Biomedical Signal Processing and Control 47 (2019) 366–379

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Robust remote heart rate estimation from multiple asynchronous noisy channels using autoregressive model with Kalman filter

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ARTICLE INFO

Article history:
Received 28 December 2017
Received in revised form 3 August 2018
Accepted 3 September 2018

Keywords:
Heart rate estimation
Blind source separation
Face tracking
Regression model
Interpolation
Search and rescue

ABSTRACT

Remote heart rate measurement has many powerful applications, such as measuring stress in the workplace, and the analysis of the impact of cognitive tasks on breathing and heart rate variability (HRV). Although many methods are available to measure heart rate remotely from face videos, most of them only work well on stationary subjects under well-controlled conditions, and their performance significantly degrades under subject's motions and illumination variation. We propose a novel algorithm to estimate heart rate. Also, it can differentiate between a photo of a human face and an actual human face meaning that it can detect false signals and skip them. The method obtains ROIs using facial landmarks, then it rectifies illumination based on Normalized Least Mean Square (NLMS) adaptive filter and eliminates non-rigid motions based on standard deviation of fixed length of the signal's segments. The method employs the RADICAL technique to extract independent subcomponents. The heart rate measures for each subcomponent, are estimated by analysis of frequency signal to find the one with the highest magnitude. A two-steps data fusion method is also introduced to combine current and previous measured heart rates to calculate a more accurate result. In this paper, we explore the potential of our algorithm on two self-collected, and DEAP databases. The results of three experiments demonstrate that our algorithm substantially outperforms all previous methods. Moreover, we investigate the behavior of our algorithm under challenging conditions including the subject's motions and illumination variation, which shows that our algorithm can reduce the influences of illumination interference and rigid motions significantly. Also, it indicates that our algorithm can be used for the online environment. Finally, the application of our algorithm in search and rescue scenarios using drones is considered and an experiment is conducted to investigate the algorithm's potential to be embedded in drones.

1. Introduction

Contactless physiological monitoring techniques open up many possibilities for easy and convenient continuous monitoring without hindering the daily-life routines of the monitored subjects. Traditional methods for physiological monitoring require sensors to be physically attached to the subject, such as photoplethysmography (PPG) finger-clip sensors, electrocardiogram (ECG) electrodes, and respiration (RSP) chest belts. Often they cause skin irritation and discomfort, in addition to hindering mobility in daily activities.

Many commercial mobile devices nowadays come with a built-in digital camera. The ubiquitousness of such devices allows ordinary commercial mobile devices such as smartphones, tablets, and laptops, to be employed for remote diagnosis, or telehealthcare. The main interest in developing remote diagnosis methods using commercial hardware is the low-cost due to not having to purchase specialized medical equipment and the convenience of having to use a readily available device. This is especially useful for telehealthcare in rural areas, where access to clinics or specialized medical equipment may be nonexistent. However, mobile devices such as smartphones can be used for self-diagnosis including heart rate monitoring [1], colorimetric tests [2], and diabetes management [3].

Identifying the underlying heart rate signal from a video recording of a subject is a challenging proposition. Under optimum conditions, the lighting and environment should ideally be static, and the video source should be recording using high-quality digital cameras. Practically, however, noise from video compression, body movements, and dynamic illumination introduces interference and may result in an inaccurate estimation of the heart rate signal [4]. Most computational estimation methods include frequency filtering to exclude signal frequencies that are above or below that of

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https://doi.org/10.1016/j.bspc.2018.09.007
1746-8094/

heart rate signals but are unable to account for noise which is very similar to the heart rate signal itself. In addition, identifying the underlying heart rate signal using computational estimation methods [5,6] typically selects only a single estimated outcome to represent the closest fit to the actual heart rate signal.

In this research, we introduce a contactless heart rate estimation schema that improves the accuracy of the measurement, compares to other methods. Additionally, the algorithm solves the challenges of unwanted signal influences including illumination variation, and rigid or non-rigid facial or environmental motions by using illumination rectification, non-rigid motion elimination, and few temporal filters. Despite the methods which are used to eliminate the effect of unwanted sources, some undetectable sources may sabotage the physiological signal in a realistic situation. Consequently, a data fusion algorithm is employed to adjust real-time measures based on the multiple measured heart rates and previous estimation.

The method employs various techniques to minimize the effect of rigid and non-rigid motions on the estimation and uses the RADICAL technique to extract independent components which outperform other ICA algorithms. Moreover, we proposed to estimate multiple heart rate measures from three different regions of the human face as well as three independent components resulted from applying ICA. So multiple measurements have been used in a proposed regression model which avoid sudden motions and noises and reduce the effect of rigid and non-rigid motions. The proposed technique increases the accuracy of the algorithm enormously as shown in the experiments.

The algorithm starts with extracting regions of interest using facial points. The physiological signals are calculated using the extracted regions. Then, an independent component analysis technique is adapted to extract subcomponents. The subcomponents are processed separately to obtain multiple heart rate measures which are later used in the data fusion method. The resulted components are transformed to the frequency domain using Fourier transformation. Afterward, peak points are obtained from the frequency signals with minimum peak distance of predefined length. Later, the frequency with the highest magnitude is chosen as the frequency of the heart rate for each signal. Finally, the heart rate measures are fused using the data fusion technique proposed in this paper, to calculate more accurate results.

In Section 2, we present a number of related works. In Section 3, we present the proposed methodology for heart rate estimation, including a method for tracking regions of interest (ROIs) of the subject's face and an algorithm to compensate for motion. In Section 4, we present a proposed data fusion method to improve the accuracy of the heart rate estimation method using the current and previous heart rate measures. In Section 5, we present the results of three experiments that are designed to test and validate our methodology. In Section 6, we discuss the conclusions drawn from the experiment.

2. Related works

The innovation of using digital cameras in mobile devices for measuring heart rate (HR) is an extension of PPG technology. A pulse oximeter device for measuring PPG illuminates the skin and measures the variations in light absorption corresponding to a change in blood pressure from heartbeats. Early PPG sensors require LEDs to illuminate the skin and a photodiode at close range for measurement.

To extract the underlying physiological signals from the illumination of the skin, several methods can be applied. Linear filters are ineffective if background noise has the same frequency band as the desired physiological signal. Any given signal is assumed to be consisting of the desired physiological signals combined with other signal sources, or noise, such as from background illumination or if the frame of reference between the camera and the measured area changes. Blind source separation methods can be used to identify and extract the desired physiological signal. [7] designed a camera for capturing PPG information on several specific wavelengths simultaneously. Similarly, [8] and [9] utilized a multi-wavelength camera system for contactless measurement and calibration for estimating arterial oxygen saturation (SpO2).

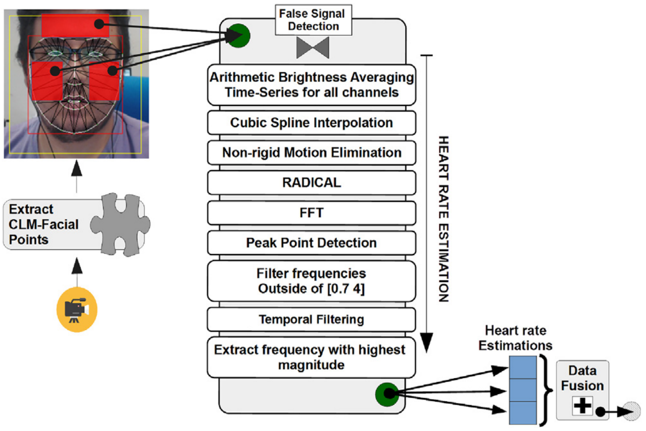

Fig. 1. The architecture of the proposed framework.

When using only ambient light and commercial digital cameras, PPG information can be extracted using blind source separation by first separating the source images into the Red-Green-Blue (RGB) color channels [5,10–12]. Another study used Cyan and Orange color channels in addition to RGB [13]. Independent component analysis (ICA) was then applied to separate the image signals into source signals. A source signal is then selected as an approximation or estimation of the physiological of interest, typically using frequency analysis. For example, heart rate signals would have a strong signal in the frequency band corresponding to the human heart rate, around 0.75 Hz (45 bpm) to 4 Hz (240 bpm).

A method of heart rate estimation which is commonly used by smartphone apps requires only the user's finger to be placed on the camera sensor, however, it is impractical and inconvenient for continuous, long-term measurement. Most contactless heart rate measurement methods observe the facial region, as it presents a wide surface area of the exposed skin particularly at the forehead or cheeks. This presents another dimension of difficulty as an automated physiological detection method would have to track the subject's face and ROI. A popular face tracking algorithm based on [14] and [15] is used in several studies for ROI tracking [5,11,16].

3. Heart rate estimation

The proposed technique in this paper is composed of a number of steps as shown in Fig. 1. In the first step, ROIs on the subject's face is located by using Constrained Local Model (CLM) presented in [17]. CLM algorithm extracts facial landmarks and generates a mask based on extracted points. Kanade-Lucas-Tomasi (KLT) algorithm [18] then is employed to track the location of featured landmarks in further image frames. The facial space is divided into three regions including the forehead, left and right cheeks based on facial landmarks. Forehead region is defined as the area between eyebrows and hairline, while left and right cheeks are defined as the areas below the eyes and above the lips.

After region extraction, a false signal detection algorithm [16] is applied to determine whether the extracted face belongs to an inanimate object and should be skipped or is an actual human face with