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Photoplethysmographic Heart Rate and Blood Pressure Estimation in Dynamic Condition

D. Zazula[1], C. Pirs[1], K. Benkic[2], D. Đonlagic[2], B. Cigale[1]
[1]*System Software Laboratory, Faculty of Electrical Engineering and Computer Science, University of Maribor*
[2]*Electro-Optics and Sensor Systems Laboratory, Faculty of Electrical Engineering and Computer Science, University of Maribor*
Smetanova 17, 2000 Maribor, Slovenia

ABSTRACT

This paper describes a novel, unobtrusive photoplethysmographic device and experiments conducted in a dynamic condition. The device complements a photoplethysmograph with a dynamometer, an accelerometer, and a thermometer. We built it in the door handle of a refrigerator and made tests during the door opening and closing. Short-term PPG signals were obtained across all fingers pulling the handle. In parallel, we measured the standard ECG lead II as a reference for the detected heartbeat verification. The blood pressure of each participant was registered before each experimental trial by a standard sphygmomanometer. Based on the PPG signals, we ran our computer algorithms for detecting the heartbeats and estimating the mean blood pressure. Satisfactory results were achieved for heartbeats, with 97.62% sensitivity and 90.31% precision. However, blood pressure estimation appeared to be not very efficient – neither linear nor exponential modeling could lower the estimated mean absolute error in comparison to referential mean blood pressures below 6 mmHg.

Key words: photoplethysmography in dynamic condition, unobtrusive sensors, heartbeat detection, blood pressure estimation.

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I. INTRODUCTION

Deterioration of public health in today's societies is due to increasing number of elderly and people with disabilities, expansion of chronic diseases, and in particular limited healthcare budgets. Current trends in Slovenia predict that 35% of gross domestic product will be spent on health and social care by 2025. However, in spite of the fact that it has long been known how home and continuous care can facilitate and prolong the independent living and that high-tech solutions became available, remote monitoring of health parameters in individual homes couldn't been carried into effect. The major reason for that lies in the parameter observations that are obtrusive; patients themselves must take care of measurements, device operation, data collection and forwarding, etc. It is now clear that home services must go automated and unobtrusive to be widely accepted.

These facts were recognized by the Biomedical Engineering Competence Center and addressed in a research-and-development project entitled *Connected Home Devices in Support of Independent and Healthy Living*. Unobtrusiveness in measuring the effects of human vital signs in the daily living environment is the project's major concern. A variety of high-tech sensors, such as accelerometers [1], fiber-optic interferometers [2], capacitive electrodes, optical and thermal cameras [3], etc., have been investigated. Within hardware prototypes we also derived a few up-to-date and efficient data-processing algorithms.

We dealt with photoplethysmography (PPG), which has long been known a convenient means for blood oximetry [4] and assessment of the cardiovascular system in general. Two light sources of red and infrared wavelengths illuminate a thin body part, usually a finger, and an optical sensor recollects the transmitted or reflected light. The signals are, afterwards, analyzed for the instances of heartbeats. Our attention was paid to robust detection methods that guarantee a stable consequent pulse oximetry. We have derived an efficient heartbeat detection method based on PPG and tested it in the presence of external forces pushing on the fingers under observation [5]. The applied forces increased and decreased in predefined steps, and at every step duration was long enough to achieve a stable condition for the PPG acquisition. Thus, we were able to detect heartbeats and to assess blood oxygen saturation rather reliably.

Nevertheless, a real living situation rarely anticipates stable conditions, in particular when unobtrusive sensing is a priority. Unobtrusive PPG measurements are incorporated in the sensory unit that we constructed and patented to be built into door handles [6]. We used it in a research of PPG heartbeat detection under the dynamic condition that accompanies the act of door opening and closing. From the heartbeat features we tried to assess the mean blood pressure. This paper brings some new findings about short-term photoplethysmography in the dynamic condition of opening a refrigerator. Section II reveals the construction of the sensory device and signal analysis methods. Section III explains briefly the experimental protocol and results, while Section IV discusses the findings and concludes the paper.

II. UNOBTRUSIVE PHOTOPLETHYSMOGRAPHIC OBSERVATIONS

The unobtrusive photoplethysmograph we developed is a part of a sensory unit that comprises other complementary sensors and the electronic and microcontroller circuitry. When used in short-term measurements, only sophisticated signal processing algorithms can provide the necessary efficiency and reliability. We explain the sensory unit construction and the background of signal processing in the following section.

a) Construction of the sensory unit

Our custom-designed sensory and signal-acquisition unit comprises a PPG, strain gauges, thermistors, and accelerometers. The PPG sensor operates in a transmission mode, so that optoelectronic sensors are placed opposite to the light sources. The door handle construction encapsulates the sensors and electronic circuits in a plastic housing that is attached to an L-shaped handle. The light sources in the form of light-emitting diodes (LEDs) reside vis-à-vis the case with sensors, in the door frame.

Fig. 1. Optical plethysmographic sensor arrays are encapsulated in a plastic housing (left part) that also protects the controlling and computing electronic circuits (right part).

Fig. 1 shows the housing and optical plethysmographic sensors. Its dimensions are 150×25 mm. Optical sensors are visible on the left-hand side of the housing. Eight linear, analogue sensor arrays TSL1401CL (amc AG company) are arranged in a row. Each sensor of dimensions 9.4×3 mm incorporates 128 in-line photodiodes whose integration time is controllable. Our custom-made acquisition electronics samples all the photodiodes sequentially in the shortest possible time, which is 0.1 μs per a diode. For the time being, we process only every second channel, which amounts to 512 simultaneous PPG signals (samples in a vector) equally distributed across an 80-mm distance. Total acquisition time per PPG sample vector equals 51.2 μs. This offers long enough integration times specified at about 34 μs, as we begin the next integration immediately after the acquisition of an optical sensor is completed.

The PPG application actually does not need that high sampling frequencies, but a fast acquisition is important to guarantee all 512 spatially-distributed PPG samples are acquired practically at the same time. The whole cycle of sampling a 512-sample PPG vector is repeated at 225 Hz, which is entirely in line with the requirements for PPG.

A miniature cap thermistor is inserted at the middle of the long side of each optical sensor to measure the fingers' skin temperature.

The construction of our sensory unit can provide information on contact forces applied to the door handle. We used two round-shaped, two-axial metallic folio strain gauges glued to an L-shaped door handle, as shown in Fig. 2. A complementary placement of the gauges at both sides of the handle allows for grasping the handle at different height and ensures correct force measurements. Each strain gauge with specified initial resistance of 120 Ω is configured in a Wheatstone bridge. Its balance voltage is amplified and sampled at a 80-Hz sampling rate and 12-bit resolution by a separate A/D converter. It is linked through an SPI bus with the master microcontroller that also samples the PPG and temperature signals.

Fig. 2. Strain gauges are glued to the door handle and measure contact forces at any handle manipulation.

Fig. 3 depicts in the left subfigure a montage of the handle with sensory device on a refrigerator's door. The sensors are placed vertically and a unit with LEDs and their drivers is inserted into the door frame. The construction seen in Fig. 3 was designed by the

Gorenje company from Velenje, Slovenia, a project partner within the Biomedical Engineering Competence Center. The LED drivers, their duty cycle, and the sequence of switching are controlled by the master microcontroller responsible for the entire sensor's operation. Four pairs of LEDs are soldered side-by-side, each pair comprising a red (650 nm) and an infrared (950 nm) LED. The two wavelengths are important for pulse oximetry. We didn't involve it in our research this time, but we used the pairs of signals in parallel to improve the detections of the events of our interest. Therefore, the LEDs were turned on at the PPG sampling frequency interchangeably; the red one was followed by the infrared one, while every third sampling acquired the ambient light (LEDs were turned off).

Fig. 3. The sensory unit is affixed vertically to the door handle that is attached to the refrigerator's door. Opposite to the optical sensors, a unit with LEDs and electronic drivers is inserted into the door frame (left subfigure). While opening the door, the fingers are forced to a position amidst the light sources and optical sensors that acquire the PPG signals (right subfigure).

The LED unit encompasses a three-axial accelerometer as well. Its digital output is linked to the master microcontroller through another SPI channel.

Infrared illumination, which is not visible, is active all the time at a greatly reduced sampling frequency. Whenever the optical sensors detecting the light are interrupted for a predefined time and number of PPG channels, a measuring event is initiated, which means that all the sensors begin data acquisition with full sampling rates. This happens if a person stretches out the fingers behind the door handle (Fig. 3, right subfigure).

b) Signal processing methods

In every experimental trial, approximately 15 s of 512-samples-long PPGs with accompanying referential ECG in parallel were recorded. Our first goal was to detect heartbeats in PPGs and compare the detection with the R-wave peaks obtained from the referential ECG recordings.

In one of our previous investigations, we derived a robust method for the detection of heartbeats based on the PPG signals [5]. This method was also deployed here as explained below.

Signal acquisition provides data vectors with 512 PPG samples taken at a sampling interval. To avoid high-frequency disturbances, we apply filtering by a low-pass filter. Out of 512 PPG signals, only those that do not saturate in any time are kept for further processing. Suppose N_j signals qualify and form the initial analysis set of filtered PPG signals, $s(n) = [s_1(n), \ldots, s_{N_j}(n)]$; $n = 0, \ldots, N\text{-}1$. The PPG values acquired in a transmission mode decrease fast to the PPG foot at every systole and increase slower to the PPG peak during diastolic intervals. Fast systolic changes can be detected by differentiating the signals:

$$\mathbf{d}(n) = \mathbf{s}(n) - \mathbf{s}(n+1); n = 0, \ldots, N-2 \tag{1}$$

Signals $\mathbf{d}(n)$ from Eq. (1) are then processed by continuous wavelet transform (CWT) using a fixed range of scales. The resulting coefficients at scale q are denoted by $\mathbf{c}_q(n)$; $q = 1, \ldots, M$:

$$\mathbf{c}_q(n) = \frac{1}{\sqrt{q}} \sum_{i=0}^{N-2} \mathbf{d}(n) \psi\left(\frac{i-n}{q}\right) \tag{2}$$

where ψ designates the chosen mother wavelet.

Wavelet coefficients maximize at different scales related to the heart rates observed. Optimum heartbeat detections, therefore, reside in the time marginals of coefficients from Eq. (2) averaged over selected scales:

$$p(n) = \frac{1}{N_j M} \sum_{j=1}^{N_j} \sum_{q=1}^{M} c_{j,q}(n) \tag{3}$$

Local minima in $p(n)$ represent heartbeats as detected in the PPG signal.

The PPG crest time, i.e. the time elapsed from the PPG peak to its foot, has been recognized in relation to the patient's mean blood pressure [7]. We derived those times from $p(n)$ as follows: after determining a minimum we searched for the first preceding and successive abrupt changes in the first derivative of $p(n)$ to locate the boundaries of the crest-time intervals (illustrated by w in Fig. 6). Crest times, t_w, are assumed inversely proportional to the mean blood pressure.

c) Statistical verification

Heartbeats found by the PPG analysis are delayed after the ECG R waves. The R waves in referential ECG recordings were determined by the Pan-Tompkins QRS detection algorithm [8]. All falsely detected or undetected R waves were corrected manually. Empirical findings confirm the PPG-based heartbeat delays after R peaks depend on the contact finger pressures [9]. In our experiments, we considered the heartbeats must appear between two consecutive R waves, i.e. within RR intervals. The heartbeat detections found within RR are supposed true positives (T_p). If the second heartbeat detection is found before the next RR begins, it is treated as a false positive (F_p). If no heartbeats are detected within an RR, this is recognized as a false negative (F_n).

The efficiency of the proposed detection algorithm was verified by the sensitivity (S) and precision (P):

$$S = \frac{T_p}{T_p + F_n} \qquad P = \frac{T_p}{T_p + F_p} \tag{4}$$

III. EXPERIMENTAL RESULTS

a) Experimental protocol

The main objective of our investigation was to experiment with an unobtrusive photo-plethysmograph in dynamic condition. We invented a special sensory unit that consists of a two-wavelength photoplethysmograph, dynamometer, thermal sensor, and accelerometer. A small and compact construction supports the unit's montage into the handles of household appliances or similar dwelling elements.

We built our sensory unit into the refrigerator's door handle in such a way that a person opening the appliance must grasp at the sensor and pull it by their fingers. Fingers touch the optical plethysmographic sensor array and the light of two different wavelengths illuminates the transparent parts of fingers. Every trial consisted of three phases. The participants gently grasped the door handle and waited at rest for about 5 seconds. This initial touching of the PPG sensor automatically turned the entire sensory unit on and the acquisition of all sensory signals began. Then he or she opened the refrigerator in most natural way and waited for another 5 seconds, the fingers clinging on the sensor all the time. The final phase of the experimental protocol required a slow door closing and waiting for the last 5-s interval with fingers holding the handle and the built-in sensors.

PPG signals were, afterwards, analyzed as described in the previous section. Our main intention was to find out whether the typical patterns caused in the PPG signals by the pulsating blood flow through the fingers' microcirculation are detectible in dynamic condition or not. When the heart pumps blood into the arteries, arterioles, capillaries, and further back through venoles and veins, a certain amount of static blood volume is superimposed by pulsative components. The finger transparency depends on the two blood volumes, the volume of other finger tissues, and the light-source characteristics. A typical photoplethysmographic construction involves two lights of different wavelengths to give sufficient information for a computation of blood oxygen saturation. Although this approach would have been feasible in our experiments, we didn't go for oximetry but decided to verify the accuracy of heartbeat detections based on the PPG pulsation. Thus, we needed a reference on the heart contractions, which electrocardiograms were used for. Participants were connected to a standard Schiller AT-1 cardiograph throughout the experiments and the lead II was recorded along with the PPG signals. Time alignment of all the signals was achieved on the microcontroller level in our acquisition device.

Referential data were also taken for blood pressure before every experimental trial. We needed them to verify the blood pressure estimates based on the PPG measurements. An automated, compact intensive-care-unit (Critikon Dinamap Pro 300) was applied for a sphygmomanometric measurement of systolic and diastolic blood pressure in every participant (Table 1). The mean pressure is averaged based on the systolic and twice the diastolic pressure values.

Table 1. Blood pressures of participant measured immediately before experiments

Person ID	Systolic/diastolic pressure [mmHg]	Computed mean blood pressure [mmHg]
1	105/69	81
2	118/70	86
3	125/77	93
4	126/66	86
5	134/73	93.3
6	142/77	98.7
7	148/85	106

b) Obtained results

Six young healthy volunteers aged 24 to 38, one of whom was female, and an older person over 60 participated in the experimental trials.

The acquired PPG signals were low-pass filtered at a 10-Hz cut-off frequency. Continuous wavelet transforms were computed with the Morlet mother wavelet at scales 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50.

The heartbeat instances were detected with the method described in the previous section. Sensitivity and precision were obtained versus the referential ECG R-peaks. Results are gathered in Table 2. They have also been reported in a paper submitted to the MBEC conference [11].

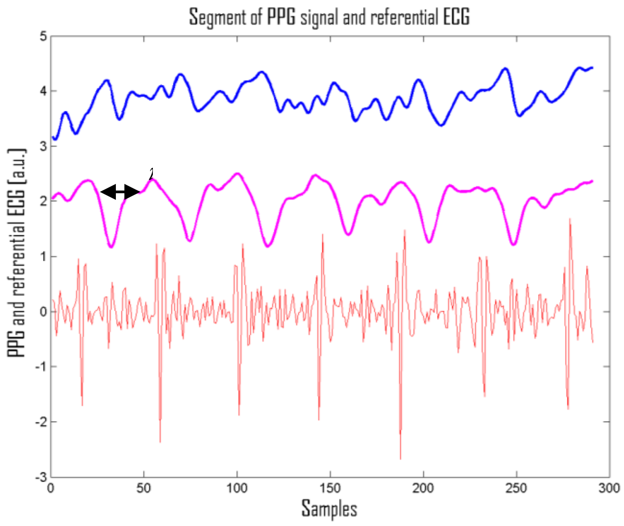

Fig. 4. Heartbeats are detected from PPG as shown: the PPG signal low-pass filtered at a 10-Hz cut-off frequency (upper blue plot) are processed by the wavelet transform and time marginals are computed (magenta plot in the middle); their minima define the heartbeat instances that are referenced by ECG (bottom red plot). Designation *w* on the marginals plot stands for the PGG peak-to-foot width (crest time).

Table 2. Sensitivity and precision for the heartbeat detections

Person ID	Sensitivity [%]	Precision [%]
1	97.56	95.24
2	97.37	100
3	96.29	86.66
4	100	80
5	97.06	97.06
6	100	74.07
7	96.66	90.62
Total	**97.62**	**90.31**

Taking into account crest times, t_w, in the time marginals of the PPG wavelet coefficients (illustrated by *w* in Fig. 6), we tried to model the mean blood pressures. Their inverse values are shown with red bars in Fig. 5. For easier visual comparison with mean pressures (blue bars), the values were scaled by a ratio of the means of mean blood pressures and inverses of crest times. We tried to model the estimated blood pressure by linear and exponential functions. In either cases, the best fit could not lower the mean absolute error in comparison to the referential mean blood pressures below 6 mmHg, on average. Visual comparison in Fig. 5 confirms that the estimates compute inconsistent and with standard deviations ranging from 10% to 20% of their means.

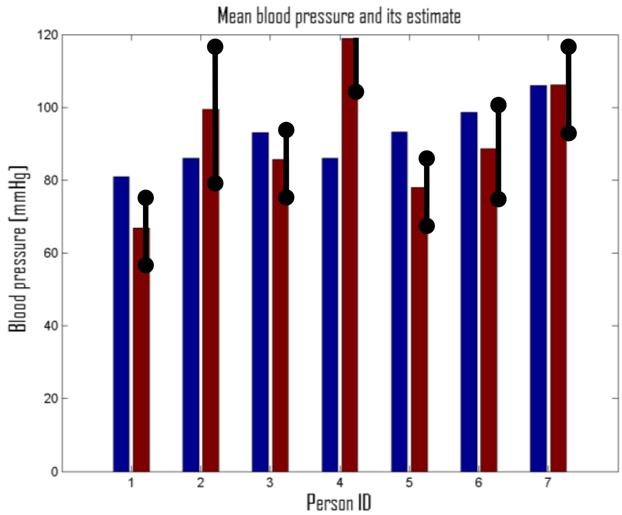

Fig. 5 Estimation of blood pressure based on the PPG crest times (designation *w* in Fig. 4): referential mean blood pressures (blue bars), estimated blood pressure (red bars). Vertical black bars with circles designate standard deviations.

IV. DISCUSSION AND CONCLUSIONS

The sensory unit embedded in the refrigerator's handle was extensively tested at the University Rehabilitation Institute Soča in Ljubljana, Slovenia (Fig. 6). The sensors there are connected via an application program interface with a computer server and a database. Whenever a hand crosses the light beams in the plethysmograph, a measuring event is triggered and all acquired signal data are transmitted and stored into the database.

Fluctuating contact force is devastating for the heartbeat detections in dynamic PPGs. If a finger, for example, is pressed, the blood flow and PPG intensity are modified by the external pressures [10]. The difference between PPG foots and peaks vary and can be entirely blurred. In spite of this fact, our multiresolutional detection proved rather robust, showing an overall sensitivity of 97.62% and precision of 90.31%. Precision decreased due to false positive detections during the refrigerator's door opening. We believe it could further be improved if the contact forces that we measured in parallel with the PPG signals were used to demodulate the PPGs accordingly.

Fig. 6. A refrigerator with sensors in the door handle is used for verification purposes at the University Rehabilitation Institute Soča.

The analysis of blood pressure alludes that crest times in PPG are not very efficient estimates. One of the possible reasons may be attributed to rather unstable wavelet coefficients due to the dynamic condition. This aggravates an exact finding of fiducial points defining the onset and termination of peak-to-foot descent as a feature in the PPG time marginals. Although we deployed the information from both the red and infrared PPG signals in parallel, robustness did not improve noticeably.

In conclusion, PPG-based heartbeat detection seemed reasonably efficient in spite of considerable dynamics during the refrigerator's door opening. On the other hand, the blood pressure estimates based on crest times didn't prove a reliable measure.

Further investigations are planned with more participants for a better statistical validation and wider range of different personal characteristics. Trials with various groups of healthy participants, people with special needs, and diseased persons, in particular cardiac and after-stroke patients, will continue at the University Rehabilitation Institute Soča.

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REFERENCES

1. Šprager S, Zazula D. A cumulant-based method for gait identification using accelerometer data with principal component analysis and support vector machine. WSEAS transactions on signal processing, 2009, 5(11): 369-378.
2. Podbreznik P, Đonlagić D, Lešnik D, Cigale B, Zazula D. Cost-efficient speckle interferometry with plastic optical fiber for unobtrusive monitoring of human vital signs. Journal of Biomedical Optics, 2013, 18(10):107001-1-107001-8.
3. Šavc M, Zazula D. Eye detection using 2D discrete wavelet transform and geometric moments. Proceedings of the 5th WSEAS International conference on sensors and signals (SENSIG'12), 2012, pp. 87-92.
4. Zislin BD, Chistyakov AV. The History of Oximetry. Biomedical Engineering, 2006, 40(1): 53-56.
5. Pirš C, Cigale B, Zazula D. A Feasibility Study of Heartbeat Detections from Photoplethysmograms With Fingers Compressed. Proc. of the 5th WSEAS International Conference on Sensors and Signals, Sliema, Malta, 2012, pp. 47-52.
6. Cigale B, Zazula D, Đonlagić D, Pirš C, Benkič K. Računalniška naprava in postopek za nemoteče merjenje parametrov funkcionalnega zdravja. SI 24037 (A), 2013-10-30, Ljubljana, Urad Republike Slovenije za intelektualno lastnino.
7. Elgendi M. On the Analysis of Fingertip Photoplethysmogram Signals. Current Cardiology Reviews, 2012, 8:14-25.
8. Pan J, Tompkins WJ. A real-time QRS detection algorithm. IEEE Trans. on Biomed. Eng., 1985, 3:230-236.
9. Teng X-F, Zhang T. Theoretical Study on the Effect of Sensor Contact Force on Pulse Transit Time. IEEE Trans. Biomed. Eng., 2007, 54(8): 1490-1498.
10. Rhee S. Design and Analysis of Artifact-Resistive Finger Photoplethysmographic Sensors for Vital Sign Monitoring. PhD Thesis, Massachusetts Institute of Technology, Boston, 2000.
11. Zazula D, Pirš C, Benkič K, Đonlagić D, Cigale B. Short-Term Photoplethysmography Embedded in Household Appliances. Submitted to the MBEC 2014 conference, Dubrovnik, Croatia.