ACQUISITION AND PROCESSING OF PHOTOPLETHYSMOGRAPHIC SIGNAL FOR REGISTRATION OF HEART RATE OF MOVING PERSON

Darius Jegelevicius[1,2], Vaidotas Marozas[1,2], Arunas Lukoševičius[1,2], Linas Svilainis[2]

[1]Biomedical engineering institute, Kaunas University of Technology, Kaunas, Lithuania
[2]Signal processing department, Kaunas University of Technology
Studentu str. 65-111, LT-51369, Kaunas, Lithuania
T. +370 37 407119; F. +370 37 407119; E. darius.jegelevicius@ktu.lt

Abstract

Investigation of photoplethysmo-graphic sensors application for subjects' heart rate monitoring for in-situ conditions is presented. Inertial acceleration sensor mounted together with PPG sensor was used for estimation of motion intensity. The sensor signal was acquired by placing it on the subject's: forehead, breastbone and wrist in the rest and active moving conditions. ECG sensor was used as a reference source. The most accurate results were obtained from the forehead. Analysis showed that time - frequency representation of PPG signal is the superposition of two time - frequency representations: noise free heart rate signal and motion intensity signal. This observation suggests possibility to remove motion induced noise from the PPG signal.

1. INTRODUCTION

Photoplethysmographic (PPG) sensors [1] are widely used in monitoring of blood oxygenation and heart rate (HR) of the subjects in clinical bed rest conditions [2, 3]. PPG sensors are attractive due to compactness, noninvasiveness and functionality. Application of PPG sensors would be very attractive in telemedicine applications [4].

When patient motion intensity is relatively low, there is a good correlation between ECG and PPG signals in heart rate measurement (Figure 1). Then PPG sensor has an advantage against the multielectrode based ECG sensor. However subject movement introduces a large noise component into PPG signal.

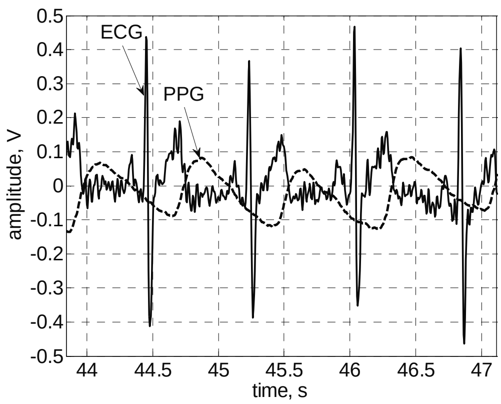


Figure 1. EKG and PPG signals while subject in rest

The subject movement induces displacements of the sensor-to-tissue and tissue-to-bone conditions which in turn cause PPG signal distortion (Figures 2, 3).

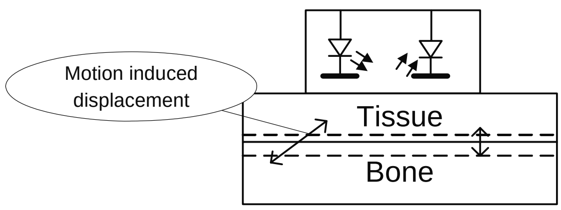


Figure 2. PPG signal registration

Subject motion influence on PPG signal is shown in Figure 3.

Figure 3 shows that subject motion causes significant PPG signal distortion which subsequently leads to heart rate estimation errors.

Thus the ability to extract accurate physiological data from PPG sensor during subject activity remains a significant challenge [5]. Several attempts have been taken to search for the best PPG sensor placement on the body: it has been suggested to use a finger-wearable sensor in [6]; yet another study [7] investigated possibility to place the sensor on a wrist. Our research was undertaken in order to systematically investigate the aspects of PPG based estimation of heart rate in three different sensor positions on human body under different motion intensity.

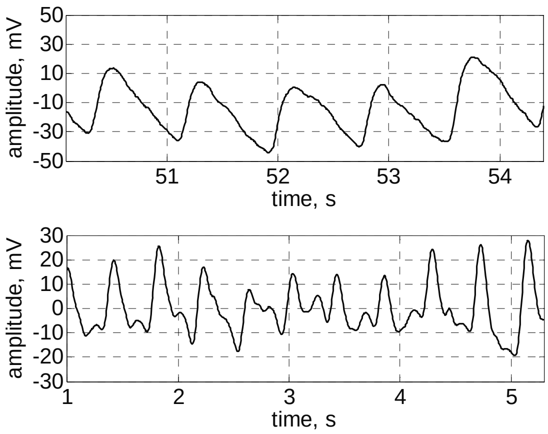


Figure 3. Subject motion influence on PPG signal. Top: PPG signal in rest; bottom: PPG signal in motion

2. ACQUISITION SETUP

An experimental infrared light sensor based on reflection was used for PPG signal registration (Figure 5).

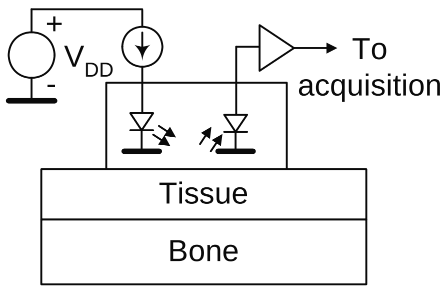


Figure 5. PPG sensor

Two TSMS3700 infrared LEDs with the excitation current 30 mA have been used to generate the luminous flux. The BPW34 photodiode was used for the reception. Signal was conditioned using operational amplifier AD8047. Motion intensity was estimated using two axes accelerometer ADXL202 with 1kHz cut-off frequency filter mounted together with PPG sensor (Figure 6).

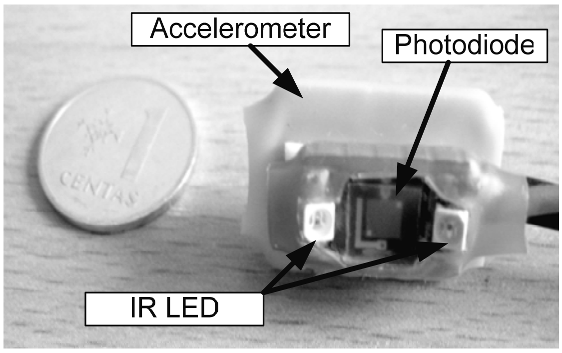


Figure 6. PPG and acceleration sensors fusion

The PPG signal was acquired (Figure 7) by placing the sensor on the subject's: a) forehead, b) breastbone, c) wrist in the rest and active moving (walking, running, jumping and elliptical cross trainer) conditions. As the reference source of heart rate the ECG chest strap (Polar Oy) was used.

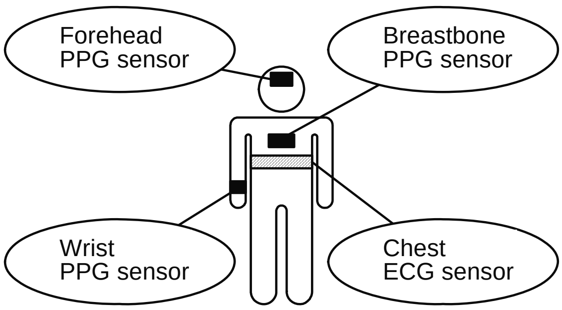


Figure 7. Sensor placement

PPG, acceleration and ECG signals were digitized (Figure 8) by using the biosignals' acquisition system MP35 from Biopack Inc. It has four isolated, human-safe, universal biopotential or transducer input amplifiers with 24bit AD converters. The sampling rate was chosen to be 1kHz. High sampling rate prevents from missing short pulses coming from heart rate monitoring strap. Raw signals were passed via USB interface to personal computer and stored for offline processing. Signal processing algorithms were developed in MATLAB.

For heart rate calculations from PPG signal, low frequency filtering, signal derivation and searching for peaks was used. Calculated HR then was filtered with moving average filter with a cut of frequency of 0.11 Hz.

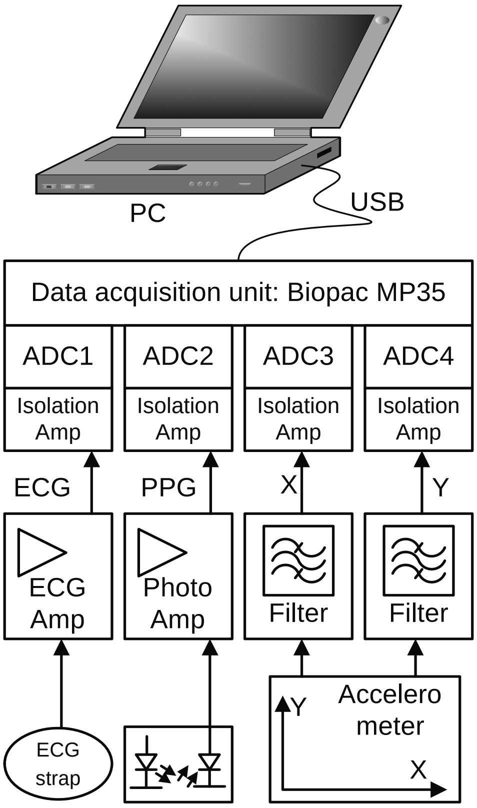


Figure 8. Acquisition system

Three performance indexes were used for the evaluation of heart rate estimated from PPG signals under different registration conditions:

a) correlation coefficient:

$$\rho = \frac{\sum_{n=1}^{N}\left[r_{\overline{PPG}}[n]\cdot r_{\overline{ECG}}[n]\right]}{\sqrt{\sum_{n=1}^{N}\left(r_{\overline{PPG}}[n]\right)^2\cdot\sum_{n=1}^{N}\left(r_{\overline{ECG}}[n]\right)^2}} \quad (2),$$

where $r_{\overline{PPG}}[n] = r_{PPG}[n] - \bar{r}_{PPG}$ and $r_{\overline{ECG}}[n] = r_{ECG}[n] - \bar{r}_{ECG}$;

b) mean of the difference $\Delta r[n] = r_{PPG}[n] - r_{ECG}[n]$:

$$\overline{\Delta r} = \frac{1}{N}\cdot\sum_{n=1}^{N}\Delta r \quad (3);$$

c) standard deviation of the Δr:

$$\sigma = \sqrt{\frac{1}{N}\cdot\sum_{n=1}^{N}\left[\Delta r[n] - \overline{\Delta r}\right]^2} \quad (4).$$

3. RESULTS

Figure 9 shows an example of the set of raw signals registered during cyclical motion.

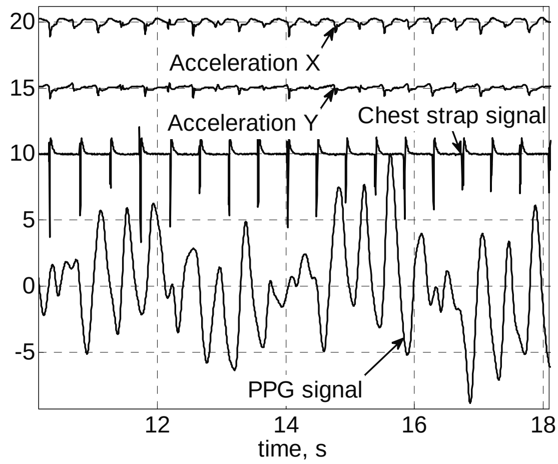


Figure 9. Registered signals

It can be observed that even at a moderate motion intensity PPG signal significantly differs from normal signal shown in Figure 1 and the heart rate is hardly discernable.

Figure 10 is presenting the correlation coefficient between the heart rate obtained from ECG and PPG sensors acquired in different physiological activity conditions. The placement of the sensor (positions are indicated in Figure 7) was varied and is indicated by three different curves.

It can be seen that forehead placement is exhibiting the best results even for complicated conditions. It can be explained that human anatomy is designed in such way that vision system that is placed in the head receives the least motion. The wrist sensor, though is most technologically desirable can be characterized as the worst performer.

The HR estimation accuracy based on ECG as a reference is presented as box-and-whisker plot in Figures 11-13. The box encloses 50% of the data (the interquartile range, IQR), a line in the box represents the median. Whiskers are 1.5 IQR. Dots represent the values out of this range.

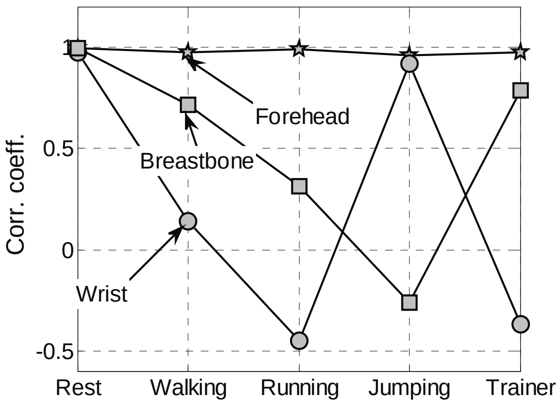


Figure 10. Correlation coefficients between ECG and PPG based heart rate estimation for different sensor positions and motion intensity

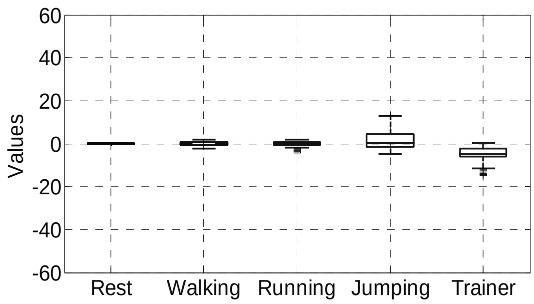


Figure 11. HR on forehead estimation

Figure 12. HR estimate on breastbone

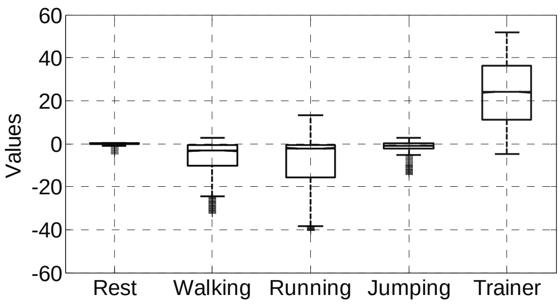


Figure 13. HR estimate on the wrist

The range of y axes in Figure 11 to Figure 13 was chosen the same in order to allow the results comparison.

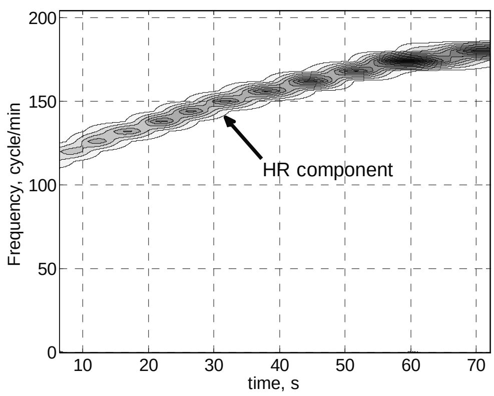
Whisked diagrams again confirm that PPG sensor placement on forehead is the best position among all investigated.

The Table 1 presents numerical results of sensor performance for forehead position. Even strong motion, e.g. jumping, does not increase the heart rate estimation error beyond limits as it was the case in other body places.

Table 1. Heart rate estimation performance using PPG signal when sensor was placed on the forehead

Movement condition	Corr. coeff.	Mean	Std
Rest	0.9964	-0.0069	0.1621
Walking	0.9723	-0.0904	0.8928
Running	0.9899	-0.2686	1.3289
Jumping	0.9562	1.5969	4.5568
Elliptical cross trainer	0.9735	-4.7784	3.4786

Investigation has been done in order to evaluate the ability to separate the errors sources. Signals from the wrist sensor were taken for the running subject case. Since it was assumed that there is no significant influence of motion axis on the clutter as explained in Figure 2, the accelerometer x and y axes were combined taking their geometrical mean vector for calculation. Short Fourier transform was used on the acquired signals in order to evaluate the spectral content variation in time. Frequency scale was recalculated into cycles/min in order to relate it to HR measurement units (beat/min).



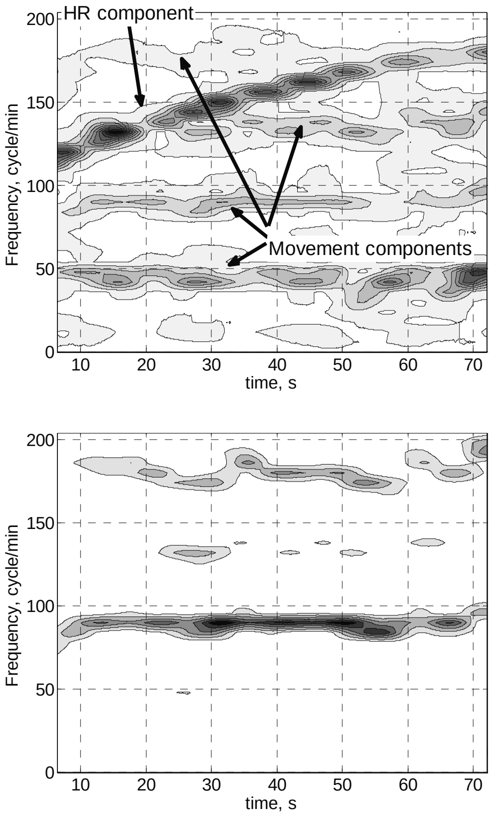


Figure 14. Temporal behavior of signals spectrum for running subject. Top: ECG, center: PPG, bottom: acc

It can be seen that there is a great correlation in spectral content between the acceleration and the PPG sensor signal. Though it can be concluded that heart rate is changing smoothly, there is an intersection of the HR and motion induced frequencies. This is clearly seen on 30'th and 60'th second of the experiment.

4. CONCLUSIONS

Analysis showed that spectrum of motion activity signal overlaps with the PPG signal. Heart rate computed from moving subject's PPG signal has significant high frequency component if we compare it with heart rate obtained using ECG chest strap. The most accurate results were obtained from the forehead PPG signal: lowest systematic error and the standard deviation of the random error were obtained. Though results for forehead placement are encouraging, it is worth trying to apply tracking phase filters or adaptive signal processing methods for wrist placement implementation of the sensor. There good candidates would be methods used in [8, 9].

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References

[1] M.J. Hayes, et al., "Quantitative Investigation of Artifact in Photo-plethysmography and Pulse-Oximetry for Respiratory Exercise Testing", *Proc. of the CNVD 97 Frontiers in Computer-Aided Visualization of Vascular Functions*, 1998, pp. 117-24.

[2] A. Sola, L. Chow, M. Rogido, "Pulse Oximetry in Neonatal Care. A Comprehensive State of the Art Review", *Anales of Pediatria*, Vol.62(3), 2005, pp. 266-80.

[3] H.M. Sami, B.S. Kleinman and V.A. Lonchyna, "Central venous pulsations associated with a falsely low oxygen saturation measured by pulse oximetry", *J Clin Monit*, Vol.7, 1991, pp. 309–312.

[4] A. Paunksnis, V. Barzdziukas, D. Jegelevicius, et al. "The use of information technologies for diagnosis in ophthalmology", *Journal of telemedicine and telecare*, Vol. 12, Suppl. 1, 2006, pp: 37-40.

[5] Y. Yamaya, H.J. Bogaard, P.D. Wagner, K. Niizeki, S.R. Hopkins, "Validity of pulse oximetry during maximal exercise in normoxia, hypoxia, and hyperoxia", *Journal of Applied Physiology*, Vol. 92, 2002, pp.162–168.

[6] H. Asada, P. Shaltis, A. Reisner, S. Rhee, R. Hutchinson, "Mobile Monitoring with Wearable Photoplethysmographic Biosensors", *IEEE Engineering in Medicine and Biology Magazine*, Vol. 22 (3), 2003, pp.28-40.

[7] Ph. Renevey, R. Vetter, P. Celka, J. Krauss, "Activity Classification Using HMM For Improvement Of Wrist Located Pulse Detection", *BioSignal 2002*, Brno, Czech Republic, June 26 - 28, 2002, pp. 192-196.

[8] R. Kazys, L. Svilainis, "Analysis of adaptive imaging algorithms for ultrasonic non-destructive testing", *Ultrasonics*, Vol 33(1), 1995, pp. 19-30.

[9] V. Marozas, A. Janusauskas, A. Lukosevicius, et al. "Multiscale detection of transient evoked otoacoustic emissions", *IEEE transactions on biomedical engineering*, Vol: 53(8), 2006, pp. 1586-1593.