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MONITORING THE VITAL SIGNS OF AIRCRAFT PASSENGERS BY CAMERA BASED REMOTE PHOTOPLETHYSMOGRAPHY

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Abstract

Monitoring the vital signs of an aircraft passenger or crew members could be beneficial for various reasons. However, providing contact based sensors during flight is not the preferred method to achieve this goal. With the ubiquity of low-cost digital cameras and advanced image processing algorithms, an image-based remote monitoring of vital signs is feasible. This work explores the usability of a non-contact image photoplethysmography (iPPG) inside an aircraft cabin to measure the heart rate of passengers. Using a consumer camera, iPPG signals were estimated based on the analysis of color intensity changes in specific regions of the face. The developed system was evaluated with respect to its robustness against subject motion and the typical vibrations occurring in an aircraft. The results showed that using a consumer camera, a reliable estimation of the heart rate was possible under certain constraints. It was also shown that the vibrations of an aircraft did not affect the accuracy of the estimated heart rate.

Keywords

Aircraft; Heart rate; Image PPG; Remote PPG; Vital signs monitoring

1. INTRODUCTION

In-flight medical emergencies are common and occur in a complex environment with limited medical resources. In-flight medical emergencies are estimated to occur on approximately 1 in 604 flights, or 24 to 130 emergencies per 1 million passengers [1]. These events occur in a unique environment because the in-flight pressure in the aircraft cabin is equivalent to an altitude of 5000 ft to 8000 ft, and passengers are exposed to low partial pressure of oxygen and low humidity. The most common in-flight emergencies involve syncope (loss of consciousness due to lack of oxygen to the brain [2]) or near syncope (32.7 %), as well as gastrointestinal (14.8 %), respiratory (10.1 %), and cardiovascular (7.0 %) symptoms [1].

There are a variety of physiological parameters that can be used for diagnostic purposes of the cardiovascular system. The most important are the electrocardiogram (ECG), blood pressure and oxygen saturation. Based on these signals, detailed diagnoses can be made and appropriate therapies initiated. Automatic external defibrillators, for example, make use of the ECG to automatically initiate therapy measures. This is particularly important for use in airplanes, where it cannot be assumed that medical personnel will be available and a decision on a life-saving measure often has to be made within seconds or minutes.

During the last decade, the camera-based, non-contact acquisition of cardiovascular parameters including the photoplethysmogramm (PPG) and the oxygen saturation (SpO2) has gained a high popularity [3–6]. In accordance with the clinical, contact-based PPG, these techniques are often referred to as remote PPG or imaging PPG (iPPG). Cardiovascular activity modulates the light reflected from the skin's surface which can be captured by a camera system. By processing the camera image and analyzing the derived signal, the iPPG can be estimated. Various approaches have been developed using different camera technologies and signal processing techniques [7, 8]. The goal of this work was to develop an iPPG system to be used in the aircraft cabin or the cockpit to monitor the heart rate of passengers or crew members.

2. PHYSIOLOGICAL BACKGROUND

PPG: The PPG signal reflects the intensity variations of light transmitted through tissue or reflected at the upper skin layers. The blood volume, movements of the blood vessel wall or the orientation of red blood cells affect and modulate the amount of light received by the optical detector (usually a photo diode) and consequently the PPG signal [9]. A PPG is either operated in a reflective or a transmissive mode depending on the measurement area [9].

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FIG 1. Perspective of the camera installed in the overhead storage compartment of the ZAL cabin mock up.

iPPG: Similar to the conventional PPG, the camera-based iPPG also uses an optical sensor to capture intensity variations of the reflected light, but the basic mechanisms between the two techniques differ. The penetration of the light in to the skin and tissue is expected to be lower and movements of the measurement areas need to be considered [7, 10]. The pulsating character of the iPPG signal is caused by (1) the blood volume effects and (2) the ballistocardiographic effect. Changes in blood volume, i. e. the variations of blood volume in the measurement area, modulate the reflected lights. The modulations can be explained by two different theories. One theory is based on changes of the vessel cross-sections which corresponds to the conventional PPG theory [11]. The second theory assumes changes of the capillary density in the uppermost layer of the dermis [12, 13]. Ballistocardiographic effects cause another pulsating component in the iPPG signal due to movements which are a result of global and local mechanisms [14, 15].

3. MATERIAL AND METHODS

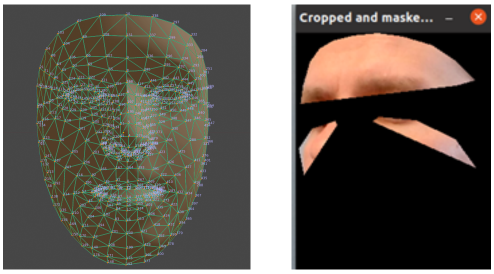
3.1. Camera and Nvidia Jetson

A USB camera (C920, Logitech, Switzerland) was used for the development of an algorithm to determine the iPPG signal inside an aircraft cabin. The camera had a maximum resolution of 1920x1080 pixels, a frame rate of 30 fps (image encoding: MJPEG), an integrated autofocus and an automatic adjustment to the lighting conditions.

The camera was connected via USB port a Jetson Nano (Nvidia, USA) running a Linux operating system (Ubuntu 18.04) . The video data with a resolution of 1024x576 pixels and framerate of 20 fps was H264 encoded and was transferred via UDP to an external laptop using a GStreamer pipeline.

3.2. Face recognition and region-of-interest determination

The initial step for the determination of the iPPG signal was the extraction of a suitable region-of-interest (ROI) in the face of the person to be monitored. According to the literature, the forehead and areas of the cheeks are particularly suitable as ROIs for determining the iPPG signal [16]. For face recognition as well as the subsequent extraction of suitable ROIs, the Mediapipe framework was used [17]. Among other parameters, this framework offers the possibility to determine a face mesh defined by 468 landmarks. Each of these landmarks is assigned to a specific position in the face (see Fig. 2a). Figure 2b shows an exemplary ROIs determined from the video stream. The ROI was used as a binary mask applied to the camera image, i. e., all values RGB values outside were set to zero, in order to keep only the RGB values necessary for further processing.



(a) Face mesh (b) Selected ROIs

FIG 2. Facial landmarks provided by Mediapipe face mesh (a) and ROI defined by landmarks (b).

3.3. iPPG signal and heart rate estimation

For measuring the heart rate (HR), a raw time series was determined from the video signal. For this purpose, the intensity values (RGB values) from one image were averaged channel by channel over the entire extracted ROI. This means that exactly one value was determined from each image per RGB color channel: $\mathrm{RGB}_{\text{mean}}(k) = \overline{\mathrm{RGB}(k, m, n)}$, where RGB is a vector containing the three RGB values, k is the k-th image and m and n are the pixel coordinates within the selected ROI. Due to the high sensitivity of the RGB channels to brightness variations, the RGB data was transformed to the L*a*b* or CIELAB color space [18]. The advantage of the transformation into the L*a*b* color space was the separation between brightness and color values. For the determination of the iPPG signal, the a* channel was used. This channel maps the hue and color intensity between red and green.

The upper graph in Fig. 3 shows the intensity-time curve of the a*-color channel estimated from the webcam's video stream. For further processing, the following filtering was applied to the raw signal: 1) removal of the mean value, 2) median filter, 3) high pass filter, 4) low pass filter, and 5) removal of the remaining mean. The median filter was used to suppress outliers in the raw signal. The high-pass filter suppressed slower signal fluctuations, which occurred due to movements of the face, e. g. caused by breathing. Low-pass filtering removed signal components above the useful signal range. By high-pass

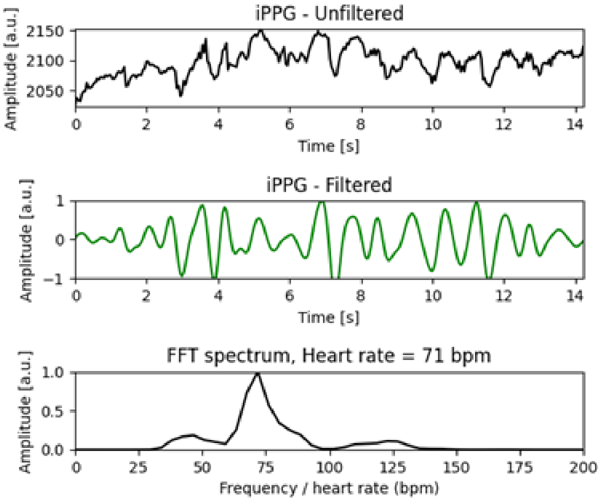


FIG 3. Raw iPPG signal estimated from the video stream (top), filtered iPPG signal (middle) and FFT spectrum of the filtered signal (bottom).

and low-pass filtering, the bandwidth of the signal was limited to a range between 0.66 Hz to 3 Hz which corresponds to a heart rate of 40 BPM to 180 BPM. The filtered iPPG signal (Fig. 3, middle plot) was used to determine the heart rate. The heart rate was only computed if the variance of the iPPG signal was below a predefined threshold. This was used to avoid false heart rate estimation in signals containing artifacts, e. g. cause by sudden head movements or larger variations of the lighting intensity. To compute the heart rate, the FFT of the iPPG signal was calculated and the maximum peak in the frequency spectrum was detected. The FFT was computed over a window length of 20 s, which resulted in a spectral resolution of 0.05 Hz or 3 bpm. This means that the accuracy of the estimated heart rate was ±3 bpm. The lower graph in Fig. 3 shows the FFT spectrum. Figure 4 summarizes the pipeline for the estimation of the raw signal and its further processing.

The estimated heart rate was compared to a conventional PPG signal which was acquired simultaneously with the iPPG using a finger clip sensor (CMS 50E, Contec, China). A qualitative evaluation was performed, i. e. the average heart rates of the PPG sensor were compared with those of the iPPG.

3.4. Influence of vibrations in the aircraft

The vibrations occurring in an aircraft can affect different types of sensor systems. Typical vibrations in the cabin were analyzed in prior experiments in an aircraft during flight and on ground. During flight, the majority of the vibration energy was in a frequency range of (150 ± 75) Hz with maximum accelerations of 0.01 g. On ground, the dominant frequencies were 100 Hz and 180 Hz with maximum amplitudes of 0.2 g. All dominant spectral components measured during the experiments were below 400 Hz. Sustained acceleration amplitudes were less than 0.05 g, with spikes observed up to a maximum of 0.2 g. Measurements were performed on the seat racks mounted at passenger cabin's floor.

To study the influence of these vibrations on a camera based sensor system, a modal shaker (Modalshaker MS 250, Dynalabs, Turkey) was used to excite the camera system. Therefore, the camera was mounted on an aluminum profile which was excited by the modal shaker. A piezoelectric probe (PCB-288D01, PCB Synotech, Germany) was used to measure the vibrations coupled into the structure by measuring forces and accelerations. Excitation frequencies of 100 Hz, 180 Hz and 360 Hz with acceleration amplitudes of 0.02 g and 0.2 g were used. For each parameter combination, a video of 2 min length was recorded. In parallel, the reference PPG was recorded for comparing the estimated heart rates.

4. RESULTS

4.1. iPPG-based determination of heart rate

The heart rates determined from the iPPG were compared with to the PPG reference signal. While the subjects were not moving, the estimated heart rates were within the accuracy range of ±3 bpm. In certain situations, e.g. during stronger head movements, more pronounced signal components in other frequency ranges occurred. If the amplitudes at these frequencies exceeded the amplitude of the heart rate, there were significant errors in the determined heart rate here, depending on the position of the peak in the FFT spectrum.

4.2. Influence of vibrations on the iPPG and the determined heart rate

The vibrations were not perceptible to the eye in the image or video for most of the frequency/amplitude combinations. Using an excitation frequency of 360 Hz and an acceleration amplitude of 0.2 g, the camera housing showed a resonant behavior leading to clearly visible vibrations and a blurring of the image. Still, a reliable estimation of the heart rate was possible in this case.

5. DISCUSSION

5.1. Determination of the iPPG signal and heart rate

Within the work, a consumer USB camera was used to determine the iPPG and the heart rate. The camera's RGB video stream was transformed into the L*a*b* color space and the iPPG signal was determined on the basis of the a* channel. By suitable filtering of the raw iPPG signal, it was possible to estimate the heart rate within the limits of the theoretical possible accuracy of the system. The system worked with daylight and artificial illumination.

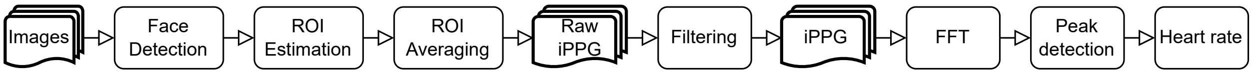


FIG 4. Processing pipeline for estimating the iPPG signal from a stream of camera images.

However, it was necessary that the subject's face moved as little as possible. While slow movements did not affect the estimated heart rate due to the filtering and avereraging of the signals, sudden movements caused large signal changes leading to changes in the frequency spectrum. As a result of such movements, the heart rate was falsely estimated. Rapid changes in ambient light conditions also caused significant signal changes despite the use of the a* channel. For the analysis of the signal quality, the variance of the signal was used. It was effective for identifiying signal sections affected by signal distortions, e. g. due to sudden head movements. Care had to be taken with the manual selection of this threshold value. If the value was too large, distortion could affect the result. A too low value would prevent the estimation of the heart rate even due to neglectable distortions. In the future, more robust methods such as Kalman filters could be used to detect such sudden and brief disturbances and suppress them accordingly. Overall, it has been shown that very good and accurate results can already be achieved with an RGB camera when determining heart rate.

5.2. Influence of vibrations on the iPPG and the estimated heart rate

When the RGB camera was exposed to vibrations with different frequencies and acceleration amplitudes, it was shown that these had no noticeable influence on the estimated heart rate. For a large part of the measurements, the vibrations in the image were not visually perceptible. Under one condition a resonance behavior occurred, which was expressed in clearly visible and audible vibrations and blurred images. It was assumed that these resonances were caused by the camera's housing and could be avoided by an appropriate mechanical design. Nevertheless, it was shown that a reliable iPPG signal and heart rate could be determined even with such strong vibrations.

6. SUMMARY AND OUTLOOK

An iPPG system was developed and analyzed with respect to its usability inside a passenger aircraft cabin. The system was based on a conventional USB webcam installed in the overhead storage compartment facing the seats and the passenger's faces. The camera allowed a robust estimation of the heart rate under certain constraints, i. e. sudden stronger movements of the head had to be avoided. A continuous analysis of the signal quality was implemented in order to avoid incorrect heart rate estimations due to signal distortions. In the future, more robust methods such as Kalman filters could be used to detect or correct distortions of the iPPG signal in order to avoid intertuptions of the heart rate estimation. With regard to the use in the cabin, it should be investigated which illuminance levels occur in a darkened aircraft cabin during overnight flights. On this basis, it would be possible to investigate the extent to which a conventional RGB cameras could be used for this purpose. The advantage of RGB cameras is their good availability and the use of the existing ambient light, i. e. additional light sources such as near infrared light are not required. Reliability could be further optimized by additional pre-processing steps. With a wide-angle lens and a correspondingly high camera resolution, larger areas could be covered by a single camera. Since Mediapipe FaceMesh enables the detection of several faces within one image and the determination of the corresponding landmarks, it would be possible to monitor the vital signs of several persons in the image with just one camera.

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