AC component will be greatly altered the PPG signals since it does not contain DC component. From Fig. 8, the least $PRMS_{AC}$ value without and with motion artifact is 4.7% (step size = 70μV) and 4% (step size = 150μV), respectively. The PPG signal without motion artifact required less number of bits compared with PPG signal with motion artifact. Higher step size is required to trace the PPG signal with motion artifact. When the number of bits is too small, the decompressed PPG signal loss its characteristic and the $PRMS_{AC}$ also increased. When the step size is small ($\alpha = 16$), the $PRMS_{AC}$ increase due to slope overloading effect. The smaller the step size, the more step is required to track the signal.

4. Conclusion

The least PRMS value with different step size has been investigated using PPG signal with and without motion artifact. Based on the simulation results, the best step size for DM implementation in the AC PPG reconstruction was obtained for $\alpha = 15$ bits when there is no motion artifacts and $\alpha = 14$ bits when one is interested to reconstruct faithfully motion artifacts. Depending on the particular application, the proper step size can be selected. The closeness of the α values to the maximum (16) is probably due to the high sampling rate which exceeds by far the Nyquist rate of the PPG signal.

A variable step size of DM algorithm will result in the lowest possible PRMS automatically even with the existence of motion artifact in the PPG signal. An area of improvement in the DM technique is to investigate and develop an adaptive delta modulation algorithm to compress the PPG signal.

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