34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

A Review of Non-Contact, Low-Cost Physiological Information Measurement based on Photoplethysmographic Imaging

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Abstract—**In recent decades, there has been increasing interest in low-cost, non-contact and pervasive methods for measuring physiological information, such as heart rate (HR), respiratory rate, heart rate variability (HRV) and oxyhemoglobin saturation. The conventional methods including wet adhesive Ag/AgCl electrodes for HR and HRV, the capnograph device for respiratory status and pulse oximetry for oxyhemoglobin saturation provide excellent signals but are expensive, troublesome and inconvenient. A method to monitor physiological information based on photoplethysmographic imaging offers a new means for health monitoring. Blood volume can be indirectly assessed in terms of blood velocity, blood flow rate and blood pressure, which, in turn, can reflect changes in physiological parameters. Changes in blood volume can be determined from the spectra of light reflected from or transmitted through body tissues. Images of an area of the skin surface are consecutively captured with the color camera of a computer or smartphone and, by processing and analyzing the light signals, physiological information such as HR, respiratory rate, HRV and oxyhemoglobin saturation can be acquired. In this paper, we review the latest developments in using photoplethysmographic imaging for non-contact health monitoring and discuss the challenges and future directions for this field.**

I. INTRODUCTION

Monitoring physiological information, such as heart rate (HR), respiratory rate, heart rate variability (HRV) and oxyhemoglobin saturation, is very important for assessing health. The conventional methods for obtaining this information are indispensable and vital tools for both medical and research use. For example, the wet adhesive Ag/AgCl electrodes are used to monitor HR and HRV almost universally in clinical applications today, the capnograph device is routinely used in hospitals and critical care centers to monitor patients' respiratory status and pulse oximetry is used to monitor oxyhemoglobin saturation during surgery. These well-established signal modalities provide a wealth of physiological information, which, by virtue of modern bioinstrumentation technology, can be harnessed noninvasively and inexpensively for the emerging global health applications of clinical physiological monitoring and medical treatment [1]. "Fixed-in-the-environment" electrodes are non-intrusive and more adequate for long-term monitoring, home health care applications as well as in other non-clinical fields, but they have some drawbacks. The main limitation is the requirement of maintaining direct contact between the bare skin of the subject and the electrodes which are fixed in the environment (chair, seats, bed, etc.) [2, 3]. Furthermore, from the perspective of patient comfort for long term use, the conventional methods are not suitable for ambulatory monitoring. Some non-contact methods with electrodes that contact clothing have been developed which address the comfort during pervasive applications [4], but they have a number of issues, including susceptibility to motion artifacts and troublesome cables between electrodes and the printed circuit board (PCB).

Most alternatives to standard physiological information monitors require the application of electrodes or transducers (such as the case of the wet adhesive Ag/AgCl electrodes), during the monitoring period. This aspect is critical but can, in the some environments, be undesirable or even impossible. Recently, there has been increasing interest in low-cost, non-contact and pervasive methods for monitoring physiological information. For example, the technique of Laser Doppler velocimetry to measure red blood cell velocity [5], vibrocardiography (VCG) to measure the velocity of displacement of the skin corresponding to chest wall movement [6], electromagnetic (EM) approaches for heart and respiration monitoring, a microwave system (a microwave Doppler radar) for respiration detection [7]. Research studies using non-contact measurements have continued for some years, such as measurement of respiration rate by an ultrasonic proximity sensor [8] and detection and evaluation of a wound and ischemic tissue by non-contact electric impedance measurements [9,10]. Optical methods are also widely used for non-contact measurements [11,12].

The use of remote, non-contact photoplethysmographic imaging has been investigated in recent years. Photoplethysmographic imaging using a cellular phone or computer camera is designed to operate without specialized hardware. People also do not need to wear any special equipment. An area of skin need only be placed in the front camera lens for several seconds as consecutive images are captured by the camera. Using computer vision and advanced signal processing technology, relative physiological signals such as HR, respiratory rate, HRV and oxyhemoglobin saturation are acquired. The principal advantage of photoplethysmographic imaging for medical applications is the intrinsic safety since there is no electrical contact between the patient and the equipment. In this paper, we discuss the latest developments in the literature along with future directions and challenges in photoplethysmographic imaging.

II. ORIGIN

The blood circulation is related to the heart (cardio) and the network of arteries and veins (vascular). The cardiovascular pulse is

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*Resrach supported by ABC Foundation.

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generated in the heart, when the chambers contract and blood is forced into the aorta from the left chamber. The blood travels through the arterial network and returns back to the heart through the venous network. Every contraction of heart creates a wave of blood that reaches the capillaries in the skin surface. Different physiological phenomena indirectly reflect the status of many different organs. Photoplethysmographic imaging to monitor physiological information uses an optical method because the sensitivity of different optical wavelengths is different in the ambient light range for blood volume and different tissue components of the body. For example, typically 660 nm (red) and 940 nm (infrared) is used as the light source for pulse oximetry because the maximum absorption by deoxygenated hemoglobin (Hb) is at the red wavelength, and that of oxygenated hemoglobin (HbO_2) is at the infrared wavelength. When the capillaries are filled with blood, they block the light resulting in lower average brightness values and more light is reflected. The change of blood volume in the capillaries is directly reflected in the changing brightness values. We are able to acquire the initial crude signal of the pulse and process it to extract physiological information such as HR, blood velocity, blood flow rate, and blood pressure .

A. *Photoplethysmography (PPG)*

Applications of PPG include monitoring of oxygen saturation, HR and respiration rates, blood pressure, cardiac output, assessment of autonomic functions and detection of peripheral vascular diseases. It is the earliest method using optical technology for monitoring the health of patients. PPG was introduced in the 1930s [13] using light reflectance or transmission and is a simple, inexpensive method that has become an important medical tool for monitoring health. PPG is based on the principle that blood absorbs light more than surrounding tissue, so a change in blood volume affects transmission or reflectance correspondingly. A typical application of this principle is pulse oximetry. The method has been realized for the noninvasive measuring of arterial oxygen saturation. A conventional pulse oximeter sensor consists of two light emitting diodes (LEDs) with different wavelengths, typically 660 nm (red) and 940 nm (infrared), and a photodiode detector, installed in a clip that is attached around a patient's finger. The LEDs are alternately lit and the transmitted light passes through the tissue and is detected by the photodiode.

Pulse oximetry signals differ depending on the specific tissue components and skin vascular distribution of the monitored area. If we assume that the increase in attenuation of light is caused only by the inflow of arterial blood into the tissue, we can calculate the oxygen saturation of the arterial blood by subtracting the Direct Current (DC) component of the attenuation from the total attenuation, leaving only the cardiac synchronous pulsatile component for the dual wavelength determination of oxygen saturation.

B. *Thermal imagery*

Thermal imaging is another novel method for measuring physiological information. It is based on the information contained in the thermal signal emitted from major superficial vessels. This signal is acquired through a highly sensitive thermal imaging system. Temperature of the vessel is modulated by pulsative blood flow. The method is based on the assumption that temperature modulation due to pulsating blood flow produces the strongest thermal signal in a superficial vessel. This signal is affected by physiological and environmental thermal phenomena. Therefore, the resulting thermal signal that is being sensed by the infrared camera is a composite signal, with the pulse being only one of its components. Our effort is directed at recovering the frequency of the component signal with the highest energy content. This is consistent with our hypothesis of pulse dominance in the thermal field of a superficial vessel [13]. After appropriate processing, the thermal imagery can yield quantitative information such as blood flow velocity, respiratory function, and perspiratory function [14].

C. *Photoplethysmographic imaging*

Remote, non-contact pulse oximetry and photoplethysmographic imaging have been investigated only relatively recently [15]. They are revolutionary methods for monitoring health using only a color camera to measure plethysmographic signals. Costa et al. propose two methods for video acquisition of HR; two of the first uses of image-based methods for physiological information monitoring. In the first, the skin near a vein is illuminated by a 2-mW HeNe laser. The reflected speckle pattern is acquired, digitized and a specifically developed code, based on speckle image processing, is used to evaluate the skin displacement caused by the mechanical deflection produced by arterial wall deflections due to the systolic pressure wave travelling along the vascular tree. In the second method, a small mirror adhered to the skin is illuminated by the laser. The position of the light spot resulting from intersection of the reflected beam with an opaque observation plane is recorded and plotted as a function of time. Both the methods proposed allow the remote sensing of pulse; the latter being minimally invasive requiring the need to adhere a mirror to the subject's skin. Both approaches do not report quantitative results; only a graph is reported and non-correlations with reference signals (i.e. simultaneous ECG) are reported [16].

Takano et al. proved that the respiratory rate, heart rate and pulse rate can be acquired simultaneously using digital cameras with normal ambient light as the light source [11]. Images of a part of the subject's skin are consecutively captured, and the changes in the average image brightness of the region of interest (ROI) are measured for a short time. When the measurement starts, the camera records the captured frames to a personal computer (PC) as a set of uncompressed AVI files. The resulting frames from the camera are processed on the PC by custom digital filtering and spectral analysis algorithms written in Matlab (The Math Work Inc., USA). Finally, some physiological signals such as HR and HRV are acquired. A correlation coefficient of 0.90 has been obtained with respect to heart rate measured with a pulse oximeter.

Compared to PPG, the photoplethysmographic imaging replaces the photodiode with the digital camera with dedicated light sources (e.g. green, red and/or infra-red wavelengths) or normal ambient light as the light source and monitors a larger field of view that improves the ability and signal-to-noise ratio (SNR) to probe biologic interactions dynamically and to capture physiological information over time. In contrast to thermal imaging, photoplethysmographic imaging has an advantage of being both inexpensive and convenient.

III. DEVELOPMENT OF MEASUREMENT METHOD

Early measurements were taken with home digital cameras (about $200) which were expensive and inconvenient for monitoring physiological information. [14]. The wavelengths of the light sources also varied, such as the single wavelength, e.g., 660 nm (red) wavelengths, 940 nm (infrared-red), 550 nm (green) [17], or two lights of different wavelengths emitted either simultaneously [15] or alternately [17]. Though these methods can acquire good results, they are impractical because of the high cost, inflexibility and lack of real-time measurements. Later, Verkruysse et al. proved the feasibility and potential usefulness with ambient light as the light source [14]. In 2010, Poh et al., using a computer webcam with an advanced algorithm, was able to monitor HB of three participants simultaneously [19].

The emergence of smartphones extends health and healthcare for the general population. The smartphones more like Personal Digital Assistants (PDAs) have super processing ability e.g. iphone4S (about $700) with more than 1 GHz main frequency. Many applications (apps) have been developed for personal medicine such as chronic disease management, remote health monitoring and body sensors networks (BSNs) [20].

IV. METHODOLOGY

There are three main stages to monitoring physiological information based on photoplethysmographic imaging: image acquisition, data collection, and parameter extraction.

Step 1: The ROI (face, fingertip or earlobe) is placed over the camera lens with the flash turned on or ambient light. The subject keeps their ROI still to reduce motion artifacts. Captured files are saved to the PC as a video file in uncompressed AVI format. All further analysis is performed on the AVI videos in Matlab (The Math Works Inc.) as described in step 2 and step 3.

Step 2: The ROI is then separated into the three RGB channels and spatially averaged over all pixels in the ROI to yield a red, blue and green measurement point for each frame and form the raw traces $x_r(t)$, $x_g(t)$, $x_b(t)$ respectively. t is a sample time point.

Step 3: For analysis of the pulse signal dynamics, previous research primarily utilized only the green band. This is because there is high absorption by hemoglobin in the green range, and it has been demonstrated to give a stronger cardiac pulse signal than the red or blue bands during remote PPG imaging [14]. By calculating the average value of spatial resolution of the ROI in the green band, a sample signal is acquired. Finally, we applied the fast Fourier transform (FFT) on the calculated signal to obtain the power spectrum. The pulse frequency is designated as the frequency that corresponds to the highest power of the spectrum within an operational frequency band.

The above method is feasible, but there is an obvious disadvantage. Though the green bands had stronger pulse amplitude and decreased noise, the red and blue bands may also contain the pulse signal. A poor SNR will result from motion artifacts or ambient light interference. Using only the green band is not a robust method. In 2010, Poh et al. at the Affective Computing research group at MIT proposed an algorithm and to address this issue. They extracted underlying source signals from R, G, B bands by using a methodology called blind source separation. Independent component analysis (ICA) is a computational method for separating a multivariate signal into additive subcomponents supposing the mutual statistical independence of the non-Gaussian source signals. It is a special case of blind source separation. Pearson’s correlation coefficients among a reference sensor and the web-camera-based system of r=1 for heart rate detection and of r=0.92 for High Frequency (HF) and Low Frequency (LF) (common heart rate variability analysis parameters) have been reported; the root-mean-squared error of the HR was 1.24 beats/min (Poh et al., 2011). Compared with previous studies, the obtained physiological information is not only more precise, but also has a better SNR during motion. Despite these definitively promising advantages, the robustness of the system and the efficiency of the procedure on a large scale need to be demonstrated and improvement on the frame rate is required for adequate analysis of HRV, which is described in the section on hardware (V).

V. FEASIBILITY OF FUTURE RESEARCH

Although measurements based on photoplethysmographic imaging can extract vital physiological parameters, such as HR, HRV, respiratory rate, and oxyhemoglobin saturation, the potential of this method has not been fully explored [20]. Many issues need to be addressed to promote measurement accuracy and extend application of this method.

A. *Region of interest*

The PPG signals derived from different ROIs exhibit differences in both shape and amplitude. When light illuminates the skin, the intensity of the reflected or emitted light will be attenuated. Research shows that the attenuation of light by the body can be divided into three independent components, arterial blood, venous blood and tissues. The absorption of light does not change in venous blood and tissues, so it displays DC components. The arterial blood flow is related to the heart beat, so it displays Alternating Current (AC) components. For example, the intensity of light transmitted across the fingertip varies in time with the heart beat and a pulsatile signal is superimposed on a DC-level signal. The amplitude of this cardiac-synchronous pulsatile signal is approximately 1% of the DC level. Studies have also shown that light reflectance measurements can be related to physiological differences at different depths within biological tissue [21]. Thus, varying the ROI may affect the ratios of AC to DC components which results in different SNRs. In previous research, ROIs were selected on the human face [14, 19], forearm [20], fingertip [22] and earlobe [23], but the SNRs were not compared.

B. *Hardware*

The processing capability of hardware is a key to realizing the complex algorithm. Some specialized clinical devices, using FPGA, DSP or ARM chips are able to obtain standard physiological signals. The latest generations of smartphones are increasingly becoming small health monitoring devices, due to their powerful on-board computing capability, capacious memories, large touch screens and open operating systems (OS). However, there may be a limitation for accurate measurements because of low camera sampling (also called frames per second; fps). It has previously been shown, when using wet adhesive Ag/AgCl electrodes, that HRV measurements should be made with a sampling rate of at least 250 Hz and for advanced clinical devices, the sampling rate reaches to 1 kHz. The maximum sampling rate with a home video or smartphone camera used in the study was less than 30 Hz. The relatively low frame rate is mostly related to the physiological characteristics of the human visual system, which can process 10 to 12 separate images per second. The camera is designed to only record and store images. To our knowledge, some industry cameras may reach 750 fps. Higher sampling rates may improve accuracy and reliability. It is possible that future smartphones will include high frame rate cameras.

C. *Physiological parameter*

Although photoplethysmographic imaging may not be able to provide the details concerning cardiac electrical conduction that the ECG offers, the method can now enable long-term monitoring of other physiological signals, such as heart rate or respiratory rate, by acquiring them continuously in an unobtrusive and comfortable manner. Measurement of respiratory rate uses a previously reported algorithm developed for use with a pulse oximeter, based on amplitude and frequency modulation sequences within the light signal. This technology can also be used with recently developed algorithms for detection of atrial fibrillation or blood loss. Christopher has demonstrated this potential by respiration rate detection with the variable frequency complex demodulation-frequency modulation (VFCDM-FM) method and HRV analysis. Assessment of R-R intervals has recently been shown to be an accurate way of detecting episodes of atrial fibrillation, and the VFCDM method has recently been shown to be capable of detecting significant decreases in blood volume from a PPG signal [20].

A higher sampling rate will be possible with advanced camera technology, and more physiological information will be captured, such as ECG and EMG.

D. Algorithm

In section V, we mentioned some algorithms such as FFT to analyze signal power spectrum, ICA for a blind source separation to capture underlying source signal. FFT is important for analyzing the signal in the frequency domain. FFT is an efficient algorithm to compute the discrete Fourier transform (DFT) which decomposes a sequence of values into components of different frequencies. FFT is a way to compute the same result more quickly than DFT. Thus, it promotes faster hardware processing speeds. ICA is a technique for uncovering the independent source signals from a set of observations that are composed of linear mixtures of the underlying sources [19].

The adaptive technique can be used in order to dynamically estimate the noise levels and set the noise threshold accordingly. The use of this technique in biomedical signal analysis is rapidly expanding, e.g. in removing motion artifacts from ECG [24] and noise cancellation in the electroencephalogram (EEG) [25], but the technique is still in development for photoplethysmographic imaging.

E. Optical spectrum

Pulse oximetry essentially uses PPG to calculate oxygen saturation. Consequently, the wavelength dependence of the photoplethysmogram is of direct relevance to the performance of pulse oximeters. The selection of optimum wavelengths is a matter of importance in the design of the photoplethysmograph for clinical use and has implications for the design of the reflectance pulse oximeter .

Previous studies have investigated the utility of reflected green-light PPG in comparison with reflected infrared PPG and ECG. The results indicated that the difference in wavelength affects the AC component to DC component ratio, and that the ratio affects the correlation coefficients of the heart rate and pulse rate. These results suggest that reflected green-light PPG has an advantage over reflected infrared PPG [26].

VI. CONCLUSION

In this paper, we review physiological information measurements based on photoplethysmographic imaging. This feasibility study shows potential for monitoring physiological information in the future. The PPG signals obtained from the camera-based system are comparable to those from traditional PPG. However, the camera-based system requires further improvement for clinical applications.

The technology has an advantage of being inexpensive, non-contact and pervasive. It is suited for home applications and particularly for telemedicine. The camera can be easily integrated on already existing home furniture or home components such as mirrors or also utilizing an already existing camera such as the one integrated in most of the modern notebook computers or mobile phones. It is also expected to find applications in sustained physiological monitoring of cardiopulmonary diseases, sports training, sleep studies, psychophysiology (polygraph) [13], intensive care, or in conjunction with other modalities such as MRI .

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