Real-Time Monitoring of Heart Rate by Processing of Near Infrared Generated Streams

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Abstract—**This paper presents a novel solution for non-invasive real-time heart rate monitoring by processing of Near Infrared (NIR) generated streams, provided by a low-cost, easy-to-use sensor, such as Microsoft Kinect™. The standard method to monitor physiological information exploits photoplethysmographic images. In fact, the changes in blood volume can be determined from the spectra of radiation reflected from (or transmitted through) body tissues. Using a mathematical processing, the study shows how it is possible to real-time estimate the heart rate of people sitting for 1 minute in front of the sensor at distance 1 meter by analysing the NIR stream and without wearing any other sensors. In order to prove the correctness of the method proposed, 35 different subjects are involved in the test phase. During the tests, each subject wears also a pulse oximeter for comparing the values calculated by our method.**

Keywords: Heart rate; Near Infrared channel; real-time; Kinect™ 2.0.

I. INTRODUCTION

The scope of this work is to present a new solution for non-invasive remote monitoring of vital signs (in particular heart rate), using an algorithm that processes the data acquired by the NIR channel of the Kinect™ sensor at medium distance (1 m). By analysing the raw signals with an appropriate mathematical elaboration, the cardiac pulse is extrapolated in "real-time" mode. In this way, it is possible to monitor the heart activity during playing games or during the execution of training programs (e.g., rehabilitation programs), even when light conditions are not optimal, without having to combine additional medical devices that are often invasive.

The Kinect™ 2.0 sensor, by combining a HD camera and an infrared camera (to estimate the depth), uses a human morphological model to match the silhouette seen through the infrared camera and to provide the position (X,Y,Z) for each one of 25 joints. In addition, each data stream (RGB, infrared) could be autonomously gathered for more accurate data analysis [1][2].

By thoroughly analyzing the work and the criticalities that have emerged in the previous tests on real-time heart rate determination via RGB channels [3], one of the key requirements for proper setup is the right lighting (natural or artificial). For this reason, it has been decided to take advantage of the supplied sensor at Kinect™ to use the near-infrared imaging technique (NIR) [4]. NIR is a source of electromagnetic radiation at the beginning of the infrared spectrum range and borders on the spectrum of visible light. Its benefits include the ability to be reflected from objects, penetrating glass and serving as an active source of illumination [5]. While most face sensors use color images as inputs, lighting variance remains a challenge because lighting can alter the color intensity in an image.

Especially in low light conditions, some faces may have a minimum contrast of intensity with the dark background, resulting in facial detection. IR images, on the contrary, remain the same despite the changes in lighting. Even in the dark, IR images can capture distinct details of the face [6].

The paper is organized as follows. The study begins in Section II with a general overview of the devices available on the market and referring to the telemedicine and various sensors for cardiac monitoring. In Section III, the analysis of the state of the art of the already implemented methods for remote monitoring of vital signs is presented. The core of this work is described in Section IV and the developed algorithms with the procedures adopted for their validations and tests are presented in Section V. In Section VII, the discussion of the results of the entire work and the conclusions are proposed in Section VIII.

II. BACKGROUND

The topic of non-invasively detection of vital parameters has been successful increased in the last few years, in part due to the use of new technologies in hospital wards and surroundings, in part because the majority of patients is in favour of personalized assistance instead of health care services provided up to now [7][8].

The market is witnessing the continuous spread of new devices and software systems that allow monitoring the vital parameters (e.g., heart rate, oxygen saturation, respiratory rate) or setting personalized triggered alerts. In this perspective, in order to enhance the daily management of diseases by facilitating self-care, e-Health and related personalized health services are steadily growing [9][10].

A further step towards non-invasive systems has been taken with the introduction of the pulse oximeter, an instrument that, thanks to the principles of photoplethysmography, is able to detect the oxygen saturation of the blood and the heart rate simply by exploiting the changes in blood volume in the microcirculation of the human tissues [11].

Considering the Physiology, the impulse of cardio-vascular wave that flows through the body periodically,

causes stretch in the vessel walls. The volumetric changes due to fluctuations in the amount of blood or air contained within the human body can be measured by photoplethysmography (PPG) [12].

These fluctuations modulate the absorbance of light passing through a given volume of tissue, so it is possible to evaluate the variation of light during a normal cardiac cycle. If these changes are recorded, they originate a waveform that corresponds to the changes in the pulsatile arterial blood in the tissue [13].

It is worth noting that the PPG is usually performed with a dedicated light's source and it considers environmental light as a source of noise. Then, applying the PPG at medium/long distance (2.5m - 3m) implicates that the environmental noise becomes more relevant.

The absorbed light of a human in NIR consists of two components [14]: one static absorption constant from muscles, fat, bones and venous blood (de-oxyhemoglobin) and one varying component from arterial blood (oxyhemoglobin). As the heart beats, the concentration of oxyhemoglobin will fluctuate in the body and effect the light absorption subsequently [15]. The red color of the blood is caused by the fact that absorption coefficient is low for the red wavelengths (620 - 700nm) and high for the other wavelengths of visible light, meaning that only the red light is reflected. The light absorption coefficient in NIR (700 - 1400nm) is very low: 5.7 cm^{-1} in 850nm. The wavelength of 540nm (green light) has around a 50 times higher absorption coefficient than what NIR has [16]. Another difference between RGB-videos and NIR-videos are the number of wavelengths captured. An RGB-camera records three wavelengths simultaneously while a monochrome NIR-camera only records one. The benefit of having more than one frequency is to use the other wavelengths that have a lower oxyhemoglobin absorption as reference to cancel out ambient light and noise as Verkruysse et al [17].

III. STATE OF THE ART

In recent years, there has been a growing interest in the study of remote monitoring of vital signs using webcam and algorithms with computational software.

One of the first experiments to extract heartbeat from video (with a webcam) was conducted by Poh at al. [18] in 2010 at MIT in Boston: they have recorded videos of a minute and then completed processing of signals from the RGB channels by computer's webcam. The results obtained from MIT are based on studies conducted few years before: Verkruysse et al. [17] had demonstrated that the blood absorbs light more than the surrounding tissues and this application can also be used to evaluate the heart rate and breathing (photoplethysmography).

Moreover, the studies conducted by Takano et al. [19] considered the use of a charge coupled device (CCD) camera for the acquisition of the person's face every 30 seconds: from these studies, it was possible to extract the heart rate and respiratory rate.

Another webcam-based heart rate measurement method, was studied in 2013 using Laplacian Eigenmap (LE) [20]: this technique is used to extract the volume of blood pressure (BVP) from subjects' videos acquired.

In recent publications [21], different tests has been conducted in order to change the technology used, by adopting a camera with five channels and demonstrating that the alternation of the frequency bands, in particular the orange band, allows a physiological measurements much more correlated to the values obtainable with a classic pulse oximeter. However, this type of camera is not included in most of the commercial devices.

The use of the Microsoft Kinect™ device is certainly linked to gaming platforms, rather than to other areas [22]. Recently, the Polytechnic University of Marche has presented a method for measuring heart and respiratory rate [23] by using the Kinect™ 1.0 sensor. The study has been based on the detection of micro-movements of the neck, abdomen and chest of supine subjects, placed a short distance (<1m) from the sensor.

In the Healthcare Innovation Conference (HIC) [24] it has been presented a study that uses a Kinect™ camera mounted on the car's dashboard in order to collect video and to calculate the driver's heart rate in real time.

Finally, our paper presented at SpliTech 2016 [3] described the implementation and the tests of a novel methodology for evaluating the heart rhythm by a non-invasive monitoring system based on Kinect™ 2.0 sensor, acting at medium/long distance (2.5 m). Furthermore, this work highlights the capability to monitor the cardiac pulse rate during the performance of physical exercises.

About Infrared system, in 2015 Zeng presented in a paper a non-invasive heart rate detection process using Kinect™ to measure the heart rate via the obtained near-infrared video, in order to decrease the interference from light and establish a non-invasive system via near-infrared camera [25].

Procházka [26] detect possible medical and neurological disorders using Microsoft Kinect™ sensors for non-contact monitoring of breathing and heart rate estimation: video sequences of facial features and thorax movements are recorded by device image, depth and infrared sensors to enable their time analysis in selected regions of interest. Spectral analysis of the time evolution of the mouth area video frames (infrared data) was also used for heart rate estimation.

IV. METHODS

The combination of the Depth camera of the Kinect™ sensor and the information contained in the signal emitted by the major surface vessels is the base of the real-time method developed for monitoring the heart rate without the direct contact between the instrument and the patient. The solution proposed is able to solve some of the problems related to an invasive monitoring system, ambient light conditions and, at the same time, to ensure the reliability of the results from a physiological point of view. In these terms, the Kinect™ camera detects the changes of blood flow (and thus the work done by the heart) by collecting the mixture of the reflected photoplethysmographic signal (with the fluctuations based on the amount of reflected light) and the volumetric changes of the blood vessels.

In order to choose the region of interest (ROI), the most suitable areas for the detection of heart rate are the forehead and cheeks [27][28]. A rectangle (size 100x140 pixels) that includes the person's face and tracks it during movements is designed from the neck joint. The sizes of the ROI are the best compromise in order to reduce the background noise and analyse the most significant pixels. Furthermore, it is decided to use the neck joint because the Kinect™ has encountered problems in identifying and tracking the face of people wearing glasses with anti-reflective lenses.

The software developed for this study, integrates a C# code able to activate the Kinect™ sensor, to detect the person's face and to proceed with the acquisition of the raw signals from the NIR channel and a Python code used for the data processing and the analysis of the signals. In this way, the Kinect™ sensor is able to maintain the 30 fps real-time images acquisition and to implement the mathematical algorithm processing, without creating duplication or data loss. Indeed, the raw IR data, i.e., the intensity average of the pixels of the ROI, are sent to the Python processes, while the Kinect™ sensor continues the real time acquisition of the frames. In order to mitigate the background noise, a bandpass Butterworth filter with infinite impulse response, double-pass, 7th order, and bandpass [0.85 ÷ 3.5 Hz] is applied.

Then, the spectral analysis (by Fast Fourier Transform) of the average of the filtered IR pixels is applied in order to represent the distribution of the power of the signal itself.

The FFT of the IR signal allows deciding the frequency corresponding to the maximum peak's intensity in the same band of the filter [0.85 ÷ 3.5 Hz], that corresponds to the range [51 to 210 bpm] of the heart rate: in this interval it is surely contained the normal range of physiological heart rate values for healthy people [60÷100 bpm] [29]. The average beats per minutes are obtained by the multiplication by 60 of this value of frequency. Every new 60 frames acquired, this analysis is re-performed. In this way, a new heart rate value is generated every two seconds. In Figure 1, the block diagram of the whole implemented algorithm is reported.
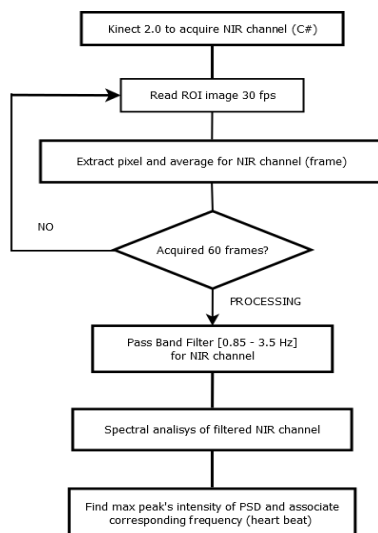

Figure. 1. Block diagram real-time processing NIR channel.

V. Experimental Setup

The technical equipment used for performing the test is based on the Microsoft Kinect™ 2.0 sensor. All the videos are acquired in NIR (8-bit IR) at maximum frame rate available (30 fps - sufficient to generate a valid real time value for the heart rate) and with a resolution of 512x424 pixels.

A test is performed by 35 participants (18 men and 17 women), between the ages of 24-60 years, in good health (some of which are also well-trained) and with different features (beard, moustache, glasses, foundation creams). During tests, they wear a GIMA OXI-10 pulse-oximeter (in order to make a later comparison of the obtained values) [30].

The distance between the subject and the sensor is approximately set to 1 meter. The choice of the distance is given after a pre-test where the subjects are placed to different distances: 1m, 2m and 3m. It is worth noting that there are not any relevant deviations of the heart rate values calculated from the Kinect™ sensor due to the distances [31].

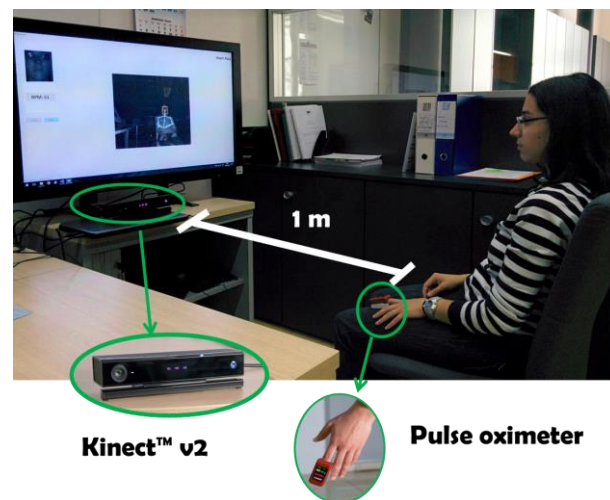Figure 2 well represents the experimental setup created during tests in laboratory environment.

Figure. 2. Experimental Setup.

During the different tests to find the right setup of Microsoft Kinect™, is used a dual data acquisition that involves real-time heart rate detection using the RGB channels and infrared channel available to device.

By analyzing the Microsoft device used, Figure 3 compares the infrared sensor with the RGB channels of Kinect™ [32].

As shown in Figure 4, the two cameras are placed few centimetres far. This implicates that also the sensor area of coverage is slightly different: for this reason it is necessary to proceed with a pre-calibration to align as much as possible the size of the ROI gained through RGB and the ROI gained through NIR, especially if the facial rectangle is constructed following the skeleton joint's trend.

	Camera Name			
	Kinect 2.0 RGB Camera		Kinect 2.0 IR Camera	
Imaging Sensor				
Type	-		-	
Resolution (pixels)	1920×1080		512×424	
Pixel size (μm)	3.1		10	
Interior Parameters				
	Value	St. Dev	Value	St. Dev
Focal length (mm)	3.291	1.0e−3	3.657	5.2e−4
Format width (mm)	6.00		5.12	
Format height (mm)	3.38		4.24	
Image width (pixels)	1920		512	
Image height (pixels)	1080		424	
Principal Point x (mm)	−0.005	5.6e−4	0.032	3.5e−4
Principal Point y (mm)	−0.016	6.9e−04	0.033	3.9e−4

Figure 3. Sensors and IO parameters of RGB and IR cameras estimated during the camera calibration procedure for Kinect 2.0.

Figure. 4. Kinect™ features.

After all these considerations, to choose the best setup, the participants are standing and sitting in front of the Kinect™ sensor, at approximately 1 meter far from the built-in camera, while the system calculates the heart rate in real time mode using the NIR channel.

VI. RESULTS

For each subject, the graph comparing the timely progression of the heartbeat detected both by Kinect™ sensor and the pulse oximeter has been plotted. Then, it has been decided to calculate the heartbeat's average in the time interval considered.

The percentage error of the mean of heart rhythm detected by the Kinect™ sensor and the one obtained by averaging the incoming values from the pulse oximeter are also calculated.

Plots in Figure 5 show the graphs of heart rate value acquired by the Kinect™ based system (red line) and gathered by pulse oximeter (blue line) during the test.
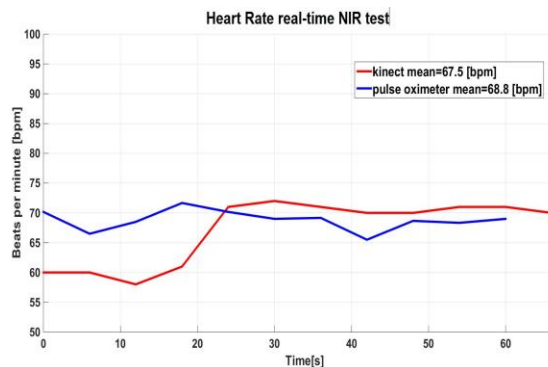

Figure. 5. Representation of heart rate-time during two different tests.

In Figure 6, the scatter graphs of mean value between Kinect™ and pulse oximeter are plotted for each test conducted: a linear trend line has been added for better understanding the graphs and the correlation coefficient (R) and the level of significance (p) are also calculated.
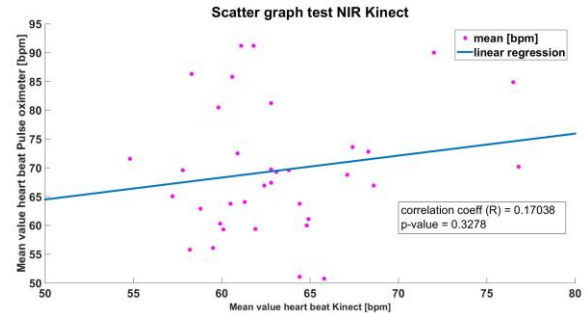

Figure. 6. Representation of scatter plot Kinect™/pulse oximeter.

The correlation coefficient (R) is a number between –1 and 1 that determines whether two paired sets of data are related: the weakest linear relationship is indicated by a correlation coefficient equal to 0. So the coefficient for the test shows a moderate positive correlation between data of heartbeat from Kinect™ and from the pulse oximeter. The p-value is a number between 0 and 1 that determines whether the correlation between variables is significant. A p-value (as calculated for the still test) of 0.30 indicates that the risk of concluding that a correlation exists—when, actually, no correlation exists—is about 30%. [33].

For each tester the average heart rate (HR) calculated is also reported in Figure 7, considering the device used and the type of the test performed. The table well summarize the comparison of the mean heart rate values obtained from Kinect™ and from pulse oximeter, according with the relative percentage error calculation.
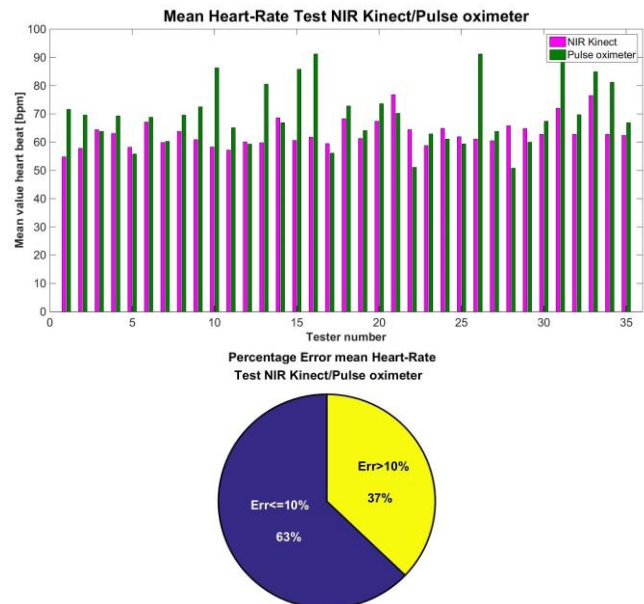

Figure. 7. Results of (HR) average of different tests and relative error.

By considering these three factors, i.e., value of correlation coefficient (R), the p-value and the relative errors (acceptable within 10%), it is possible to say that, the values of the heart rate calculated with this novel solution are comparable with the values gathered by the medical device only during the still tests. Moreover, the obtained values are also comparable with the previously acquired data and analyzed through RGB channels of the Kinect™.

VII. DISCUSSION

As discussed above, it is possible to consider the system implemented as a valid system for gathering the real-time heart rate values in static position, even when light conditions are not optimal. While considering the pulse oximeter as a reliable system, the device used has inherent accuracy $\pm 2\%$. For these reasons, part of the deviation between the values gathered by the Kinect™ sensor and the GIMA oximeter should be related to a non-correct use of the oximeter.

Finally, not significant variations of the results are due to gender, age and fitness status of the testers.

VIII. CONCLUSION

This work describes the implementation and the tests of a novel methodology for evaluating the heart rhythm acting at medium distance (1 m), by analysing the NIR stream. The performance of the proposed method (applied in real-time) is tested in adverse situations, such as in the dim light condition. The study starts showing the real-time processing of the video acquired by the Kinect™ built-in NIR camera. The procedure begins with the automatically choice of the ROI with a strong passage of blood modulation and with the reduction of the background noise with a band-pass filter. Then, it continues with the analysis the signals coming from the IR channel of camera and it finishes by creating an ad-hoc algorithm for accurate heart rate detection using FFT.

The system and the algorithm implemented are validated by 35 participants sitting in front of the sensor at approximately 1 meter.

As described in the results, the study has shown a quite good reliability in detection of heartbeat at distance and in real-time, when the subject is in a static position in front of the sensor.

As a future development, it could be considered the possibility of applying this heart rate detection solution using infrared sensor, in situations where it is difficult to wear sensors for a long period of time (e.g., driving, neonatal department, etc.). Generally this type of monitoring can be useful in all the situations in which acquiring remote vital parameters is easier than wearing medical devices.

After the results obtained with a sufficiently reasonable number of testers, as a future work, it is designed to continue the study with large-scale testing to validate and perform the entire algorithm in a robust manner.

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