TEHNOLOGIJE/TECHNOLOGIES

Unobtrusive heartbeat monitoring by using a bed fiber-optic sensor

Nemoteče spremljanje delovanja srca z optičnim senzorjem v postelji

Peter Podbreznik,[1] Denis Đonlagić,[2] Dejan Lešnik,[3] Boris Cigale,[2] Damjan Zazula[2]

[1] *Univerza v Mariboru, Fakulteta za gradbeništvo*

[2] *Univerza v mariboru, Fakulteta za elektrotehniko računalništvo in informatiko*

[3] *Piktronik d.o.o.*

Korespondenca/ Correspondence:
Peter Podbreznik, e: peter.podbreznik@um.si

Ključne besede:
plastično optično vlakno; pegasta interferometrija; nemoteče merjenje vitalnih znakov; zaznavanje srčnih utripov; balistokardiografija

Key words:
plastic optical fiber; speckle interferometry; unobtrusive monitoring of human vital signs; heartbeat detection; ballistocardiography

Citirajte kot/Cite as:
Zdrav Vestn 2014; 83: 901–7

Izvleček

Izhodišča: Demografski trendi kažejo, da bo do leta 2050 približno 11 % svetovnega prebivalstva starejših od 80 let. Če dodamo še hitro naraščajoči obseg kroničnih bolezni, postane jasno, da sedanje zdravstvene zmogljivosti obremenitev ne bodo zdržale. Starejšim in ljudem z omejenimi sposobnostmi bo treba pomagati, da bodo čim dlje ostali samostojni v svojem domačem okolju, in tako omejiti hospitalizacije ter nujnost oskrbe v zdravstvenih zavodih. Današnje računalniške in komunikacijske tehnologije ponujajo pametne naprave, ki bodo kmalu omogočile bistveno intenziviranje zdravstvenih storitev na domu, predvsem kot nemoteče nadziranje parametrov funkcionalnega zdravja na daljavo.

Metode: Metode za telemetrično spremljanje zdravstvenega stanja so že dolgo znane, vendar pa njihovo vsesplošno uporabnost ovirajo zahteve po ročnih posegih pri nameščanju merilnih naprav, njihovem upravljanju in posredovanju podatkov. Na fakulteti za elektrotehniko, računalništvo in informatiko v Mariboru smo zato razvili merilnik, ki popolnoma nemoteče zaznava učinke delovanja srca, kot sta balistokardiogram in fonokardiogram.

Merilnik sestavlja kombinacija nizkocenovnih elektronskih in optičnih komponent. Na vgrajenem mikroračunalniku tečejo izpopolnjeni algoritmi za obdelavo optičnih signalov. Jedro senzorja je plastično optično vlakno, skozi katerega pošilja laserska dioda snop koherentne svetlobe. Vsak mehanski ali akustični vpliv na vlakno povzroči, da svetloba ob izstopu iz vlakna tvori interferenčni pegasti vzorec. Spreminjanje vzorca posnamemo kot zaporedje slik. Z računalniškim programom zaznavamo spremembe v pegastih vzorcih in vzporedno gradimo signal, katerega dinamika je v sorazmerju z zunanjimi silami, ki pritiskajo na optično vlakno. Ko signal nazadnje spustimo skozi pasovno prepustni filter v frekvenčnem območju, ki ustreza frekvenci bitja srca, lahko natančno določimo trenutek srčnih utripov, pulz in morebitne aritmije.

Rezultati: Razviti optični merilnik smo v laboratorijskih razmerah preizkusili na petih mladih, zdravih osebah. V času meritev so ležali na vzmetnici z vgrajenim optičnim vlaknom. Statistična analiza rezultatov je pokazala, da sta senzor in detekcijska metoda učinkovita, saj smo pri zaznavi srčnih utripov dosegli občutljivost 98,4 ± 1,1 % in natančnost 98,2 ± 2 %.

Zaključki: Merilnik za nemoteče spremljanje delovanja srca temelji na principu pegaste interferometrije. Senzor je tako občutljiv, da odlično sprejema vibracije in zvoke, ki so posledice bitja srca, tudi posredno, recimo skozi vzmetnico. Nadaljnje raziskave usmerjamo v povečanje robustnosti senzorja in metod za obdelavo ter analizo signalov, kar bo omogočalo, da bo deloval zanesljivo v dejanskem bivalnem ali kliničnem okolju.

Prispelo: 20. dec. 2013,
Sprejeto: 27. maj 2014

Abstract

Background: Demographic trends suggest that by 2050 approximately 11 % of the world population will be 80 or older. If a fast increase of chronic diseases is also considered, it becomes clear the present healthcare capacities won't be enough. The elderly and people with limited abilities must be assisted in their home environment and, thus, reduce needs for hospitalization and institutionalization. Today's computer and communication technologies provide different smart devices, which is a core of emerging intensification of homecare services, in particular remote and unobtrusive monitoring of human functional-health parameters.

Methods: Telemetric methods for human health monitoring have been available for a long time, but their wide implementation is hindered by the necessary manual interventions when preparing and controlling a measuring session and transmitting the data. These facts encouraged a research at the Faculty of Electrical Engineering and Computer Science in Maribor aiming at an entirely automated and unobtrusive device for monitoring the cardiac activity, such as ballistocardiogram and phonocardiogram.

The monitoring device comprises a combination of low-cost electronic and optical components. An embedded computer runs advanced algorithms for processing the optical signals. The sensor's core consists of a plastic optical fiber which is illuminated by coherent light of a laser diode. Any external mechanical or acoustic influence on the optical fiber results in an interference spackle pattern at the fiber's exit face. Speckle-pattern changes are saved as a sequence of images. A computer program detects the changes and transforms them into a signal whose dynamics is proportional to external forces pressing against the optical fiber. Finally, this signal is filtered in the frequency band that corresponds to the range of heart rate in order to detect individual heartbeats, heart rate, and possible arrhythmias.

Results: Developed heartbeat monitor has been tested in laboratory conditions by five young, healthy subjects lying supine on a mattress with embedded optical fiber. Statistical analysis confirmed the proposed device and heartbeat detection algorithms are highly efficient with sensitivity of 98.4 ± 1.1 % and precision of 98,2 ± 2 %.

Conclusions: Proposed approach for unobtrusive heartbeat detection is based on optical speckle interferometry. The sensor used is extremely efficient in reacting to tiniest vibrations and sounds caused by the heart, even indirectly through a mattress. Our future research focuses on improving the sensor's and detection method's robustness in order to achieve reliable validation in aggravated dwelling and clinical environments.

I. Introduction

Major demographic changes are predicted in future decades, especially in the segment of the oldest.[1] Aging, accompanied also by chronic diseases, frequently urges for the hospitalization, which increases healthcare costs steadily. Several novel technical solutions, such as smart-home devices, can assist the elderly and people with limited abilities in their home environment. Smart homes help persons to greater independence and good health.[2] Monitoring of daily living activities can detect changes in residents' daily routines, which may suggest increased medical attention. Home healthcare systems, however, need to avoid the necessity of any human interaction when the functional health parameters are acquired and transferred to a healthcare unit. Inexpensive low-power sensors, embedded processors, and wireless communications are available today for building unobtrusive home healthcare facilities.[3] Advanced sensors motivated new signal processing developments and efficient methods have been derived for unobtrusive human vital signs detection, mostly heartbeat and respiration.[4]

The sensors' properties define the most adequate physiological features to be observed in unobtrusive home care. Respiration can be assessed by extracting the acceleration or motion of person's chest.[5] Heartbeat perception can be based on mechanical activity of cardiac muscle, the so called ballistocardiography[6] or mechanocardiography,[7] or on heart sounds, the so called phonocardiography.[8] All these features have been

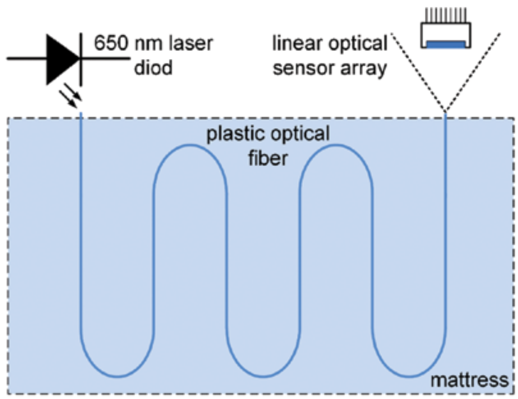


Fig 1: Principle schema of fiber-optic speckle interferometer.

measured by the Michelson fiber-optic interferometer in.[9-12] Its construction is rather complex and less appropriate for wider usage in home healthcare systems. A simpler solution with comparable sensitivity based on speckle interferometry is reported in this paper.

Digital speckle pattern interferometry has been widely applied in different areas. In general, speckle patterns can be observed either in laser light reflected from the surface of examined objects or at the output of coherently illumined multimode optical fibers. The latter are generated by the interference among propagating fiber modes and are highly sensitive to the external fiber perturbations, such as strain or axial load. When the optical fiber is in direct or indirect contact with human body, speckle images reflect mechanical and acoustic influence of human activity. Such a sensor can be unobtrusively embedded into various home devices and objects that get in physical contact with the observed person during daily living situations. The most common are beds, chairs, doors, handles of household appliances, floor carpets, slippers and shoes, etc. This paper describes preliminary tests of a fiber-optic system based on speckle interferometry for unobtrusive monitoring of heartbeat. A device prototype was revealed in [13].

In our study we were mainly focused on heartbeat detection and measuring heart rate (based on beat-to-beat intervals), whilst the existing experimental environment also enables measuring heart rate variability. We also noticed that measurements of heart sounds would be feasible after slight modifications of the sensor's construction and detection algorithm.

The paper is organized as follows. In Section II, fiber-optic speckle interferometer is presented along with the methodology for data analyses, while the experimental set-up and protocol are explained in Section III. Discussion and conclusions are given in Section IV.

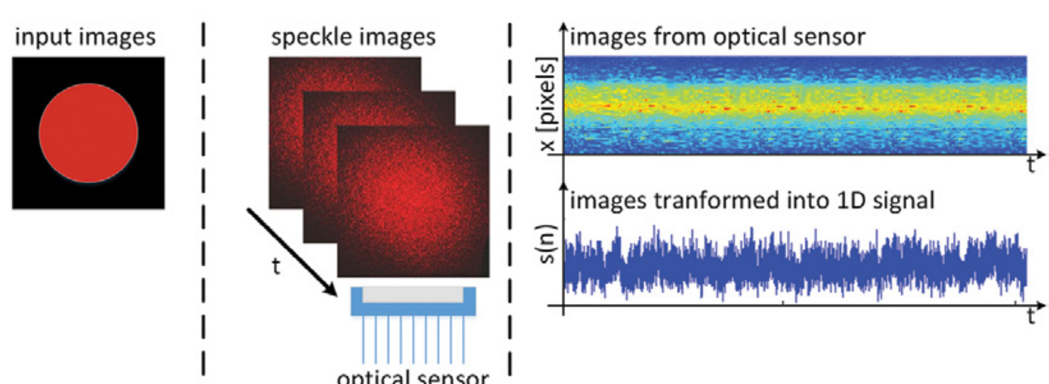


Fig. 2: Basic principle of speckle interferometry: input laser light (left panel), speckle images at the optical fiber output (middle panel), and time-sequence of images as grabbed by a linear optical sensor (right upper panel) and algorithmically transformed into a discrete-time signal (right lower panel).

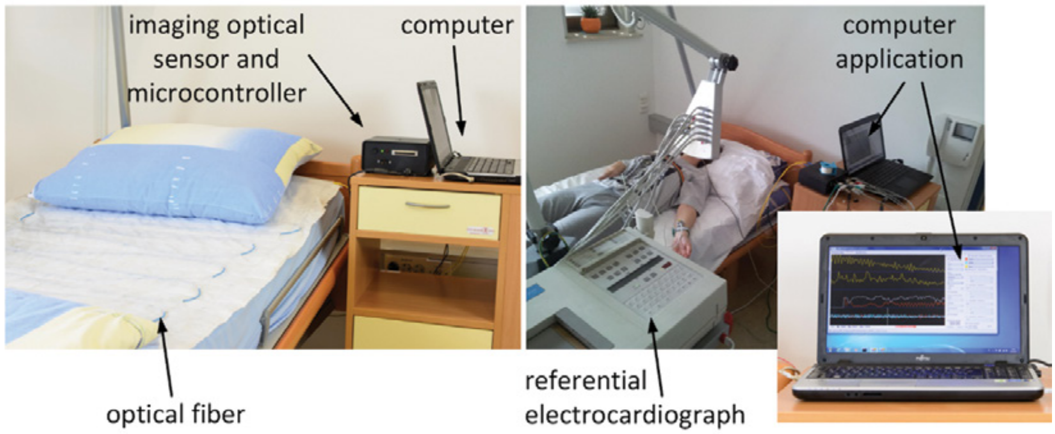


Fig 3: Experimental setup includes the following components: optical fiber, imaging sensor, a microcontroller and a computer (left picture). Experimental results were verified by a comparison of fiber-optic signals and referential electrocardiograms (right picture).

II. Fiber-optic speckle interferometer and heartbeat detection

Speckle interferometer

Today's consumer-electronics market offers opto-electronics components needed to build a fiber-optic speckle interferometer. A 650 nm laser from digital-video-disc (DVD) systems emits laser light through a section of standard plastic optical fiber (POF) with 980/1000 µm core/cladding and numerical aperture of 0.5, whose exit face points at the sampling device with 102-element liner optical sensor array. Fig. 1 schematically depicts the speckle interferometer design. When it is in a direct or indirect contact with a human body, its output carries the information on vital signs, e.g. heartbeat.[14–16]

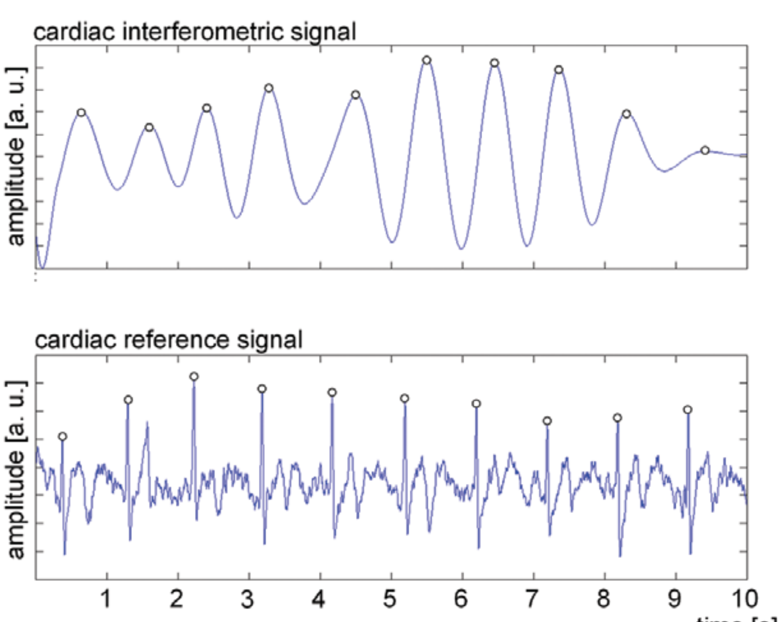
The laser diode is butt-coupled to the fiber, without using any additional optical components. An example image of the light emitted by the diode is depicted in Fig. 2 left. Speckle pattern images at the fiber output are acquired by an imaging optical sensor and are controlled by a microcontroller. Appropriate software was written to set up the sensor's amplification, time of integration, and sampling frequency. The sampling frequency was set equal to 1000 images per second. A sequence of speckle images is shown in the middle panel of Fig. 2.

For the cost reasons, we implemented a linear optical sensor that grabs only the central row from each of speckle images. These rows of pixels are gathered in a time sequence, as shown in Fig. 2, right upper panel. The sequence is then algorithmically transformed into 1D signal suitable for further search of heartbeat patterns (Fig. 2, right lower panel).

Data model and processing

Consider each image grabbed by linear optical array denoted by I and, in general, of dimensions equal to $K \times L$ (in our case $K = 1$ and $L = 102$). Mechanical perturbations of optical fiber change speckle patterns and consequently the time sequence of images I. On a short-time scale, it can be expected the spackle pattern, and consequently the

Fig. 4: Heartbeat feature signal extracted from the interferometric measurements (top) and referential ECG signal with pronounced R-wave spikes (bottom). Signals were sampled at 1000 Hz and aligned in time by hardware synchronization. Local maxima in the interferometric signal correspond to individual heartbeats.



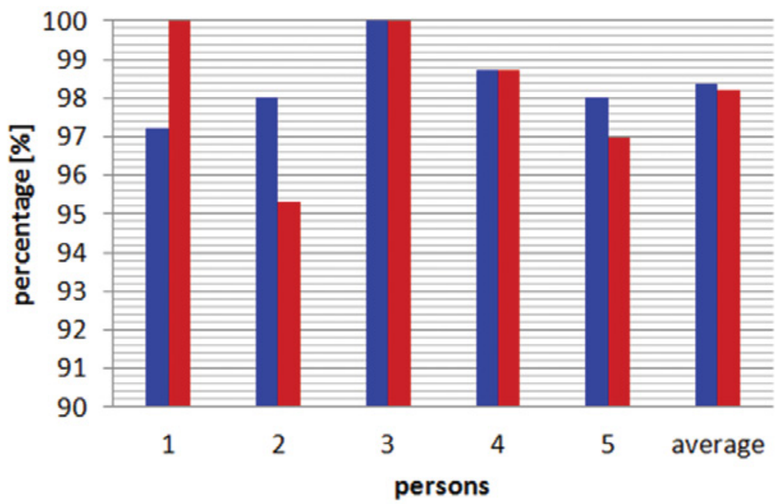


Fig 5: Sensitivity of detected heartbeats (blue bars) and precision (red bars) depicted versus the experiment participants.

images, are stable if no external forces press against the optical fiber, and vary according to external forces when applied.

Images are preprocessed by transforming their features into 1D signal, s(n), by using a phase-shift transformation.[17] Such a transformation helps decrease high 2D computational complexity of the vital signs analysis. Detection of cardiac activity is, therefore, built on the analysis of constructed 1D signals (see Fig. 2, right lower panel).

Heartbeat detection

Human heart rate varies between 45 and 210 beats per minute (bpm) when considering the whole range from the sleep to high physical efforts. We focused on daily normal physical condition, with heart rate up to 120 bpm. The 1D signals generated from speckle images contain frequency components induced by mechanical activity of the heart. In our case, the boundaries for heart rate were set equal to 0.75 and 2 Hz. Signals were prefiltered within this frequency band. The amplitude of filtered signal varies according to heartbeats. By using a peak detection method, local maxima correspond to cardiac systoles.

III. Experiments and results

Experimental protocol

We designed an experimental protocol to verify proposed detection of heartbeat by a referential electrocardiograph. The sensor's optical fiber was spirally twisted and inserted in a thin mattress. Five healthy persons participated in the experiment. They rested supine on the mattress and fiber-optic signals were acquired by custom-made sampling device for 2 minutes as depicted in Fig. 3.

Experimental measurements were accompanied by referential signals taken simultaneously with interferometric speckle images. Hardware synchronization was built in our sampling device.

Referential signals

Referential signals for heartbeat were obtain by a standard Schiller ECG device. Time locations of ECG R waves indicate heartbeats and were determined by Pan-Tompkins QRS detection algorithm.[18] An example of 10-second-long reference ECG signal is depicted in the bottom panel of Fig. 4. Sharp R waves that correspond to the individual heartbeats are easily noted.

Heartbeat detection results

Referential instants on R-wave peaks correlate with detected heartbeats significantly. We evaluated obtained detections statistically. The following events were counted:

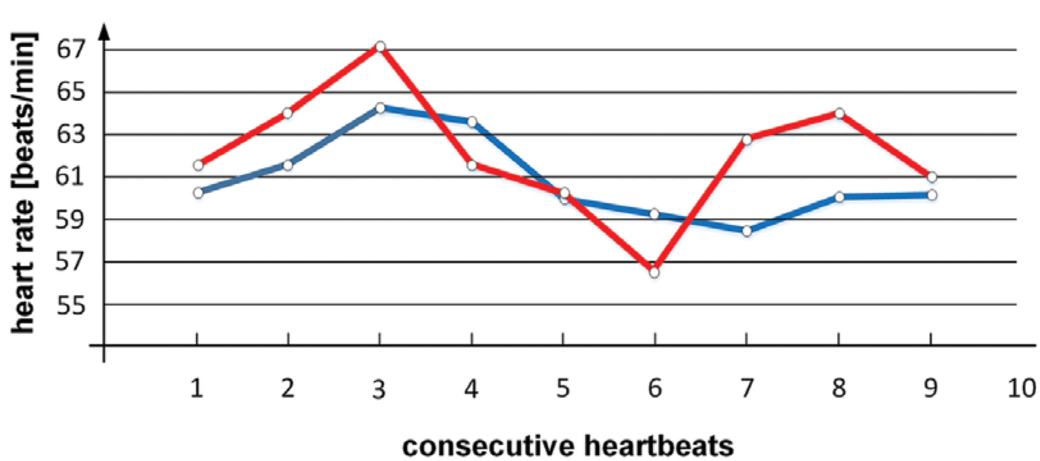


Fig. 6: Absolute values of heart rates assessed from the speckle interferometric signal (red graph) and referential ECG signal (blue graph).

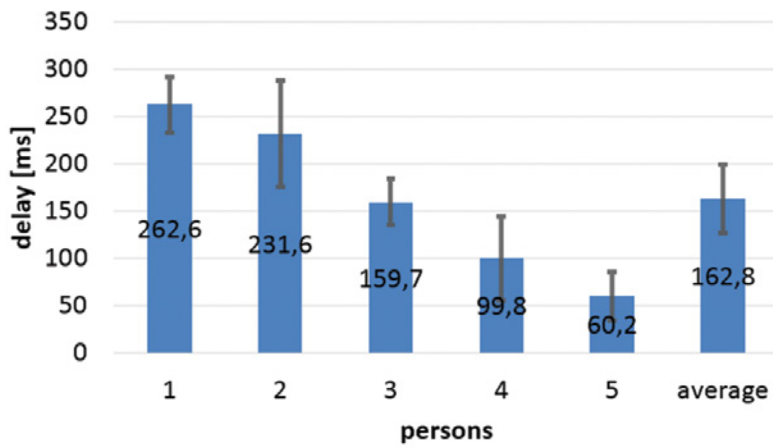


Fig. 7: Means and standard deviations of delays between referential and interferometrically detected heartbeats.

i) the number of interferometric-feature-signal maxima detected first in the intervals between two consecutive referential R waves (true positive – TP), ii) the number of all false identified interferometric maxima between two consecutive referential R waves, i.e. more than one detection in any interval (false positive – FP), and iii) the number of no interferometric maxima between two consecutive referential R waves (false negative – FN).

The efficiency of proposed approach is assessed by:

- sensitivity: $S = \frac{TP}{TP + FN}$
- precision: $P = \frac{TP}{TP + FN}$
- mean delays between referential and interferometrically detected heartbeats, and
- standard deviation of delays between referential and interferometrically detected heartbeats

Total number of heartbeats detected in all speckle interferometric measurements was 795, whilst at the same time the number of R-wave detections in referential ECG totaled 785. The number of missed heartbeats in speckle interferometric measurements was 6 and the number of false detections was 4. Sensitivity and precision were computed for five tested persons and graphically presented in Fig. 5.

Exemplify the efficiency of heartbeat detections by a short segment for person 2. Fig. 6 compares heart rate based on heartbeat detections in the interferometric signal (red graph) and referential heart rate based on the ECG R-R intervals (blue graph). Heart rates were computed as running averages of 3 beat-to-beat and R-R intervals, respectively.

Monitoring of time delays between detected and referential heartbeats is important to infer on the detection accuracy. It is clear that the electrical cardiac activity must precede the mechanical vibration of myocardium systole that is measured by our fiber-optic sensor. The mean and standard deviation of the delays are depicted in Fig. 7 for the five tested persons.

IV. Discussion and conclusions

A fiber-optic speckle interferometer for unobtrusive monitoring of human vital signs was proposed. By transforming captured speckle images into 1D signals, computational complexity of subsequent analyses decreased considerably. Proposed detection of cardiac activity was found very successful when based on the frequency contents of heartbeats, as they appear in obtained 1D signals. By using digital filtering, the extracted signal's local maxima determine the phenomenon looked for.

Obtained detection results are fully comparable to, or better than with, known analysis approaches for unobtrusive heartbeat detection. Average heartbeat sensitivity of 98.4 ± 1.1 % and precision of 98.2 ± 2 % are in line with the results of other known approaches for unobtrusive estimation of heartbeat, such as the methods based on ballistocardiograms,[6] phonocardiograms,[7] or fiber-optic Michelson interferometer.[11]

The same can be considered for means and standard deviations of delays between interferometric and referential heartbeat events. Fig. 7 shows the delays and their deviations, on average 162.8 ± 85.4 ms, that suggest a similar method's accuracy as previously reported with the Michelson interferometer.[11]

In our future research, we are going to test proposed detection setup in a broader population. Patients with cardiac disorders are expected to validate the sensor's and detection method's robustness.

Acknowledgments

All persons signed an informed consent to participate in our experimental protocols that were approved by the National Medical Ethics Committee of the Republic of Slovenia (no. 81/10/10). We also acknowledge financial support of the Slovenian Ministry of Education, Science, and Sport (contract no. 3211-10-000464 for the Competence Centre of Biomedical Engineering).

References

1. Chan M, Estève D, Escriba C, Campo E. A review of smart homes-present state and future challenges. Comput Methods Programs Biomed. 2008; 91(1): 55–81.
2. Chan M, Campo E, Estève D, Fourniols J-Y. Smart homes - current features and future perspectives. Maturitas. 2009; 64(2): 90–97.
3. Ding D, Cooper R a, Pasquina PF, Fici-Pasquina L. Sensor technology for smart homes. Maturitas. 2011; 69(2): 131–136.
4. Lim YG, Kim KK, Park KS. ECG recording on a bed during sleep without direct skin-contact. IEEE Trans Biomed Eng. 2007; 54(4): 718–25.
5. Jourand P, De Clercq H, Puers R. Robust monitoring of vital signs integrated in textile. Sensors Actuators A Phys. 2010; 161(1-2): 288–296.
6. Brüser C, Stadlthanner K, de Waele S, Leonhardt S. Adaptive beat-to-beat heart rate estimation in ballistocardiograms. IEEE Trans Inf Technol Biomed a Publ IEEE Eng Med Biol Soc. 2011; 15(5): 778–86.
7. Quiceno-Manrique AF, Godino-Llorente JI, Blanco-Velasco M, Castellanos-Dominguez G. Selection of dynamic features based on time-frequency representations for heart murmur detection from phonocardiographic signals. Ann Biomed Eng. 2010; 38(1): 118–37.
8. Chourasia VS, Tiwari AK. Wireless data acquisition system for fetal phonocardiographic signals using Bluetooth. Int J Comput Healthc. 2012; 1(3): 240–253.
9. Zazula D, Đonlagić D, Šprager S. Fibre-Optic Interferometry as a Means for the First Heart Sound Detection. In: Advances in applied information science. Greece: World Scientific and Engineering Academy and Society Press; 2012: 30–35.
10. Zazula D, Đonlagić D, Šprager S. Application of Fibre-Optic Interferometry to Detection of Human Vital Signs. J Laser Heal Acad. 2012; 2012(1): 27–32.
11. Šprager S, Zazula D. Heartbeat and respiration detection from optical interferometric signals by using a multimethod approach. IEEE Trans Biomed Eng. 2012; 59(10): 2922–9.
12. Šprager S, Đonlagić D, Zazula D. Heartbeat Detection Applying Activity Index on Optical Interferometric Signal. In: Vincenzo Niola, Zoran Bojkovic MIG-P, ed. IMMURO'12 Proceedings of the 11th WSEAS international conference on Instrumentation, Measurement, Circuits and Systems, and Proceedings of the 12th WSEAS international conference on Robotics, Control and Manufacturing Technology. World Scientific and Engineering Academy and Society Press; 2012: 77–82.
13. Škrabec J, Cigale B, Lešnik D, Đonlagić D, Zazula D. Preliminary Detection of Periodic Perturbations using Speckle Imaging and Interframe Gradient. In: Recent Advances in Applied & Biomedical Informatics and Computational Engineering in Systems Applications. Florence, Italy; 2011: 251–256.
14. 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. J Biomed Opt. 2013; 18(10).
15. Podbreznik P, Djonlagic D, Lesnik D, Cigale B, Zazula D. Fiber-Optic Speckle Interferometry for Unobtrusive Heartbeat Monitoring. J Laser Heal Acad. 2013; 2013(2): 27–30.
16. Podbreznik P, Zazula D. Detekcije življenjskih funkcij s pomočjo pegaste interferometrije. In: Potočnik B, ed. ROSUS 2012: računalniška obdelava slik in njena uporaba v Sloveniji 2012 : zbornik 7. strokovne konference. Maribor, Slovenia; 2012: 43–50.
17. Liu W, Tan Y, Shang HM. Singlemode optical fiber electronic speckle pattern interferometry. Opt Lasers Eng. 1996; 25(2-3): 103–109.
18. Pan J, Tompkins WJ. A real-time QRS detection algorithm. IEEE Trans Biomed Eng. 1985;BME-32(3): 230–6.