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Multi-Channel Optical Sensor-Array for Measuring Ballistocardiograms and Respiratory Activity in Bed

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***Abstract*— Our work covers improvements in sensors and signal processing for unobtrusive, long-term monitoring of cardiac (and respiratory) rhythms using only non-invasive vibration sensors. We describe a system for the unobtrusive monitoring of vital signs by means of an array of novel optical ballistocardiography (BCG) sensors placed underneath a regular bed mattress. Furthermore, we analyze the systems spatial sensitivity and present proof-of-concept results comparing our system to a more conventional BCG system based on a single electromechanical-film (EMFi) sensor. Our preliminary results suggest that the proposed optical multi-channel system could have the potential to reduce beat-to-beat heart rate estimation errors, as well as enable the analysis of more complex breathing patterns.**

I. Introduction

Recently, the recording and analysis of body vibrations caused by the mechanical activity of the heart has gained increasing interest in the biomedical engineering community. Depending on the measurement modality, these types of signals are commonly referred to as ballistocardiograms (BCGs) or seimsocardiograms (SCGs). Most current research on these topics is motivated by two sightly different applications: on the one hand, unobtrusive, long-term monitoring of cardiac (and respiratory) rhythms, and on the other hand, non-invasive diagnostics of hemodynamic parameters. For the latter application, the cardiac vibration signals are usually recorded simultaneously with an electrocardiogram (ECG) which is then used to delineate individual heart beats in the vibration signal. Based on timing or morphological variations in the vibration signal, hemodynamic parameters are derived. For the former application, only cardiac vibration signals are used to monitor the patients' cardio-pulmonary rhythms unobtrusively. In this case, the goal usually is to develop systems for long-term home monitoring where traditional tools, such as the ECG, are unsuitable due to their invasiveness or the necessary user compliance.

For this purpose, the integration of cardiac vibration sensors into objects of daily life is particularly compelling. Accordingly, various types of sensors have been integrated into objects such as beds [1]–[9], (wheel-) chairs [10], [11], or weighing scales [12]. For the application in beds, a multitude of different sensors have been applied such as electromechanical film (EMFi) and polyvinylidene fluoride (PVDF) foils placed on top or beneath the mattress [1], [2], pneumatic mattresses [3], [4], hydraulic under-pillow sensors [5], infra-red sensor integrated into spring-coil mattresses [6], strain gauges under bed posts [7] or on the bed frame [8], as well as ultrasound sensors placed in a cavity beneath the mattress [9]. Most of these bed-based systems provide a single BCG signal which correlates with the integral of the forces acting on the entire mattress surface, or a large portion of it. Hence, they do not provide any spatial information. A notable exception to this is a system proposed by [1] which consists of an array of EMFi foils.

In this work, we propose a novel optical sensor capable of recording cardiac vibrations, respiratory movements and general body movements in bed. The proposed sensor can be mounted underneath a regular bed mattress and be either used individually or configured into an sensor array which provides a coarse spatial resolution. Conceptually, our sensors each consist of an infrared light source which emits light into the bed's mattress and a photodetector which continuously records the intensity of the light that is scattered back through the mattress over time. Any type of movement, such as respiratory movement, cardiac vibrations, as well as any other body movements of the subject lying on the mattress causes (slight) deformations of the mattress. Through this change in geometry, the optical properties of the mattress change which in turn causes a change in the intensity of light which is reflected or scattered back to the photodetector. By recording the light intensity over time, a curve containing respiratory, cardiac, and other activity can be obtained. Unlike the sensor described in [6], we did not enclose neither the light source nor the photodetector within in a cavity in the mattress. Instead, both are located underneath the mattress. This allows for easy maintenance and retrofitting of existing beds.

II. Optical BCG Sensor-Array

Figure 1 shows a picture and a schematic representation of a single sensing unit. As shown in Fig. 1a, each individual sensor consists of three light emitting diodes (LEDs) and a matched photodiode located at a distance of 1.5 cm in the center of the three LEDs. We used LEDs with a near-infrared peak wavelength of 850 nm (SFH4250, OSRAM, Munich, Germany). A photodiode with a peak sensitivity of 880 nm and a daylight filter (BPW34FAS, OSRAM, Munich, Germany) serves as the photodetector. Its photocurrent is amplified and converted to a voltage signal by a transimpedance amplifier with a gain of 100. Figure 1b

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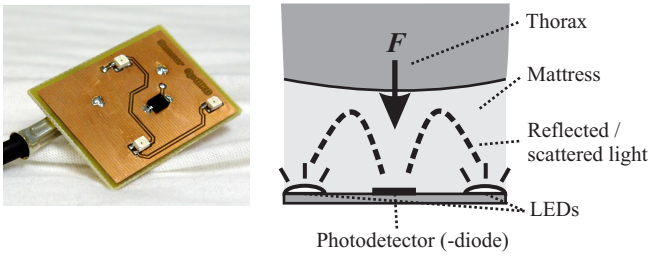


(a) Top view (b) Side view

Fig. 1: In (a), a picture of the top side of a single sensor prototype with three LEDs and the central photodiode is shown. A schematic side view of a single sensing unit is shown in (b). The dynamic force F acting on the mattress surface deforms the mattress which modulates the intensity of the light reaching the photodetector.

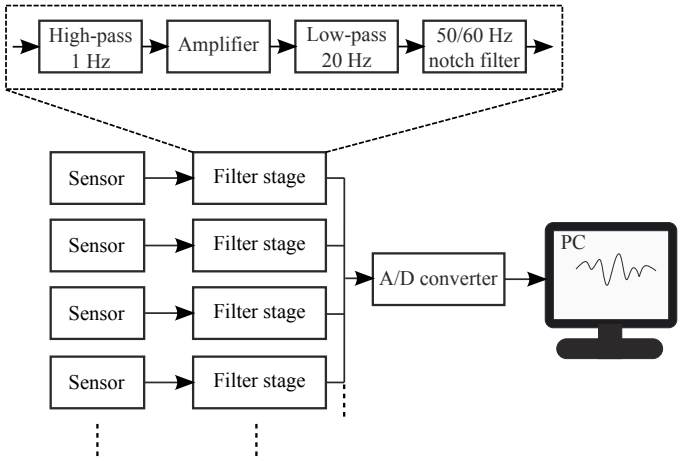


Fig. 2: Overview of the multi-channel BCG system and the analog filter stages.

visualizes the operating principle of the sensor. Dynamic forces acting on the mattress surface cause deformations of the mattress which in turn modulate the intensity of the light which is sensed by the photodiode.

An overview of the entire system containing several sensors is shown in Fig. 2. After the initial amplification and conversion on the sensor module itself, each sensor's signal is further processed by an analog filter stage before being digitized and recorded by a personal computer. The filter stage first applies a 1st order high-pass filter with a 3 dB cutoff frequency of 1 Hz. The main purpose of the high-pass filter is to remove the significant signal offset caused by static illumination of the photodiode. Intuitively, a cutoff frequency of 1 Hz might seem too high considering the typical frequencies of respiratory and cardiac rhythms. However, due to the low filter order and the fact that the respiratory amplitude is significantly higher than the amplitude of the cardiac signal, both components remain clearly visible in the filtered signal. This is exemplary shown in Fig. 3.

The high-pass filter is followed by another amplifier and a 2nd order low-pass filter with a cutoff frequency of 20 Hz. To further reduce power-line noise, an additional 50/60 Hz notch filter is applied. The filtered signals are then digitized with a sampling rate of 200 Hz and 14 bit resolution using a commercial data acquisition module (NI USB-6009, National Instruments, Austin, TX, USA). All signals are stored and displayed on a personal computer using the software LabVIEW (National Instruments, Austin, TX, USA).

If multiple sensors are used in the system, then several advantages are gained. Firstly, light is transmitted into the mattress from a variety of different locations, which increases the likelihood that the physiological rhythms being monitored will be picked up by the sensors. Furthermore, the redundancy offered by the use of multiple sensors can be exploited by signal processing algorithms in order to improve the reliability and accuracy of the physiological monitoring. For our initial proof-of-concept prototype, we used a setup of four sensors arranged underneath the bed's mattress in a diamond configuration (see Fig. 4).

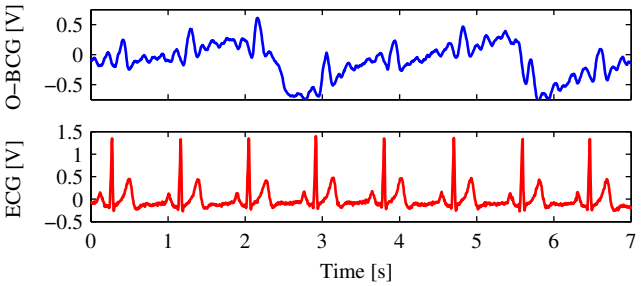


Fig. 3: Optical BCG (O-BCG) signal of a single sensor showing cardiac and respiratory activity after the analog filter stage. The bottom plot shows a simultaneously recorded reference ECG.

III. System Evaluation

A. Spacial Sensitivity

First, we evaluated the spatial sensitivity of a single sensor, i.e. how does the maximal amplitude of the sensor response to a fixed mechanical impulse depends on the origin of the impulse with respect to the sensor position. This as well as all following experiments were performed on a full-foam mattress with a thickness of 11 cm.

Due to the sensor geometry, we approximated the sensitivity map to be rotation-invariant, i.e. we assumed that the sensitivity solely depends on the distance to the sensor center. Hence, we measured the maximal signal amplitudes caused by dropping a 10 g steel ball on the mattress from a height of 5 cm at varying distances from the considered sensor. Repeated measurements were taken and averaged to determine the sensitivity versus distance characteristic of a single sensor. Figure 5a shows the resulting normalized sensitivity curve. Based on the assumption of rotation-invariance, we obtain the sensitivity map of a single sensors show in Fig. 5b. We then estimated a sensitivity map of the proposed sensor arrangement by superposing the individual sensor maps. The resulting sensitivity map is shown in Fig. 5c. It clearly shows the area of highest sensitivity is, as intended,

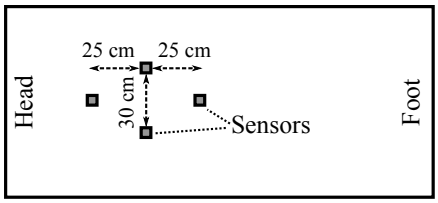
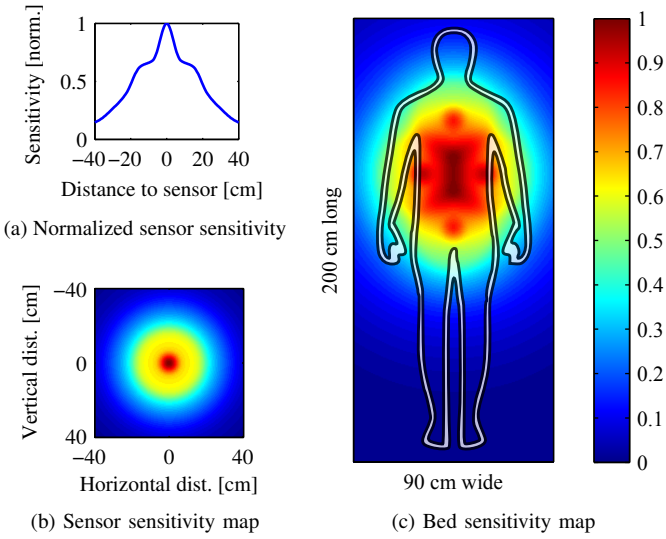


Fig. 4: Diamond configuration of four sensors underneath the bed's mattress.



(a) Normalized sensor sensitivity

(b) Sensor sensitivity map

(c) Bed sensitivity map

Fig. 5: Normalized spatial sensitivity of the optical sensor system using an 11 cm thick foam mattress.

located underneath the thorax. Furthermore, we can see that, while there is an overlap between the sensors, each sensor provides distinct spatial information. Nonetheless, while four sensors are sufficient for this early proof-of-concept study, this analysis also shows that more sensors have to be added to the array to cover more mattress area and to ensure that useful signals can be recorded no matter how the subject is positioned in bed. It should be noted that the non-linearity of the spatial sensitivity does not negatively affect the sensor's applicability to our target scenario. Since measurements are to be performed in a completely uncontrolled environment in the first place, we only expect to be able to extract information on the rhythms anyway. Absolute amplitude readings will likely convey little useful information due to the large number of unknown variables affecting them, most notably the exact location and posture of the subject.

B. Proof-of-concept Measurements

Using the proposed multi-channel system, we performed measurements on a single subject (male, 28 years, 80 kg). In addition to the four optical BCG channels (O-BCG), a lead II reference electrocardiogram (ECG) was simultaneously recorded at a sampling rate of 200 Hz. Furthermore, we placed a single electromechanical-film (EMFi) sensor (Emfit Ltd, Vaajakoski, Finland; dimensions: 30 cm $\times$ 60 cm, thickness $<$ 1 mm), which was mounted on the underside of a thin (2.5 cm) foam overlay, on top of the regular mattress of the bed. A charge amplifier was used prior to sampling the EMFi signal at 200 Hz. We included the EMFi foil in our measurements to be able to compare our sensors' signals to an established type of bed-sensor which we have employed in previous studies [13]. Note that the EMFi foil, which is opaque, is placed on top of the bed's mattress whereas our sensors are located beneath the mattress. The EMFi foil only has a negligible influence on the optical BCG signals since the intensity of the light which makes the round-trip, through the mattress, to the foil, and back to the photodiode, is minimal with respect to the overall modulated intensity.

Figure 6 shows an excerpt of the recorded signals. Up to the vertical marker, the subject was breathing normally. After the marker, the subject started to hold his breath. The breathing movements clearly show up in the EMFi signal as well as in the fourth O-BCG channel. The other three O-BCG channels also show some respiratory modulation, even though it is less obvious. Since sensor four was located underneath the subject's abdominal region, this indicates abdominal breathing as opposed to chest breathing, which was indeed the case. These early results suggest that our proposed system, ideally including an increased number of sensors, might be used to infer more complex breathing patterns. As expected, the respiratory variations cease when the subject held his breath. In addition to the respiratory component, the cardiac component is visible in all channels. Just as it is typical for this type of sensor setup, each heart beat in the vibration signals (O-BCG and EMFi) consists not of a single peak, but of a complex group of waves.

C. Beat-to-beat Heart Rate Estimation

Since the intended application for our proposed system is unobtrusive monitoring of cardiac activity, we also evaluated its suitability for automatic beat-to-beat heart rate detection. Each individual vibration channel was processed by the continuous local interval estimation algorithm (CLIE) to extract the beat-to-beat intervals. The results were evaluated by means of the mean relative error between the estimated intervals and the corresponding RR intervals obtained from the reference ECG.

In addition to considering each channel individually, we also applied an extension to CLIE algorithm which jointly considers all optical BCG channels. The original CLIE algorithm estimates beat-to-beat intervals not by detecting fiducial points but instead by continuously analyzing the periodicity of the signal in an adaptive moving window (ideally covering two heart beats). Our multi-channel extension now shifts this analysis window across all channels simultaneously and averages the periodicity estimates in the estimation domain.

The results on a 30 min recording of one subject are given in Table I. We can see that the combination of all four O-BCG channels reduces the mean error compared to each individual O-BCG or EMFi channel. It is interesting to observe that the EMFi sensor produced the best performance

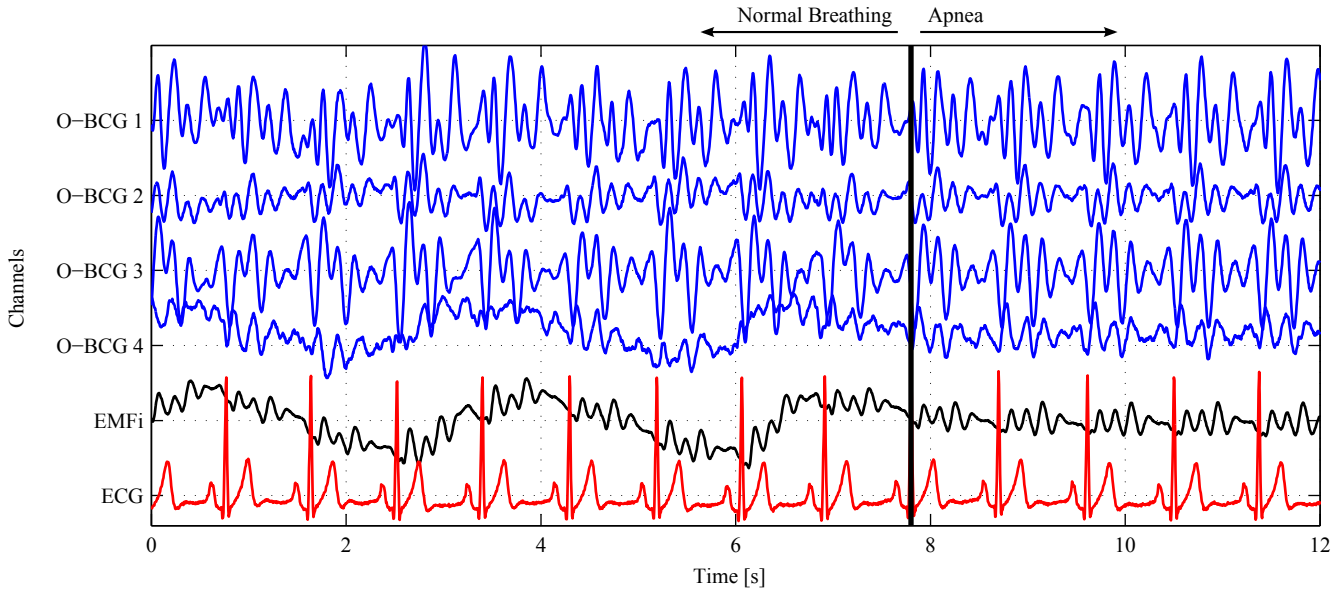


Fig. 6: Four optical BCG channels (O-BCG 1-4) as well as a simultaneously recorded EMFi BCG signal and reference ECG. The black vertical lines indicates the time at which the subject started to hold his breath.

TABLE I: Beat-to-beat interval errors and coverages.

Channels	Rel. Error [%]	Coverage [%]
O-BCG 1	0.87	71.6
O-BCG 2	0.71	65.0
O-BCG 3	1.03	33.1
O-BCG 4	3.64	44.2
O-BCG Combined	0.49	67.1
EMFi	0.62	71.1

of all individual channels. This might either be caused by the fact that it has a larger sensitive area than an individual optical sensor or that is located closer to the subject's thorax than the optical sensors (which were placed underneath the mattress).

We expect our sensor to provide improved long-term stability over EMFi sensors which show a noticeable decrease in sensitivity over a time frame of multiple months of use. The active semiconductor components of our sensors age during much longer time scales and they are also not exposed to any significant physical stress.

IV. Conclusions

We presented a novel infrared sensor-array to measure cardiac and respiratory vibrations in bed. In a first proof-of-concept experiment, we obtained encouraging results on its effectiveness for monitoring vital signs in bed. It must be stressed, however, that these results have to be interpreted very cautiously due to the limited data set. They should merely serve to illustrate that our proposed concept warrants further investigations on this topic.

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