Method for Measuring the Heart Rate Through Fingertip Using a Low-end Video Camera and Its Application in Self Care

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***Abstract*—This article presents a method for monitoring the heart rate using a low-end video camera. The user places the fingertip on the camera lens and the software detects the periodic variations in light intensity caused by the pulsation of blood in the capillary tissue. The measurement technique is based on extracting beat-to-beat intervals by passing the color intensity average through a processing pipeline comprised of six stages. Our tests indicate a measurement error below 3 bpm, when compared to commonly available home care devices. We present a possible application of our method in the area of stress diagnosis and treatment. The application can be used at home to monitor personal health and enable individuals to perform enhanced self care.**

I. Introduction

HEART rate and heart rate variability are important indicators of the cardiac function, providing valuable information that can help the early diagnosis of cardiovascular diseases. Studies show that an increased heart rate value indicates a high risk of cardiac failure [1]. It has also been shown that heart rate variability can be an indicator of emotional strain and elevated anxiety [2].

This article describes an original, convenient, and practical method for measuring the heart rate that does not need any specialized equipment — only a personal computer and a cheap video camera. The user gently covers the camera lens with the soft part of the fingertip while the software detects the subtle changes in light absorbance correlated with heart pulsations. The measurement technique is based on extracting beat-to-beat intervals by passing the color intensity average through a processing pipeline comprised of six stages. This original processing method is reliable, has a low-computational cost, and works well with the low-end video cameras integrated in a wide range of consumer electronics. Our tests indicate a measurement error below 3 bpm, when compared to commonly available home care devices.

We present a possible extension of our method in the area of stress diagnosis and treatment. For diagnosis we propose the analysis of heart rate variability over a longer period of time. For treatment we recommend music therapy using computer-generated music. The tool for computer music generation has already been developed and used with success [3].

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Existing software for measuring the heart rate

The presented method is not intended to replace or even compete with specialized medical equipment. Clinical instrumentation must respect certain standards and pass numerous clinical tests, to which the presented method was not subjected. Consequently, we consider previous work software applications that run on general purpose computers and use non-specialized sensors to measure the human heart rate. We can group these programs into four categories, based on the working principle.

Phonocardiograph applications. Phonocardiographs are medical devices that use microphones, amplifiers and filters to record heart sounds. Software applications based on this principle extract the pulse rate from the heart sounds recorded with the integrated microphone. Consequently, this technique is very sensitive to noise, making it difficult to obtain accurate measurements.

Accelerometer-based applications. Accelerometers can be used to measure chest vibrations caused by the heart's movement. Like in the case of phonocardiograph applications, this method is very sensitive to noise and produces incorrect results most of the time.

Fingertip PPG applications. The underlying heart rate measurement technique used by the software in the third category is fingertip photoplethysmography (PPG). The user places the fingertip on the camera lens and the software detects the periodic variations in light intensity caused by the pulsation of blood in the capillary tissue [5]. The measurement method described in this paper is based on fingertip PPG. Our results (section IV) demonstrate that this technique is reliable and produces accurate results, if it is implemented correctly.

Face motion magnification applications. This category includes applications that use the video camera to record invisible physiological changes on the face of the user. Each heart beat produces a bulge in the walls of the arteries. This motion is invisible to the human eye, but special algorithms can amplify the changes between successive frames (a technique called "Eulerian Video Magnification" [6]). These algorithms use significantly more computing power and are less suitable for computers with lower resources.

The method described in this paper differs from the existing methods in several aspects. First, the method has a very low computational cost, which makes it suitable for less capable hardware. A direct benefit of being lightweight is that it draws little battery power, thus it can be used more frequently and for prolonged periods of time. Another important asset of the presented method is that it yields accurate results even with low quality video cameras that have reduced resolution and capture rate. This makes the presented method appropriate for running on a wide range of consumer electronics, from smart-

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phones and tablets, to computers and smart TVs. Furthermore, the method described in this article is resistant to noise and produces good results even in unstable conditions.

While this kind of tools are available for smart-phones and tablets, to the best of our knowledge there is no such application available for personal computers. The application can be used essentially cost-free at home by individuals to monitor personal health, enabling them to perform enhanced self care.

In the next section we explain the principle behind the described technique. Section III presents the method, providing details about the processing pipeline. In section IV we show the results obtained by testing the application within a diverse group of users. We present in section V a possible extension of our method in the area of stress diagnosis and treatment. Conclusions are presented in section VI.

II. Working principle

Clinically, the pulse rate is detected using photoplethysmography, a technique that employs optical measurements to record the changes in blood flow. The working principle is the light-tissue interaction. Water absorbs light very strongly in the ultraviolet and the longer infrared wavelengths, melanin absorbs the shorter wavelengths, leaving just a small window in the absorption spectra that allows the measurement of blood flow. This window corresponds to red and near infrared wavelengths, between 720–820 nm [5].

The method we propose for measuring the heart rate is based on fingertip photoplethysmography. Instead of a specialized photodetector, we use a low–end video camera. The image sensor is essentially a two dimensional matrix of photodiodes coated with filters for red, green and blue wavelengths spread in a Bayer pattern [7]. The filters allow a little amount of near-infrared light to pass through, making it possible to detect the subtle changes in absorbance correlated with higher (systolic) and lower (diastolic) volumes of blood.

III. Implementation

The method uses a processing pipeline comprised of six stages (Figure 1).

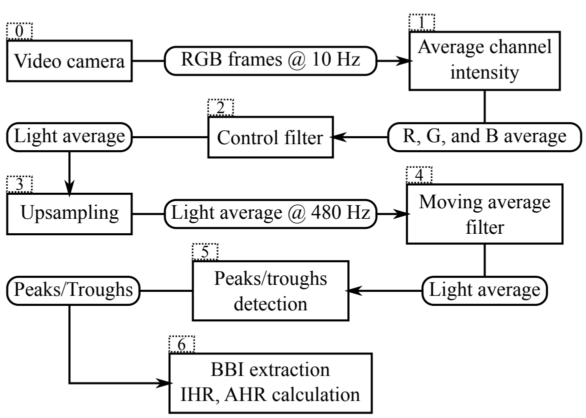

Fig. 1. Processing pipeline comprised of six stages

A. Channel intensity

The first stage in the pipeline processes raw image frames produced by the video camera. For each frame this stage computes the average intensity of individual color components (channels): red, green, and blue.

We use $F[T]$ to denote the image frame captured at moment T (measured in milliseconds). For a given frame $F[T]$ with width w pixels and height h pixels, equation 1 computes the average intensity of the red channel, denoted as $R_{avg}(F[T])$. $r(p_i)$ is the red component of the pixel stored at position i in $F[T]$. It is important to notice that since $r(p_i) \in [0, 255]$, then R_{avg} is a real number in the same interval. The average intensities for green ($G_{avg}(F[T])$) and blue ($B_{avg}(F[T])$) are computed similarly.

$$R_{avg}(F[T]) = \frac{\sum_{i=0}^{w \cdot h} r(p_i)}{w \cdot h} \tag{1}$$

The average channel intensities R_{avg}, G_{avg}, and B_{avg} are used throughout the pipeline in a form or another. They represent the "building blocks" of the presented method.

B. Control filter

The control filter stage (Figure 2, first trace) is responsible for managing the data flow, acting as a "control valve" for the entire pipeline. It detects when all conditions for making a measurement have been met, including:

- whether the fingertip covers the camera lens (red to green and red to blue ratios are above $th_{ratio} = 1.5$)
- if the light is too dark or too bright (red intensity is between $th_{low} = 10.0$ and $th_{bright} = 245.0$)
- if the camera is done adjusting the exposure time ($T - T_0 \geq \Delta_{warmup}$)

This is also the moment when the three channel intensities are added up together to determine the average light intensity ($L_{avg}(F[T])$) used as input in the next stages of the pipeline.

C. Upsampling

Upsampling (Figure 2, second trace) mitigates one of the biggest drawbacks of using general purpose video cameras — the low capture rate. This stage increases the sampling rate of the L_{avg} signal received from the *control filter* by a factor of 48. Thus, this step takes as input a signal with a sampling frequency of approximately 10 Hz and outputs a signal with a frequency of 480 Hz. This is essential for the next stages in the pipeline, because they do no work correctly for low sampling frequencies.

We are using cubic interpolation to preserve the wave trend of the signal. We chose *Catmull-Rom* coefficients because they allow for smoother splines that pass through all the control points [8]:

$$P(t) = \frac{1}{2} \cdot \begin{pmatrix} 1 & t & t^2 & t^3 \end{pmatrix} \cdot \begin{pmatrix} 0 & 2 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 2 & -5 & 4 & -1 \\ -1 & 3 & -3 & 1 \end{pmatrix} \cdot \begin{pmatrix} P_{i-2} \\ P_{i-1} \\ P_i \\ P_{i+1} \end{pmatrix} \tag{2}$$

where $P(t)$ is $L_{avg}(F[T_{i'}])$, and P_i is $L_{avg}(F[T_i])$.

D. Moving average filter

The purpose of the fourth stage (Figure 2, third trace) is to eliminate random noise and attenuate the photoplethysmogram curve. It takes as input the upsampled L_{avg} signal generated by the previous stage and applies a moving average [9]. We experimented with various moving average filter variants, including: simple moving average, exponentially weighted moving average and median moving average. The best results were obtained using a moving average filter, defined as:

$$L'_{avg}(F[T_{i'}]) = \frac{1}{M} \sum_{k=-\frac{M}{2}}^{\frac{M}{2}} L_{avg}(F[T_{i'+k}]) \qquad (3)$$

Where M is the order of the filter ($M = 60$ works best in practice).

E. Peak detection

The fifth stage (Figure 2, blue circles) performs peaks and troughs detection. Peaks are local maxima (diastolic), while troughs are local minima (systolic). Successive peaks are used in the next stage to determine beat-to-beat intervals. Beat-to-beat intervals give a good estimation of the heart rate [10]. We define $P[T]$ as:

$$P(F[T_{i'}]) = \sum_{k=-2}^{2} L'_{avg}(F[T_{i'+k}]) \qquad (4)$$

Position $F[T_{i'}]$ is considered a peak if it satisfies the following condition: $P(F[T_{i'}]) > P(F[T_{i'-1}]), P(F[T_{i'}]) > P(F[T_{i'+1}])$. Troughs are detected analogously.

F. Pulse rate derivation

The final stage (Figure 2, blue vertical bars) in the pipeline performs the actual heart rate detection and measurement. Peaks that are not surrounded by troughs are eliminated. Invalid peak slopes, that are not symmetrical, are also removed. Beat-to-beat intervals (BBI) are derived by subtracting the timestamps of successive peaks. A BBI $\tau_i = (T_i - T_{i-1})$ is considered valid if it is no shorter than 150 milliseconds and no longer than 2200 milliseconds. Successive BBIs are passed through a median filter with a window size of 5. The role of this filter is to suppress isolated noise and irregular heart beats. Resulting median intervals for each window τ_{med_j} are averaged to compute the heart rate:

$$AHR_i = \frac{6 \cdot 10^4}{\sum_{j=0}^{i} \tau_{med_j}} \qquad (5)$$

IV. Results

A total of 15 subjects participated in testing our heart rate monitor application. We selected a diverse group of people, including: 2 children (8–10 years), 1 teenager (15 years), 5 young adults (21–35 years), 5 mature adults (38–55 years) and 2 seniors (68–73 years). The computer used in our testing is a MacBook Air laptop (1.8 GHz Intel Core i5 processor, 4 GB DDR3 RAM) running OS X 10.8. For our tests we used two video cameras interchangeably: a Logitech HD Webcam C525 (standalone) running at 960x540 and the MacBook Air integrated video camera (FaceTime HD) running at 1280x720 resolution. Both cameras were set to a capture rate of 10 frames per second. We compared our results against measurements taken using a commonly available wrist blood pressure monitor, Healthy Line SHL-168DA.

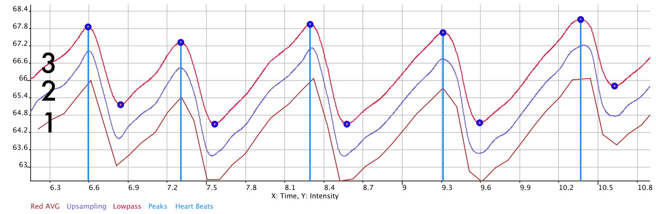

Fig. 2. Waveform output of stages 3–6

All tests were done in a sitting position with the hands relaxed on a table. Readings were taken from the thumbs and index fingers, from both the left and the right hands. The trials were performed during the day in a well lit room. Artificial lightning was not needed.

Table I shows how measurements taken with our application compare against readings from the wrist device. Our subjects completed four successive trials of 30 seconds each (columns 3–14). In each trial readings were taken simultaneously from the application and from the Healthy Line monitor. A trial corresponds to 3 adjacent columns in the table: A_i, B_i, d_i. The A_i columns show the result obtained using the heart rate monitor application. The B_i columns show the measurement taken with the wrist device. d_i represents the absolute error. Column 15 (ERR) shows the average error of a trial, measured in beats per minute (bpm).

The tests uphold an average error of only 2.47 bpm with a small standard deviation (1.44 bpm). There does not seem to be any correlation between the measurement error and the age or sex of the subjects (we cannot draw any definitive conclusion based on the test data). It is important to note that the error is computed against the readings from a wrist blood pressure monitor, which itself is rated at 2 bpm accuracy.

Even though it may not be suited for clinical use, our method does compete with currently available personal health and fitness devices like: low-end pulse-oximeters, HR monitor watches, chest straps and wrist blood pressure monitors.

V. Towards stress diagnosis and treatment

The heart rate monitor application presented in this paper is the first step towards a framework for stress diagnosis and treatment. Although stress is a common problem of our daily life and it affects an increasing number of people, very few solutions have been developed in this area.

Mental stress is closely related to the state of the autonomic nervous system (ANS). The ANS acts as a control system for many unconscious visceral functions, including the regulation of the heart rate. The function of the ANS is well reflected

TABLE I. MEASUREMENTS TAKEN WITH THE APPLICATION

S	Age	Trials (bpm)												ERR
		A1	B1	d1	A2	B2	d2	A3	B3	d3	A4	B4	d4	
1	8	78	79	1	76	78	2	75	79	4	76	80	4	2.75
2	10	76	74	2	76	72	4	74	74	0	72	73	1	1.75
3	15	69	72	3	69	71	2	73	70	3	73	74	1	2.25
4	21	67	69	2	66	70	4	68	72	4	71	73	2	3
5	24	67	72	5	70	73	3	69	71	2	70	73	3	3.25
6	25	65	68	3	66	69	3	67	68	1	61	67	6	3.25
7	28	73	69	4	76	70	6	72	70	2	73	72	1	3.25
8	35	60	62	2	59	61	2	60	62	2	60	62	2	2
9	38	75	70	5	72	73	1	72	71	1	71	74	3	2.5
10	42	62	59	3	59	61	2	60	61	1	61	62	1	1.75
11	45	70	68	2	65	68	3	64	67	3	67	69	2	2.5
12	50	71	71	0	72	70	2	73	71	2	70	72	2	1.5
13	51	73	76	3	73	78	5	74	80	6	78	79	1	3.75
14	68	63	60	3	61	59	2	62	60	2	61	61	0	1.75
15	73	60	59	1	60	57	3	59	57	2	61	60	1	1.75
													Average Error:	**2.47**
													Standard Deviation:	**1.44**

in the heart rate variability (HRV), defined as the variation of beat-to-beat intervals over a longer period of time. Consequently, HRV is a good indicator of the stress level of a patient [2].

With minor changes to the sixth stage of the processing pipeline (Section III) the presented method for measuring the heart rate can be extended to include the long-term analysis of HRV [10]. Certain indicators can be extracted to determine whether a patient needs stress therapy.

For the treatment of stress we propose music therapy. The soothing power of music has a proven effect in slowing the heart rate, reducing the blood pressure, and decreasing the levels of stress hormones. Music therapy is a known field in medicine and has been used with success for many years [11].

Computer-generated music has the advantage that it can be tuned according to the preferences of the subject. We developed a tool for generating computer music according to classical harmonic rules. Many parameters can be customized to create a powerful effect on the emotion centers of the brain [3], [4].

We believe that our computer music generation tool can be used in the effective treatment of stress. Further work is needed, but we consider that such an application holds great promise in self care.

VI. CONCLUSIONS

We showed that the original method presented in this paper produces accurate results even with low-end video cameras, like the ones integrated in personal computers and mobile devices. We reliably extract beat-to-beat intervals by passing the color intensity average through a six-stage pipeline. The filters used in the pipeline are computationally lightweight, making our method suitable for devices with low resources.

Experimental results indicate that the method can be trusted to produce reliable measurements within an average error below 3 bpm. Users can conveniently run the application when they are relaxed at home, in the park, or during the daily routine. With our tool individuals can track their heart activity on a regular basis. They can detect emerging heart diseases before symptoms arise and know when to seek medical attention.

In section V we discussed a possible application of our method in the area of stress diagnosis and treatment. For diagnosis we propose the analysis of heart rate variability over a longer period of time. For treatment we recommend music therapy using computer-generated music.

Further work includes the development of the proposed extension and the porting of the application to smartphones and tablets. We think that this kind of software will become increasingly popular among the young and elderly alike and will have an important role in monitoring personal health at home.

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