journal homepage: www.intl.elsevierhealth.com/journals/cmpb

Detection of heartbeat and respiration from optical interferometric signal by using wavelet transform

Sebastijan Šprager, Damjan Zazula*

University of Maribor, Faculty of Electrical Engineering and Computer Science, Smetanova ulica 17, SI-2000 Maribor, Slovenia

ARTICLE INFO

Article history:
Received 13 April 2012
Received in revised form
21 January 2013
Accepted 5 March 2013

Keywords:
Heartbeat detection
Respiration detection
Optical interferometer
Unobtrusive monitoring of human vital functions
Wavelet transform

ABSTRACT

A novel approach for the heartbeat and respiration detection based on optical interferometer and wavelet transform is proposed in this paper. Optical interferometer is a sensitive device that detects physical elongation of optical fibre due to external perturbations. Mechanical activity of cardiac muscle and respiration reflects in interferometric signal when the interferometer is in contact with human body and, thus, enables unobtrusive detection of human vital signs. The efficiency and accuracy of the proposed approach was estimated in two experimental protocols. The first one collected interferometric signals from 20 subjects during rest. In the second experiment, 10 participants cycled an ergometer until reaching their submaximal heart rate, and were measured immediately after that. Heartbeat detection results show high efficiency (99.46 ± 1.11% sensitivity, 99.60 ± 1.05% precision) and accuracy (mean relative error (MRE) of beat-to-beat intervals 3.16 ± 2.32%) for the first experiment, and slightly lower efficiency (96.22 ± 2.96% sensitivity, 95.35 ± 3.03% precision) and accuracy (MRE of 9.56 ± 3.67%) for the second experiment. Considering respiration detection, high efficiency (97.64 ± 7.28% sensitivity, 99.38 ± 2.80% precision) and accuracy (MRE of intervals between respiration events 7.37 ± 7.20%) for the first experiment, and acceptable efficiency (92.05 ± 6.10% sensitivity, 93.45 ± 3.08% precision) and accuracy (MRE of 16.28 ± 6.25%) for the second experiment confirm a practical value of proposed approaches.

1. Introduction

Unobtrusive monitoring of human vital signs has become popular lately andopenedan alternative way to classical approaches that involve a large number of devices and electrodes attached to subject's body. The development of the unobtrusive type of monitoring bloomed with appearance of new sensors and technologies that are capable of capturing even tiniest electrical, mechanical, or acoustic features that accompany human vital signs, e.g. mechanical activity of cardiac muscle or respiration as the two of most important vital functions. The unobtrusive sensors acquire, in general, different signal patterns in comparison to conventional non-invasive, or even invasive, measuring methods. Hence, special signal processing and pattern recognition algorithms are necessary.

One of very sensitive devices for detecting subtle mechanical, acoustic, or temperature changes is optical interferometer. Its operation is based on changes of optical-fibre length under adirect or indirect influence of forces from the environment. Additional advantages of optical sensors are their accuracy, insensitivity to electromagnetic radiation, and light weight [1]. Due to these properties, optical sensors are capable of

* *Corresponding author at*: University of Maribor, Faculty of Electrical Engineering and Computer Science, System Software Laboratory, Smetanova ulica 17, SI-2000 Maribor, Slovenia. Tel.: +386 2 220 7494; fax: +386 2 220 7272.
E-mail address: sebastijan.sprager@uni-mb.si (S. Šprager).
0169-2607/$ – see front matter
http://dx.doi.org/10.1016/j.cmpb.2013.03.003

monitoring heartbeat and respiration when put in a direct or indirect contact with human body. Mechanical and acoustic activity of cardiac muscle and respiration elongate and shrink optical fibre, which generates the interferometric signal proportional to those activities. This potential for unobtrusive measurements was recognized in the US patents [2,3], however, these documents provide just the principle of measurement, but do not suggest any concrete methods for the detection of vital signs.

When optical fibre is mounted in a direct or indirect contact with human body, the output interferometric signal comprises the contributions of all different influences on the fibre, including human vital signs, such as heartbeat and respiration. The main goal is then to successfully decompose such a compound signal. As a matter of fact, several advanced signal processing approaches for heartbeat and respiration detection have been published [4–6]. Nevertheless, none can be directly applied to fibre-optic interferometric signals for two reasons: either they expect linear sensor's characteristics or they do not deal with compound signals. This is why we performed a series of experiments and researched options for a decomposition of interferometric signals to their components belonging to human vital signs.

The interferometric signals are not in a linear relationship with the measured activities, because the fibre-optic interferometers show highly nonlinear, i.e. cosine, transfer characteristics. Thus, a preprocessing step is always needed to make a demodulation before further detection algorithms may be applied. A clue for the decomposition of the transformed interferometric signal is the observed human vital signs have partially non-overlapped frequency contents. Thus, our first attempts focused on experiments with filter banks [7], showing a great decomposition potential. We also tried the heartbeat detection by using pseudo Wigner–Ville distribution [8]. However, these approaches were accompanied by disadvantages, such as the inaccuracy and disability to perform detection in more demanding circumstances, when body movement and variable heart rate appear. A logical decision was to improve our methods by higher efficiency and accuracy obtained in a multi-scale analysis.

2. Background

Optical interferometry is one of most reliable principles of measuring optical fibre elongation due to external influences. Such sensors are very sensitive, capable of detecting micrometric changes in optical-fibre length [1]. The fibre length changes due to forces pressing against optical fibre as a consequence of many factors, such as sound air waves or light fibre touching, and also environmental temperature drifts. It has been shown that optical interferometer can be used for monitoring human vital functions [7–9]. Considering heartbeat and respiration as the two most important vital functions, their mechanical activity causes perturbations in the form of interferometric signal.

We experimented with a Michelson optical interferometer. The sensor has a cosine transfer characteristic, whereas

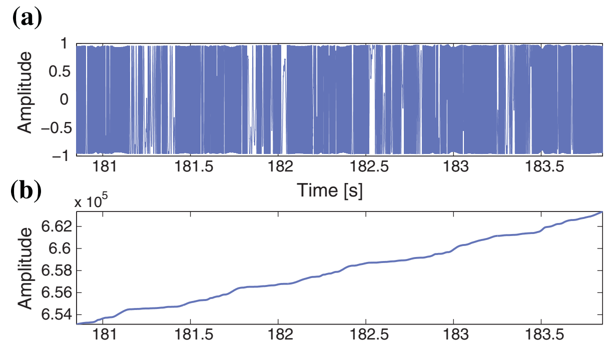

Fig. 1 – An example of 3 s long interferometric signal $i(n)$ from optical interferometer (a) and demodulated interferometric signal $\phi(n)$ from (a) using Hilbert transform (b).

one period in the output signal corresponds to a change of fibre length that is equivalent to the half wavelength of the optical source (650 nm in our particular case). The interferometric signal $i(n)$ is obtained with acquisition of optical power on the sensor output (Eq. (1)). We observe minute fibre-length changes, caused by vital signs when a person is in contact with the fibre. Denote fibre-optic influence of the k-th vital sign by $s_k(n), k = 1, \ldots, K$, and all other impacts on the fibre elongation in time, i.e. environmental noise, temperature drift, etc., by $\varphi(n)$. Hence, a highly nonlinearmodel of interferometric signal $i(n)$ can be constructed as:

$$i(n) = A(n)\cos\left[\sum_k s_k(n) + \varphi(n)\right] \tag{1}$$

where $A(n)$ stands for amplitude changes in interferometric signal. An example of interferometric signal $i(n)$ is shown in Fig. 1a.

Analytic representation of interferometric signal $i(n)$ derived by using the Hilbert transform:

$$x(n) = i(n) + jH[i(n)] = A(n)\left\{\cos\left[\sum_k s_k(n) + \varphi(n)\right] + j\sin\left[\sum_k s_k(n) + \varphi(n)\right]\right\} \tag{2}$$

where $H[i(n)]$ stands for the Hilbert transform of interferometric signal $i(n)$ and j for imaginary unit.

The phase of the obtained analytic signal can be derived from Eq. (2) as follows:

$$\tan\phi \quad (n) = \frac{\sin\left[\sum_k s_k(n) + \varphi(n)\right]}{\cos\left[\sum_k s_k(n) + \varphi(n)\right]} = \tan\left[\sum_k s_k(n) + \varphi(n)\right]. \tag{3}$$