Review on Advancements in PPG Based Heart Rate Monitoring During Physical Exercise; from Contact to Contactless

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Abstract— *The important physiological indicator heart rate (HR) says a lot about the person's fitness and variation in this parameter can reveal information about their life style, stress levels or sleep quality. A study on bout of innovations and experimentations on heart rate estimation using the photoplethysmographic (PPG) signal is carried out in this paper. There are a number of signal processing algorithms that can be applied to the raw PPG signals from which we can have the heart rate measurement. But motion artifact (MA) comes into play when the subject is undergoing some type of motion and is the main factor that degrades the accuracy of this HR measurement. Most of the modern research in this area is mainly concerned on this MA reduction or attenuation to extract the actual HR. With the advance of computer and photonics technology, this contact-PPG based HR measurement could be extended to contactless imaging photoplethysmography (IPPG). So here we try to explore the concepts of all PPG based HR measurement.*

Key words: *Heart rate, photoplethysmography, motion artifact, signals processing algorithms, imaging photoplethysmography.*

I. INTRODUCTION

The existing method for heart rate measurement is by using ECG (electrocardiography), where it measures the spikes of the electrical activity generated in the heart by the electrical signals that control the expansion and contraction of heart chambers. But the use of ground and reference sensors in ECG that are attached to the chest makes it uncomfortable for extended periods. Even though this current HR monitoring method has a role to play in medical and exercise settings, it is not a viable means for continuous purpose and when unconstrained movement is required. So, for users who want to take continuous HR measurements as part of their health, fitness tracking and life style monitoring, comfortable methods that can interface to a smart phone or computer is required.

Clearly the ECG is not suitable for this purpose. In fact, an alternative is already widely adopted by medical professionals for HR monitoring by measuring the changes in the volume of blood as it distends the arteries and arterioles in the subcutaneous tissue and this optical measurement method is so called photoplethysmography (PPG). And this blood volume changes in the subcutaneous tissue are synchronous with the heart rhythm. In the field of non-invasive HR measurement, optical sensors with photons as sensing elements are highly relevant. PPG based HR monitoring make use of sensors that can be attached on the peripheral positions such as fingertips, wrists or earlobes is seen as a much more comfortable solution.

The PPG sensors [1] are embedded in some wearable wrist bands or watches and it emits a beam of light into the skin and measures the changes in light intensity which is reflected or transmitted through the skin. The amount of light received at the sensor falls sharply at periodic intervals, as the increased volume of blood absorbs more of the light. The signal from the sensor is a saw tooth like curve and the periodicity of these measurements reflects the heart rhythm. Thus PPG signal provides an efficient means of HR estimation.

But PPG-based HR estimation becomes particularly challenging because of the presence of motion artifacts (MA), especially in free living conditions. MAs that are caused by body movements and sensor deformation would results inaccurate measurements, unless the system cancelled out their effect through the application a compensation algorithm. A number of methods and algorithms have been proposed to reduce the effect of MAs in PPG signals.

Due to advancements in the field of microelectronics, photonics, and image processing technologies, the past decades have witnessed grand progress in the development of a non-contact PPG based HR monitoring system that is, imaging photoplethysmography or IPPG. This non-invasive optical method has been proven to be superior in its convenience, simplicity, ease of use, low cost and ability to offer multiple physiological parameters.

II. PHOTOPLETHYSMOGRAPHY

A. Background of PPG

In the 1930s Hertzman and his colleagues first introduced the term ‘Photoplethysmography’ which represents the volumetric changes. The word ‘Plethysmo’ is a word derived from Greek which means enlargement. The early history of PPG is described in excellent review article by Challoner. Optoelectronic components like light source and photo detector are the basic elements of this technology. The light source is used to illuminate the tissue by placing it on the skin and the photo detector to measure the small changes in the intensity of the light associated with the variations in perfusion of the circulation in the catchment volume. Development in the PPG technology rely on the key factors such as low cost, non-invasive, small, portable, simple to use and reliable cardio-vascular assessment techniques. Also innovations in the optoelectronics and clinical instrumentation have contributed to its advancement. Improvements in semiconductor technology, i.e., light emitting diode (LED), photodiodes and phototransistors have made considerable reduction in the size, portability, reliability and reproducibility in the design of PPG probes. Despite of its simplicity, knowledge of the origins of various components in the PPG signal are still rudimentary. But it is generally accepted that these basic components of PPG could give valuable information about the cardiovascular system. Thus PPG has widespread medical applications in cardiovascular system assessment, vital sign monitoring and blood oxygen detection, as this technology is implemented in commercially available medical devices such as pulse oximetry, digital beat-to-beat blood pressure measurement system and vascular diagnostics.

B. Principle of PPG

PPG is a simple optical blood perfusion technique that can be used to detect the blood volume changes that occurs in the micro vascular bed of tissue beneath the skin. These volume changes are due to the pulsatile nature of the circulatory system. The basic principle behind the PPG is the differences in the sensitivity of various optical wavelengths for blood and other subcutaneous tissue components. As the interaction of the light with the biological tissue seems to be more complex (including scattering, absorption, reflection etc), the design of light source wavelength is very important criteria. It is understood that the ideal wavelength of light source for the PPG should have greater absorption for blood compared to other tissue elements like blood pigments and water as this would allow accurate measurement of blood volume changes in the micro vascular tissue. It is known that blood pigments like melanin strongly absorbs shorter wavelengths of light and water absorbs light in the ultraviolet (UV) and longer infrared (IR) regions. Therefore red and near IR light are primarily used as light sources in PPG sensors. But recent studies have shown that green wavelengths show large intensity variations in modulation during cardiac cycle. Also green LED has more absorptivity for both oxyhaemoglobin and deoxyhaemoglobin. So green LEDs can result in a better signal to noise ratio (SNR) and higher accuracy of heart rate detection.

During the systole, as the heart pumps blood to the body and lungs, more amount of blood reaches the capillaries in the subcutaneous tissue that results in greater light absorption. Decreased blood volume in the capillaries during diastole results in less light absorption. The PPG waveform therefore comprises a pulsatile (‘AC’) physiological waveform attributed to cardiac synchronous changes in the blood volume with each heart beat, and is superimposed on a slowly varying (‘DC’) baseline with various lower frequency components attributed to respiration, sympathetic nervous system activity and thermoregulation [1].

C. Operational configurations

Depending on the geometric arrangement of the light source and the photo detector, there are two types of operational modes, i.e., transmission mode PPG and reflection mode PPG. In transmission mode, the source and photo detector are placed opposite to each other as the skin in between them. So photo detector has to detect the light that is transmitted through the tissue. Thus measurement sites for this mode of operation are limited to finger

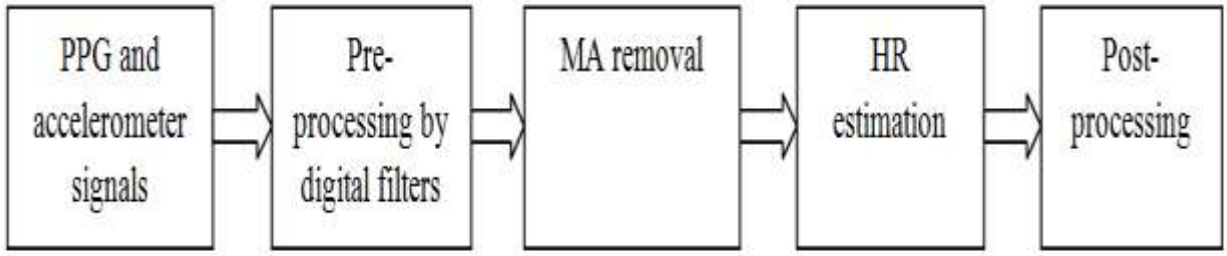

Fig 1: Flow chart of contact-PPG based HR estimation system

tips and earlobes, so that the transmitted light can be easily detected. But these measurement sites are more susceptible to environment factors such as low ambient temperature and the daily activities and movement of the subject may interfere the PPG sensor.

In the reflection mode, both LED and the photo detector are placed on the same side of the skin and photo detector measures light that is reflected or backscattered from the tissue, bone or blood vessels. This mode of configuration enables measurements by placing the sensor on any point on the skin surface. With this mode, we can measure from the points that may be hard to access with the former mode of operation. For accurate and reliable measurement the sensor should firmly attached to the skin surface and thus the site normally need a flat skin surface.

III. DATABASE AND METRICS

A. Database

The data sets used were provided for the IEEE Signal Processing Cup 2015. It is given in Table I. The dataset consist of 23 recordings which were collected subjects (18 -58 years old) performing different physical exercises. The dataset consist of PPG, 3-axis accelerometer and ECG signals. The PPG signals were recorded using two PPG sensors and the acceleration signals were recorded using a 3-axis accelerometer along with the ECG signal recorded simultaneously from the chest using wet ECG electrodes. PPG sensors make use of green LEDs that is having a wavelength of 515 nm. All the above signals were sampled at rate of 125 Hz.

The subjects are asked to perform three types of activities. T1 involved walking or running on a treadmill, T2 involved various rehabilitation arm exercises and T3 involved of intensive forearm and upper arm movements. The ECG signals were used as ground truth HR in BPM as described in [2] and [3]. The ECG based HRs were measured for every 8 s window with a 2 s shift. The same window length and shift are suggested for the PPG

B. Metrics

The metrics which are usually computed in other studies [3] are reported here. The Absolute Error (AE) is used as the measure of accuracy of each HR estimate:

$$AE_i = | f_{est} (i) – f_{true} (i) | \qquad (1)$$

Where f_{est} (i) and f_{true} (i) are the estimated and the true HR value in the i^{th} time window in BPM. The below three metrics are used to evaluate the performance of the developed algorithm.

$$avAE = 1/N \sum_{i=1}^{N} AEi \qquad (2)$$

$$sdAE = (1/N \sum_{i=1}^{N}(AEi - avAE))^{1/2} \qquad (3)$$

$$avRE = 1/N \sum_{i=1}^{N}(AEi / ftrue\ (i)) \qquad (4)$$

Where avAE is the Average absolute Error, sdAE is the Standard Deviation of the Absolute Error, avRE is the Average Relative Error and N is the total number of estimates.

IV. METHOD

When the subject is at rest, the periodicity in the PPG signal directly indicates the cardiac rhythm. But when MA comes into play, this periodicity gets disturbed. So accurate HR measurement need step-by-step processing of the raw PPG signal which is shown in Fig 1. The PPG and accelerometer signals are first filtered using some band pass filters along with which scaling and segmentation can be done. For signal denoising, a number of filter designs were implemented and the most recent one is the wiener filter [17] which outperformed all other filter designs. Two concatenated wiener filter gives the better result. Thus MA attenuation is avoided to an extent. Even though MA is reduced, a true signal need to be recovered from the denoised signal. So that signal estimation and post processing stages are required which will result in a even more accurate HR that is comparable with the ECG measurements.

TABLE I

DATABASE OF 23 PPG RECORDINGS FROM IEEE SP CUP

Rec	Subject ID	Activity type	Age / Weight / Height	Sex	Healthy?
1	1	T1	18-35y /- /-	M	Y
2	2	T1	18-35y /- /-	M	Y
3	3	T1	18-35y /- /-	M	Y
4	4	T1	18-35y /- /-	M	Y
5	5	T1	18-35y /- /-	M	Y
6	6	T1	18-35y /- /-	M	Y
7	7	T1	18-35y /- /-	M	Y
8	8	T1	18-35y /- /-	M	Y
9	9	T1	18-35y /- /-	M	Y
10	10	T1	18-35y /- /-	M	Y
11	11	T1	18-35y /- /-	M	Y
12	12	T1	18-35y /- /-	M	Y
13	13	T2	20y/64kg/162cm	M	Y
14	14	T2	29y/70kg/169cm	M	Y
15	15	T2	21y/77kg/188cm	M	Y
16	15	T3	21y/77kg/188cm	M	Y
17	16	T3	19y/54kg/174cm	M	Y
18	13	T3	20y/64kg/162cm	M	Y
19	17	T3	20y/57kg/174cm	M	Y
20	18	T2	19y/70kg/180cm	M	Y
21	18	T3	19y/70kg/180cm	M	Y
22	19	T3	21y/73kg/180cm	M	Y
23	20	T2	58y/70kg/156cm	F	N

V. LIMITATIONS OF PPG

Despite of its wide range of applications, PPG is having several drawbacks which limits the evolution of conventional contact PPG.

a) Spot measurement: A PPG sensor can only monitor the dynamic changes of the blood volume at single site per probe. Nowadays multi-sensor PPG system have been developed to measure the volume changes at different sites simultaneously [4] –[6]. But for clinical applications these multi-sensor system typically require electronic and optical matching of each PPG sensor used and should possess high temporal synchronization and also anatomically symmetric site locations. But these multiple sensing locations may interfere by the daily activity of the subject. Moreover, it may be inconvenient for the user and infeasible for everyday use.
b) Contact measurement: Conventional PPG sensors are attached to the skin very tightly only by which we can have accurate measurements. But this limits its practicality in situations such as skin healing evaluation, wound diagnostics like burn, ulcer and trauma, and when free movement of the subject is required. This direct contact may also make discomfort to the user during continuous monitoring. Also this contact measurement can cause arterial wall deformation at the measuring site as the device is firmly placed for a long period. It may even block micro-circulation in capillaries. This makes the conventional PPG infeasible from the perspective of patient comfort.
c) Motion artifact: Motion induced signal corruption is one of the main factor that limits the use of conventional contact-PPG. MA reduces the accuracy of measurement as it causes errors during processing of the signal. And it also limits the physiological monitoring capabilities in real world environment such as ambulance, sport performance assessment and homecare.

VI. IMAGING PHOTOPLETHYSMOGRAPHY

To enhance the comfort of the subject and facilitate long-term recordings, a great effort has been made to develop a contactless PPG system. Dramatic developments of imaging techniques and innovations in imaging instrumentation have contributed for the development of IPPG, which was started in 1996. Conceptually, IPPG is a non-invasive imaging technique for remote measurement with camera as the key element. It helps in the visualization of dermal blood vessels and for the detection of blood perfusion in different skin areas. Primarily Wu and his colleagues

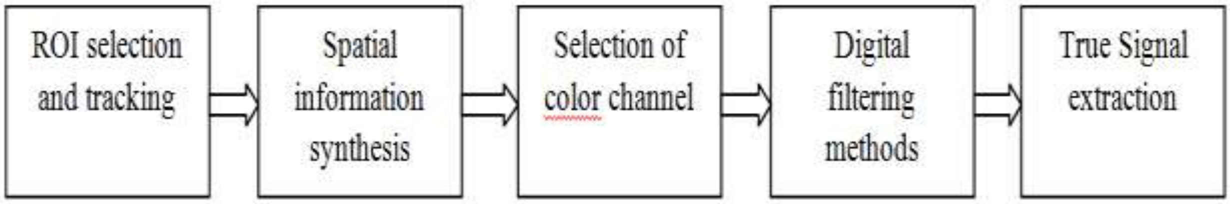

Fig 2: Flow chart of IPPG based HR estimation system

developed a charge coupled device (CCD) based IPPG system and it was feasible for assessing local changes of blood volume[7].

IPPG also operates on the similar optical principles of conventional contact-PPG. Specific tissue is illuminated with the help of LED and a photo detector measures the light leaving the tissue with an imaging sensor. It enables remote sensing for large areas and avoids the physical restrictions and cabling in the conventional system that causing discomfort to the user. Since it has no contact with the subject, it does not cause any arterial wall deformation and provides more reliable signals for medical applications. The use of imaging sensor helps in MA attenuation and doesn't need to compromise for the region of interest (ROI) selection, which of these enable a flexible and robust HR measurement system. The characteristics of the camera, which is the key part of the IPPG system, greatly influence the recorded images and thus further parameter extraction. The camera should have more sensitivity over the region of chosen light source.

A. Signal extraction algorithm

In IPPG, the raw signals captured by the camera are embedded in a sequence of image frames. These raw signals need to be processed before further analysis, as in Fig 2, which mainly depends on the application for which it is used.

The first step is to locate or adjust the ROI with the subject's motion. For this many approaches have been developed and most recently Wang et al., developed a skin/ non-skin pixel classification method [8], in which a 'tracking-by-detection' with Kernels (CSK) method [16] is utilised for face detection on different skin types. According to Wang et al., [8], once the ROI has been successfully chosen for every frames, then spatial averaging or spatial concatenation can be done to obtain the spatial information by reducing the effect of motion induced residual errors. As the optical absorption of the haemoglobin varies across the light spectrum, proper color channel should be selected for the camera.

Before going to signal extraction, a filtering stage is employed to attenuate the noise effect. Several filters like a moving average filter [11], a band pass filter [10], an adaptive BPF [8], and wavelet de-noising [12] were successfully implemented for the signal de-noising of the IPPG raw signals. From the de-noised signal, true signals can be recovered. McDuff et al., developed a time domain pulse peak detection method [9], [14], by detecting the local maximum in a moving window. More recently, a support vector regression technique is introduced by Hsu and his colleagues for peak signal detection [13]. But the probabilistic approach BayesHeart for HR monitoring by Fan et al., outperformed all other state of art methods [15].

I. CONCLUSION

This review has started with brief introduction of conventional contact PPG based HR monitoring system and is going to end with the nascent technology IPPG. Even though IPPG based HR monitoring system provide some insights into the progress of IPPG applications, real aspect of this technology is beyond this paper. The results are showing that the contact-PPG, with an average error of 1.37BPM with the most advanced methods, had already replaced the ECG system. Moreover the experiments and analysis have showed that the physiological signals obtained from the IPPG system shows equivalence with the contact-PPG systems and the maximum heart rate difference was less than 3BPM in all states.

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