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Fiber-Optic Speckle Interferometry for Unobtrusive Heartbeat Monitoring

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ABSTRACT

In this paper, a speckle interferometer with optical fiber system is reported for unobtrusive heartbeat monitoring. The sensor consists of a laser diode butt-coupled to the plastic optical fiber whose exit face projects speckle patterns onto a linear optical sensor array. Speckle images are acquired in a sequence and 1D features are extracted based on time differentiation and space averaging. These were analyzed in the frequency band that corresponds to the cardiac activity in order to detect individual heartbeats. Preliminary experiments with five young, healthy persons lying supine on a mattress with embedded optical fiber showed the proposed system and detection algorithms are highly efficient.

Key words: fiber-optic speckle interferometry, unobtrusive monitoring, human vital signs, heartbeat detection, band-pass filtering.

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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 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].

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.

II. MATERIALS AND METHODS

a) 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.

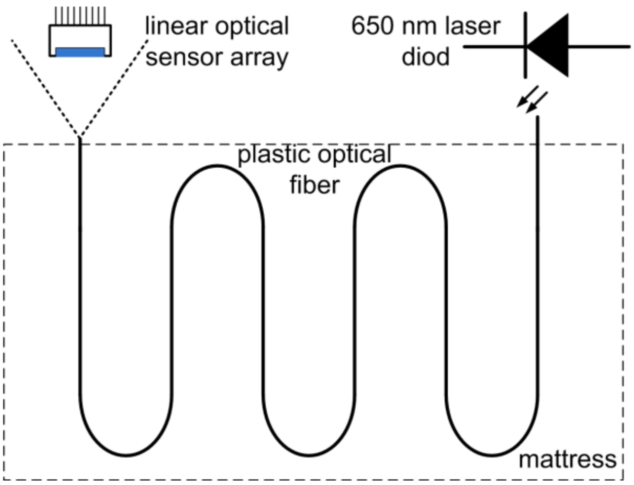

Fig 1: Principle schema of a speckle interferometer.

The 650 nm laser diode is butt-coupled to the fiber, without using any additional optical components. Speckle pattern images at the fiber output must be acquired by an imaging optical sensor. In general, it would be a digital camera, but in proposed solution a silicon linear optical sensor array means a better trade-off [14]. Losing the information on the whole speckle image is compensated by the sensor's lower price, higher sampling frequency, and easily controlled settings. A microcontroller is further required to control and acquire data from the sensor array. 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 lines of 102 pixels per second.

b) Data model and processing

Consider each image grabbed by the 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 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 [15]. 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.

c) 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. RESULTS

a) 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 (Fig. 1) for 2 minutes.

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

b) 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 [16]. An example of 10-second-long reference ECG signal is depicted in the bottom panel of Fig. 2. Sharp R waves that correspond to the individual heartbeats are easily noted.

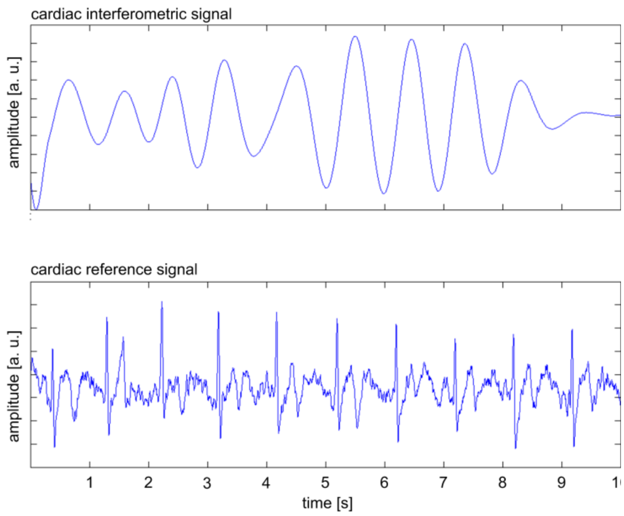

Fig. 2: Heartbeat feature signal extracted from the interferometric measurements (top) and referential ECG signal with pronounced R-wave spikes (bottom). Signals were sampled at 1000 Hz and aligned in time by hardware synchronization. Local maxima in the interferometric signal correspond to individual heartbeats.

c) Heartbeat detection results

Referential instants on R-wave peaks correlate with detected heartbeats significantly. We evaluated obtained detections statistically. The following events were counted: 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: $P = \frac{TP}{TP+FP}$,
- mean delays between referential and interferometrically detected heartbeats, and
- standard deviation of delays between referential and interferometrically detected heartbeats.

Sensitivity and precision were computed for five tested persons and graphically presented in Fig. 3.

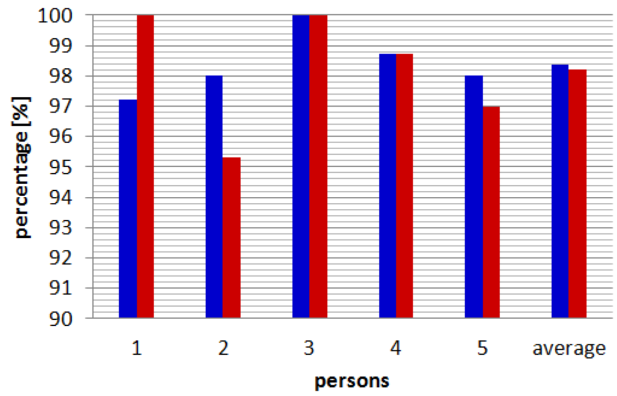

Fig 3: Sensitivity of detected heartbeats (blue bars) and precision (red bars) depicted versus the experiment participants.

Monitoring of time delays between detected and referential heartbeats is important to infer on the detection accuracy. The mean and standard deviation of the delays are depicted in Fig. 4 for five tested persons.

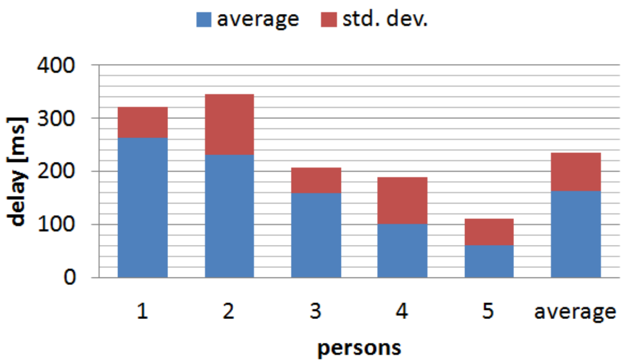

Fig. 4: Means and standard deviations of delays between referential and interferometrically detected heartbeats.

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 fibre-optic Michelson interferometer [11].

The same can be considered for means and standard deviations of delays between interferometric and referential heartbeat events. Fig. 4 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 set-up in clinical environments. Patients with cardiac disorder rs are expected to validate the sensor's and detection method's robustness.

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