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Measurements of heart and respiration rates in thermovision

Abstract

Human life parameters such as the frequency of heart contractions, temperature, arterial pressure and breathing frequency are one of the most important parameters used to assess the basic vital functions of the most important organs of the body. In addition to describe health status, they can be used to assess the state of human activity, its efficiency and fatigue. Traditional techniques for measuring physiological parameters require appropriate sensors connected to human body. However, attaching the sensors to a human body may be undesirable or impossible, such as in newborns or during sports training. The article presents the method of measuring the frequency of heart rate and the frequency of breathing based on the analysis of the thermographic image of the human head.

Keywords: thermographic camera, heart rates, respiration rates, medical observations.

1. Introduction

Measurement and monitoring of physiological parameters, including heart rate (HR) and respiratory rate (RR), play an important role in many applications in healthcare, psycho - physiological research (polygraph), sports training and animal studies laboratory. Dynamic changes in physiological parameters may reveal changes in the physiological state and human function. In addition, apnea (sudden respiratory arrest) and bradycardia (a rapid decrease of heart rate) are often the cause of infant death.

Traditional techniques for measuring physiological parameters require the connection of sensors to human body, such as an electrocardiograph, a pulsometer, and a breathing rate sensor. Contact-based methods of this kind may cause skin irritation, discomfort or may not be possible, for example, with newborns. It may be undesirable to attach the sensors to a human during sleep tests, sports training or various activities by a human being, because they may adversely affect mobility. Remote monitoring of respiratory function also reduces the risk of suicidal death among patients of psychiatric hospitals, prisoners in penitentiary institutions and persons placed in police detention centers.

One of the methods of non-contact measurement of heart rate and respiratory rate is the measurement using a video camera [1-6]. The principle of these methods is to record the light reflected through the skin when the blood circulates in the arteries and veins or detects movement of the chest during breathing. However, these methods cannot be used in conditions of limited visibility or in poor light conditions, such as night monitoring of the infants or night driver's work. In medicine, more and more often innovative solutions of phenomena analysis are used, such as thermographic cameras [7]. Therefore, the use of a thermographic camera was assumed for observation and measurement of vital signs in conditions of limited visibility. However, due to the different nature of the signal being recorded, it is not possible to use existing methods. For this reason, an attempt was made to develop a method for measuring the frequency of heart contractions and respiration rate based on the analysis of the thermographic image of the human head. Breathing frequency estimation based on thermal imaging analysis may extract information from body movement due to breathing (e.g. chest movement), temperature change caused by breathing air movement or detection of carbon dioxide emission [8].

The heart rate signal recorded by the thermographic camera should be the result of blood flow. Every heartbeat pushes fresh blood into the veins and we assume that fresh blood is warmer, so with every heartbeat, the radiation emitted by skin will change. In this case, there is no need to record the exact temperature, but only changes of the signal from the infrared radiation detector. The typical frequency of heart contractions is between 50 to 90 beats per minute (bpm) in calm conditions. However, the full range of changes in the heart rate may range from 30 (resting for a trained athlete) to 220 (stress) beats per minute. This means that in the thermograms analyzed in time one should expect an impulse signal with a frequency in range from 0.5 to 3.67 Hz. In addition, the frequency of heart contractions varies over time. For this reason, it was assumed that the period in which the frequency of heart rate will be determined should not exceed 60 seconds.

The typical breath rate for an adult is from 16 to 20 breaths per minute (bpm). However, during exercise, the frequency of breath may multiply 3 (young people) to 7 (athletes' performance) times. It follows that during exercise the respiration rate may increase to 60 and even to 140 bpm. This means that the respiration rate signals typically are between 0.267 and 0.333 Hz, reaching a maximum of 2.333 Hz. Also in this case, it was assumed that the period of time during which the breath rate will be determined should not be longer than 60 seconds.

2. Laboratory setup

In order to register the data for the verification of the developed method of thermographic signal analysis, a special laboratory setup consisting of several elements was made. The main element was a FLIR cooled thermographic camera SC 7900 working in the far infrared spectrum (LWIR). The camera is equipped with a high performance mercury cadmium telluride photon detector (MCT), which provides a temperature resolution below 25 mK. Basic camera parameters are presented in Table 1.

Tab. 1 Basic parameters of FLIR SC 7900 camera

Parameter	Value
Detector type	MCT
Resolution	320×256 pixels
Wavelength	(7.7…11.5) μm
Number of pixels	76 800
Pixel size	30 μm
Sensitivity (NETD)	< 25 mK
Quantization bits	16 b

Using a thermographic camera, image of the face of a seating person was recorded at a distance of about 2 m. The sequence of the images was recorded at 50 frames per second in full spatial resolution (320×256 pixels) and saved using a PC. With each thermogram, a set of reference data: the frequency of heart contractions and respiration rate was recorded. For this purpose, a finger-mounted heart rate monitor and chest-mounted breathing sensor were used. Signals from these sensors were recorded at a frequency of 250 samples per second and stored in the computer. The diagram of the laboratory setup is shown in Figure 1.

3. Thermographic signal analysis method

In order to determine the frequency of heart contractions and the frequency of breath by means of thermographic image analysis, measurement data containing K images should be recorded, each one having M rows and N columns. Thermographic signal $y(m,n,k)$ is read for each matrix detector located in m - th row and n - th column in k - th picture (frame).

Figure 2 shows the process of taking measurements.

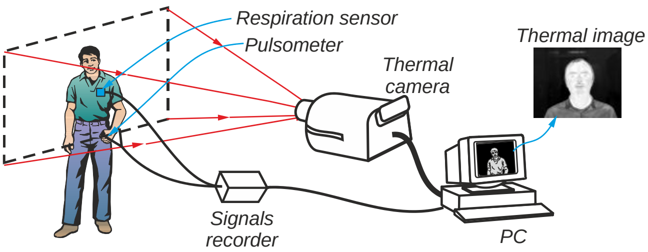

Fig. 1. Diagram of laboratory setup for thermographic image, heartbeat and breath frequencies registration

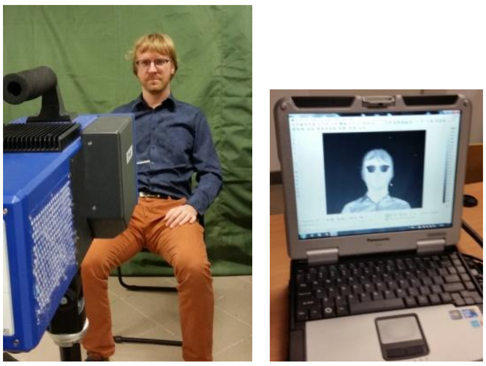

Fig. 2. Registration of thermographic images, breath and heartbeat frequency

The first activity performed by the algorithm is selecting the analyzed human area in the thermographic image (region of interest). The region of interest is a rectangular area of $N_w \times M_w$ limited by m_L to m_R of the row and from n_L to n_R of the column. An example thermal image with the selected region of interest is shown in Figure 7.

Due to the principle of operation of thermographic's camera detection system, the bad pixels can occur in the thermographic image. Those values significantly differ from the recorded signal (radiation) [9, 10]. Therefore, such pixels are removed in the analyzed area. In the case under consideration, the incorrect pixel value is changed by the average value from the neighboring pixels. For the region of interest, the average values of the signal for each recorded image (frame) were determined as a function of time according to the formula:

$$\bar{y}(k) = \bar{y}(k) = \frac{1}{N_w \cdot M_w} \sum_{m=m_L}^{m_R} \sum_{n=n_L}^{n_R} y(m,n,k) \quad (1)$$

Figure 3 presents a graph of signal averages for the region of interest for subsequent frames of the thermographic image.

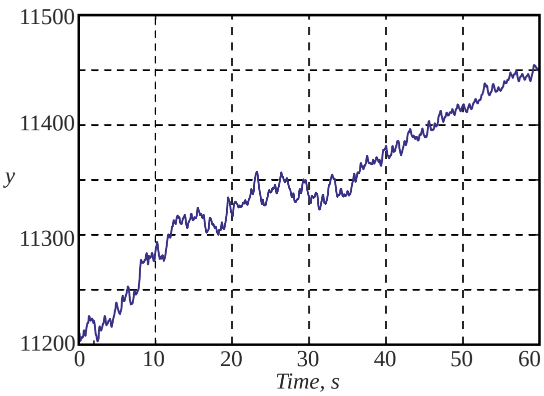

Fig. 3. Mean signal values as a function of time for the selected region of interest

The functioning of the cardiovascular and respiratory systems is dynamic. The dynamics of such a system is similar to the dynamics of other deterministic systems with chaotic properties that have irregular periodicity, as well as considerable sensitivity for initial conditions. In order to determine the nature of the signal, it must be reconstructed and processed accordingly, based on the recorded time samples. At the same time, the signal is characterized by the variability of shape and the occurrence of the low-frequency component in the form of a trend. Therefore, the first stage of signal processing is the removal of its constant component. Implementation of this task with bandpass filtration is difficult due to the narrow bandwidth of the filter, the required small slope and the relatively low filter order (slight delay). Bandwidth filters that meet the above requirement often cause degradation of the useful signal and introduce significant oscillations. Therefore, after such a signal filtration, it is not possible to reproduce the required signal parameters. The procedure of removal of the constant component was conducted by subtracting from the current signal value its local average determined as the average value from R of previous samples of the so-called moving average in the form of:

$$m_R(k) = \sum_{r=1}^{R} \bar{y}(k-r+1) \quad (2)$$

Then the signal after removing the constant component takes the form:

$$y^*(k) = \bar{y}(k) - m_R(k) = \bar{y}(k) - \sum_{r=1}^{R} \bar{y}(k-r+1) \quad (3)$$

The number of samples was assumed experimentally the way the number of samples R was equivalent to a specific time period. For the measurement of heart rate, the time is about 250 ms.

Figure 2 presents a graph of signal averages for a selected region of interest after removing a fixed component.

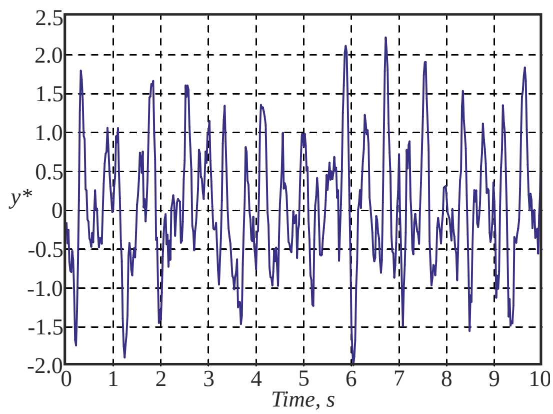

Fig. 4. Graph of mean signal values as a function of time for a selected region of interest after removal of a constant component

The next necessary step is to remove the violent local disturbances most often associated with the noise of analog to digital converters. In order to remove this type of distortion, the determination of signal samples using the so-called local (moving) median for P last signal samples was calculated. In the algorithm, the P value was assumed experimentally and equals 3. The process of removing local violent disturbances can be described by the formula:

$$\tilde{y}(k) = \mathrm{median}_{i=1\ldots P}[\{y^*(k-i+1)\}] \quad (4)$$

In order to determine the number of heartbeats, one must determine the level of the signal w_y which, if exceeded, counts the signal related to the heart contraction. In order to determine the threshold from the signal, the value of the local (moving) standard deviation for L of the previous samples is determined in accordance with the formula:

$$S_y = \sqrt{\frac{1}{L}\sum_{i=1}^{L}\left[\tilde{y}(k-i+1) - \overline{\tilde{y}(k)}\right]^2} \tag{5}$$

where $\overline{\tilde{y}(k)}$ is value of signal $\tilde{y}(k)$ calculated from L previous samples. The number of L samples corresponds to a time period equal to 1 second. Then the value of the threshold level is calculated using the formula:

$$w_y(k) = k_y \cdot S_y(k) \tag{6}$$

where the k_y factor is selected experimentally. In the presented algorithm, the k_y coefficient is 1.5.

Figure 3 shows the graph of mean values of the signal as a function of time for the selected region of interest after removal of the constant component and reduction of local disturbances (blue line) and the adaptive counting threshold (red line).

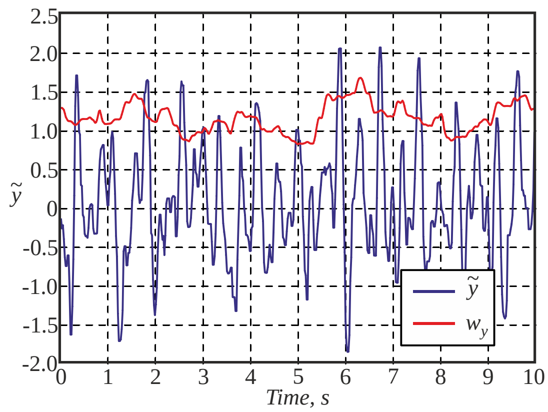

Fig. 5. Mean signal values as a function of time (blue line) for the selected region of interest after removal of the constant component and local disturbances and adaptive counting threshold (red line)

Detection of heart contractions consists in counting the number of signal exceedances over the threshold w_y in the period of 60 seconds for a rising signal which can be represented by the formula:

$$HR = \frac{1}{H}\sum_{k=1}^{H}\begin{cases}1 & for \quad \tilde{y}(k) > w_y(k)\\ 0 & for \quad \tilde{y}(k) \le w_y(k)\end{cases} \tag{7}$$

where H is the number of samples corresponding the time of 60 seconds.

The method of breath rate measurement is based on an identical method of signal processing, however, without the use of local median (4) and with a different values of R, L and k_y parameters. In the algorithm for determining the respiration rate, these parameters were chosen to describe the appropriate time intervals. For the parameter R, this is the period of 5 seconds and the parameter L equals 2 seconds. The parameter k_y has been experimentally determined and equals 3. Also in this case, the formula (7) is used to count and detect breaths.

4. Measurement results

In order to analyze the recorded data, special IR Image Analysis software working in the MATLAB environment was developed in Military University of Technology. The software has implemented functions such as selecting the analysis region of interest (ROI), modules for calculating the parameters of the thermal imaging, methods of analyzing the parameters of the region of interest as a function of time. In addition, the software implemented developed methods for determining the frequency of heart contractions and respiration rate. Figure 6 shows selected windows of the IR Image Analysis program. The application calculates and analyses parameters in selected ROI.

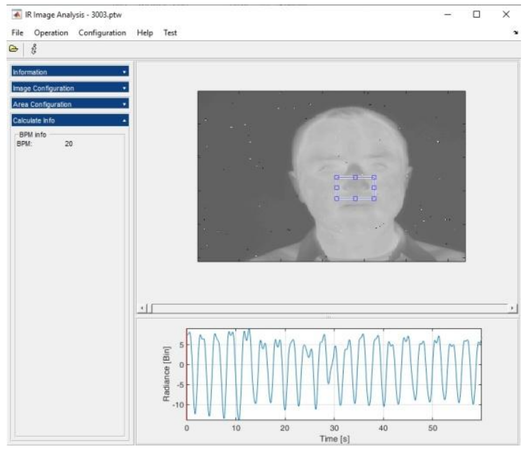

Fig. 6. IR Image Analysis application window

The analysis starts by selecting region of interest on the thermogram. For this purpose, for the registered faces of several people, the parameters of the region of interest as a function of time were analyzed. Many regions of interest have been analyzed, such as: the inner corner of the eye, neck, forehead, nasal area, nostrils. The analysis shows that for the measurement of heart rate, the area of the nasal bridge should be chosen as the region of interest, while the area containing the nostrils should be used for breath rate measurement. Figure 7 presents an example infrared image with selected areas of interest for pulse measurement and breath rate measurement.

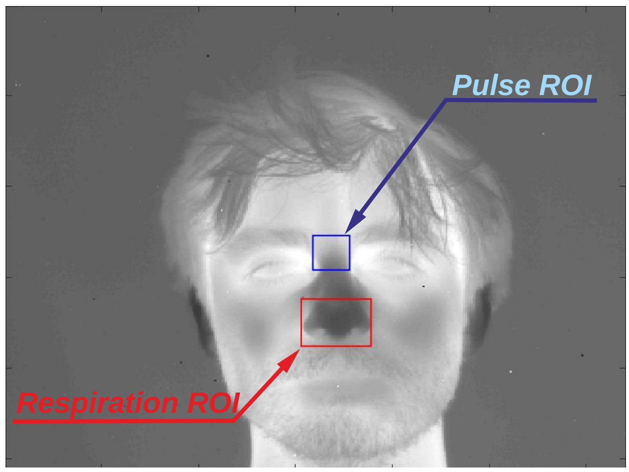

Fig. 7. The view of registered thermogram with regions of interest for pulse and respiration frequency

According to the method of measuring heart rate and respiration frequency presented in the article, their values were determined in selected regions of interest for several different people. The results of the obtained measurements of heart rate and respiration rate are presented in Tables 2 and 3. The analysis of the obtained results shows that in most cases a good result was obtained for which the relative error is less than 1%. However, both measurements were able to register such results for which the measurement error is very large. This is due to the difficulty in choosing the correct region of interest. Choosing the wrong region of interest means that the useful signal has very high noise (low signal-to-noise ratio) or is not present in this region. Therefore, the algorithm works improperly and is characterized by the occurrence of a large measurement error. Therefore, in order to reduce the probability of obtaining an incorrect signal, the algorithm should be extended with the method of signal quality evaluation. This will allow to detect the lack of a signal or signal with very high noise and thus allow to find another better region of interest.

Tab. 2. Pulse measurement results

Person number	Pulse, bpm		Absolute error	Relative error
	Pulsometer	Thermogram		
1	55.3	75.1	19.83	35.88 %
2	75.9	75.2	-0.73	-0.97 %
3	64.4	65.0	0.63	0.97 %
4	75.4	75.1	-0.25	-0.34 %
5	78.6	78.1	-0.49	-0.63 %

Tab. 3. Breath frequency measurement results

Person number	Breath frequency, bpm		Absolute error	Relative error
	Accelerometer	Thermogram		
1	10.9	11.0	0.10	0.92%
2	20.1	20.0	-0.10	-0.50%
3	9.5	10.9	1.40	14.74%
4	15.8	16.0	0.20	1.27%
5	17.9	18.0	0.10	0.56%

5. Summary

The paper presents a new method of measuring the frequency of heart contractions (cardiovascular) and the frequency of breath by analysis of thermal images. The developed method uses periodic properties of the thermal field caused by the pulse of the heart and exhaled air. The advantage of the method is its computational simplicity, which allows to be used in portable and battery-powered devices (especially when the method would be positively verified with microbolometric cameras). The developed method is non-contact, passive, automated with the use of a thermographic camera, which allows measurements of physiological properties in conditions of limited visibility and insufficient lighting, e.g. at night.

The developed method shows good accuracy compared to measurements from medical sensors that are used in standard medical practice. The obtained experimental results clearly show that the measurements of the frequency of heart contractions and the frequency of breath with a thermographic camera are possible and feasible. Despite the fact that the results of the work are promising, in order to increase the effectiveness of the method, it is planned to develop a method for assessing the quality of the recorded signal. As part of further research, it is planned to check the presented algorithm by means of signals from body parts, such as: hand, arm or chest.

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