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ASCII-character-encoding based PPG compression for tele-monitoring system

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ABSTRACT

Photoplethysmogram (PPG) is becoming one of the most important techniques for assessing several vascular parameters, but the area of digitized PPG signal compression still remains largely unexplored. This paper presents an efficient PPG compression algorithm, and is developed on the basis of five major sequential steps: noise elimination through Butterworth low-pass filter, down-sampling, inter-sample difference computation, grouping and American Standard Code for Information Interchange (ASCII) character encoding of reduced dataset. The compressed file is then either uploaded to a Hypertext Preprocessor (PHP)-based web-application or transmitted to doctor's mobile phone in the form of short message service (SMS) depending upon the availability and feasibility of services. Efficiency of the compression algorithm is measured in terms of compression ratio and the performance of the reconstruction protocol is tested through a variety of numerical assessments such as the cross correlation coefficient and percent root mean square difference. As per the gold standard subjective measure, the mean-opinion-score of the reconstructed signal is found to be 'very good'. Finally, heart rate is also calculated with no more than 1.68% error from the compressed data without actually reconstructing the signal.

1. Introduction

Photoplethysmogram (PPG) is a non-invasive measurement technique developed by A.B. Hertzman in 1938 [1] that measures relative blood volume changes in the blood vessels. The signal can be easily acquired by using a light source (usually infrared light) to send light into the tissue and then measuring the amount of the backscattered light corresponding to the variation of the blood volume via a photo sensitive element [2]. The measurement is absolutely independent of individual skin color, thickness and blood volume [3]. Since 1987, the technique has been accepted as the standard measure of oxygen-saturation level by the International Standards Organization (ISO) and European Committee for Standardization [4].

PPG is a low-frequency signal and it does not contain clinical information above 15 Hz [5,6]. Use of lowpass or bandpass filters having higher cutoff frequency up to 40 Hz of different orders (up to 8th order) have been reported for de-noising the PPG signal [7,8].

Recently, researchers have hypothesized the ability to extract additional information embedded in the PPG signal and it has become an indispensable tool for detecting and diagnosing the heart rate (HR) [9] and heart rate variability (HRV) [10], Blood oxygen saturation (SpO_2) [11], blood pressure [12], respiratory rate [13], sleep apnea [14], blood glucose [15], etc. In [14], a study of HRV for obstructive sleep apnea syndrome screening is presented. A PPG-based non-invasive blood-glucose estimation technique is reported in [15]. A robust PPG feature extraction algorithm (detection of systolic and diastolic waves) is proposed in [16] for estimating arterial stiffness, hypertension and cardiovascular ageing using these extracted feature. Recent research findings have also shown that PPG signal contains sufficient information to be used in biometric applications. A PPG based robust face detection method in video stream is proposed by Gibert et al. in [17].

Since bio-signals are highly subjective, symptoms of physical or cardiac abnormalities may appear at random in the timescale [18]. Hence, bio-signal pattern analysis has to be carried out for extended periods of time (24 h monitoring) [10]. Therefore, the volume of the data handled would be enormous. Researchers from different parts of the world are continuing to develop dedicated, high performance and reliable biomedical signal compression-reconstruction algorithms exploiting various signal processing techniques. Standard compression algorithms such as Huffman coding (HC) and run length encoding (RLE) are sometimes used as part of a multi-layered compression algorithm [19,20].

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Only a few attempts have been made so far in recent days addressing the issue of PPG data compression [19,21–25]. In [22,23], Reddy et al. proposed a technique for removal of motion artifacts (MA) from a PPG signal using cycle-by-cycle Fourier series analysis (CFSA). The CFSA method represents each PPG cycle with a reduced set of Fourier coefficients, which enhances the storage efficiency by 12 times. In [21], delta modulation (DM) is used to compress digitized PPG signal, where the step size is fixed to $1/2^{16}$. A major disadvantage of using a fixed and very small step size is that it cannot track high-slope regions and introduces slope overload. On the other hand, to get better performance, i.e., less reconstruction error, the PPG signal must be sampled at a much higher rate which increases the size of the data. Hence, DM-based techniques might not be suitable for PPG signals recorded at very low sampling rates. However, DM-based techniques produce a train of '1' at each rising edge of the PPG cycle, which can be used to count the number of systolic peaks and hence, the HR from the compressed data. A real-time, low-complexity and lossless PPG compression technique based on second-order delta and HC is proposed in [19]. Alam et al. proposed a modified delta-modulation and RLE-based PPG compression technique in [25]. They categorize the whole PPG signal into two zones, viz., 'complex' or 'plain' based on thresholding. These zones are quantized and then a compression algorithm is applied. However, the compression ratio obtained using these two algorithms ([19,25]) are too low to be used in real time remote monitoring applications. Moreover, since HC and RLE transform the signal into a completely new domain, it is also not possible to calculate the HR from the compressed data using these two methods. In [39], a new paradigm, called compressive sampling (CS) technique is used to acquire the PPG signal. Since the PPG signal is sparse in the frequency domain, the use of non-uniform-sampling-based CS technique could be beneficial in acquiring the PPG signal [40]. This enables the acquisition of the PPG signal at a rate which is below that of the Nyquist and results in significant power savings. These advantages are exploited in [39] and it is shown that using the CS-based techniques, the data-size can be reduced by a factor of 30 over that of using uniform sampling. Moreover, the Lomb-Scargle periodogram technique is used in [39] for the spectral analysis of the compressively sampled PPG signals and the spectrum thus obtained is used to calculate the average HR and HRV with standard accuracy. In [41], a very low-power (172 μW), fully integrated CS-based PPG acquisition, and real-time HR and HRV extraction system was developed. The algorithm and the techniques presented in [39,41] are able to calculate HR from the compressed PPG. As described in [39], the main problem associated with the CS-based data acquisition technique is that the compressed data need to be processed through a complex convex optimization technique to be restored fully. The algorithm proposed in this paper differs from the above two in many aspects such as: (1) the compression operation is performed in [39,41] at the time of PPG acquisition, whereas the proposed compression algorithm is applicable on the acquired PPG signal, (2) the proposed algorithm can reconstruct the time-domain PPG signal using the algorithm that is a reverse of the compression algorithm and the reconstruction process does not depend on the compression ratio, but the algorithm proposed in [39] is unable to reconstruct the PPG signal if the compression ratio exceeds a certain limit and (3) since the proposed compression algorithm is applicable only on the uniformly-sampled PPG data, the sampling instances does not have to be stored, whereas the technique proposed in [41] needs to store the non-uniform sampling instants corresponding to each compression ratio in a lookup table.

Compression of biomedical signals is not only essential for reducing the storage overload, but also for efficient use of transmission bandwidth in real time tele-monitoring applications over wired/wireless communication networks. In recent years, a number of mobile tele-monitoring systems have been designed using different communication technologies such as global system for mobile communication (GSM), code division multiple access and wireless mesh networks [26]. Short message service (SMS) was also used in [27,28] to transmit compressed biomedical signals to a remote healthcare center or to an expert. A number of web-applications and cloud computing-based tele-monitoring systems have been reported in recent years [29–31]. In [30], Hsieh et al. proposed a cloud and pervasive computing-based 12-lead ECG tele-diagnosis system. Discharged patients' health-related quality of life (HRQoL) and vital signals monitoring system for domestic care is proposed in [31]. It is predicted that by the year 2050, 20% of the global population will be at least 60-years of age [32]. Tele-monitoring/tele-healthcare could be a solution to defer institutionalizing older persons and reducing the overall expenditure. Objective of all these tele-monitoring systems is to continuously monitor patients' vital sign and health status to ensure better healthcare service. Insufficient healthcare services and acute shortage of medically-trained staff personnel are serious healthcare issues in developing and underdeveloped nations [28]. Motivation behind the design of this proposed PPG compression and tele-monitoring architecture is to develop a user-friendly and fast PPG processing system, which can efficiently compress and transmit digitized PPG signal, thereby spreading the healthcare facilities beyond the hospital boundary.

In this research work, dedicated PPG signal compression and reconstruction algorithms are developed. First, the PPG signal is de-noised using a Butterworth low-pass filter and the sampling frequency (SF) is reduced. Then the first difference of the down-sampled PPG signal is computed. Those numbers are amplified, neighbor integers logically merged (grouping) and finally printed in the output in their corresponding ASCII characters. It is well known that the size of an ASCII character is 1-byte (8-bit) and a single byte allows a numeric range from 0 through 255. Hence, all the information that is to be printed in the output file must be within this numeric range. There are several advantages of having ASCII characters in the output file. First of all, it can be transmitted using most of the communication protocols (GSM, General Packet Radio Service (GPRS), web-based system, SMS etc.) without any further processing and secondly, standard ASCII compression algorithms (HC, RLE etc.) can further be used to recompress the data. The protocols used here in this research for remote data-transmission are web-application and SMS. PPG signal is reconstructed using the reverse programming approach. The algorithm can also calculate the HR from the compressed PPG data and thereby reduce the delay.

A few ASCII-character-encoding-based ECG compression techniques have been proposed by Mukhopadhyay et al. in [33–35]. The PPG compression algorithm presented here is different from those in many aspects:

(1) The ECG compression techniques in [33–35] are implemented on C platform, whereas MATLAB is used here for coding and developing the algorithm.
(2) The algorithms in [33,34] do not include any down-sampling operation.
(3) The main compression algorithm, i.e., the merging techniques of neighbor integers are completely different. Different types of merging techniques such as merging 2-integers in the forward direction and also in the backward directions are implemented in [33], whereas only the forward-merging technique is used in our PPG compression algorithm. The techniques of handling the non-merged integers are also different. Moreover, the algorithms [33–35] store addition data-bytes with merged integers for proper data reconstruction.
(4) In this compression algorithm, special care has been taken to encode the first-PPG-sample, which ensures better sig-