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Contact-free measurement of respiratory rate using infrared and vibration sensors

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HIGHLIGHTS

- A multi-modal system for respiratory rate measurement is described.
- The multi-modal system consists of two PIR sensors and a vibration sensor.
- An error of less than 2 breathings/min is achieved for different lying positions.
- Fusion of the data of different types of sensors provides a robust respiratory monitoring.
- The multi-modal system is capable of detecting sleep apnea as well.

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ABSTRACT

Respiratory rate is an essential parameter in many practical applications such as apnea detection, patient monitoring, and elderly people monitoring. In this paper, we describe a novel method and a contact-free multi-modal system which is capable of detecting human breathing activity. The multimodal system, which uses both differential pyro-electric infrared (PIR) and vibration sensors, can also estimate the respiratory rate. Vibration sensors pick up small vibrations due to the breathing activity. Similarly, PIR sensors pick up the thoracic movements. Sensor signals are sampled using a microprocessor board and analyzed on a laptop computer. Sensor signals are processed using wavelet analysis and empirical mode decomposition (EMD). Since breathing is almost periodic, a new multi-modal average magnitude difference function (AMDF) is used to detect the periodicity and the period in the processed signals. By fusing the data of two different types of sensors we achieve a more robust and reliable contact-free human breathing activity detection system compared to systems using only one specific type of sensors.

1. Introduction

Respiratory rate is an important vital sign in assessing the physical and psychological health of human beings. Respiratory rate, especially the expiratory time is a good predictor of the level of individual anxiety [1]. It is reported in [2] that a serious increase in the breathing activity is the most important indicator of cardiac arrest in hospital wards. It is also known that many lung and heart diseases such as pneumonia affect respiratory rate [3]. Therefore respiratory monitoring is a crucial tool in intensive care units, hospitals, elderly care units, and home medical care services.

Systems for respiratory monitoring can be classified into two categories: (i) systems which are worn on the human's body, e.g. thoracic impedance pneumography, photoplethysmography, and (ii) systems which measure the human's near-environment, e.g. sound recording, carbon dioxide sensing. The work in [4–7] are good examples of the first group. Carmo and Correia [4] use a wireless electronic shirt with embedded sensors to measure the heart rate and respiratory frequency. An electromagnetic biosensor centered on the subject's sternum is used for respiratory monitoring in [5]. Peng et al. [6] propose a system with video, pyro-electric infrared (PIR) sensors and wearable actigraphy based monitoring system for sleep monitoring. However it fails to detect the period of breathing and PIR sensors are only used in on/off mode. In [7] a wireless wearable bioimpedance device is developed. But the device basically aims to detect the abnormal breathing waveforms in the bioimpedance signal and cannot estimate the respiratory rate accurately.

The studies in [8–14] exemplify the second group. In [8,9], radar sensor based systems for central apnea detection and respiratory monitoring are described, respectively. A biosignal measurement

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system, which measures the air pressure in an air mattress, to monitor the heartbeat and respiration of a person lying in bed is introduced in [10]. Wang et al. [11] propose a sensor based sleep monitoring system to assess the quantity and quality of sleep for elderly people. But it uses PIR sensors in on/off mode only and does not determine the period of breathing. They also use bed sensors but not for detection of the breathing activity.

Infrared camera based imaging systems are also used to monitor the respiratory activity [12]. Wai et al. [13] describe an array of bed sensors and cameras to monitor client position in bed and different situations when the client is out of bed. While the article describes a bed monitoring system to detect sleep patterns, the system focuses on monitoring falls but not the breathing activity. Furthermore, the use of cameras in bedroom raises issues related to personal privacy of the individual.

In [14], a system including only PIR type sensors to monitor the respiratory movements is presented. Fourier analysis of the sensor signals are used to find out the abnormalities, in particular sleep apnea, in a patient's breathing activity. Respiratory rate measurement is mentioned as a further investigation in the study. In [14], analog signal acquisition from the PIR sensors is not described. In Section 2, we present a circuit structure developed for analog data acquisition from a PIR sensor.

In this paper, we describe a novel contact-free human breathing activity detection system using a plurality of sensors. The system is also capable of estimating the respiratory rate. In contrast to the single-sensor type systems, our multi-modal system consists of two types of sensors: PIR and vibration sensors. PIR sensors are placed onto a stand near the bed and the vibration sensor is placed on the bedding frame. A typical graphical description of the multi-modal system setup is shown in Fig. 1. Vibration sensors pick up small vibrations due to breathing activity. Similarly, PIR sensors pick up the thoracic movements. Sensor signals are sampled using a microprocessor board and processed using wavelet analysis and empirical mode decomposition (EMD) on a laptop computer. Our data analysis is different from [14]. We process the sensor signals using wavelet analysis. Since breathing is almost periodic, average magnitude difference function (AMDF) is used to detect the periodicity. We also define a novel AMDF by fusing the PIR and vibration sensors' signals. By using two different types of sensors we achieve a more robust and reliable contact-free human breathing activity detection system compared to systems using only one specific type of sensors.

The paper is organized as follows: Operating principles of the sensors and data acquisition from the sensors are described in Section 2. Wavelet analysis and EMD based sensor data processing is described in Section 3. Section 4 reports the results of experimental validation and Section 5 concludes the paper.

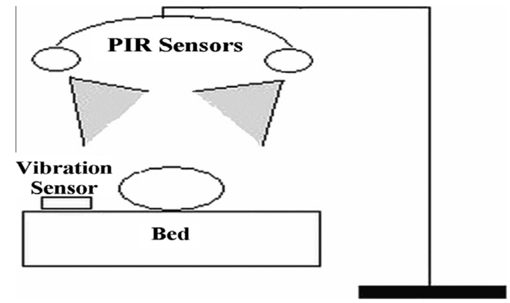

Fig. 1. A typical illustration of the contact-free multimodal human breathing activity detection system consisting of two PIR sensors and a vibration sensor.

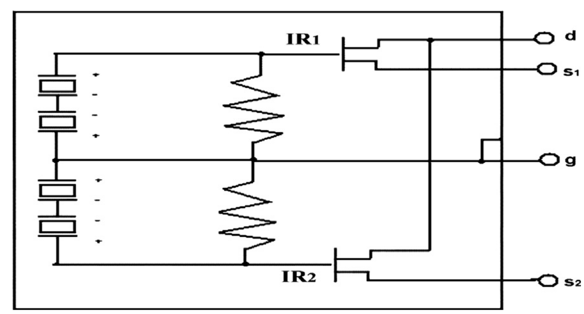

Fig. 2. Model of the inner structure of a differential PIR sensor.

2. Data acquisition

2.1. PIR sensors

PIR sensors are widely used commercially for motion detection, e.g. in automation of electrical appliances [15], design and implementation of a home embedded surveillance systems [16]. These applications are, in general, based on the on/off decisions of the PIR sensors.

A differential PIR sensor basically measures the difference of infrared radiation density between the two pyro-electric elements (IR_1, IR_2) inside. Fig. 2 shows the block diagram of a typical differential PIR sensor, (s_1) and (s_2) are the outputs of the pyro-electric elements and (g) is ground. Normal temperature alterations and changes caused by airflow are cancelled by the two elements connected in parallel. If these elements are exposed to the same amount of infrared radiation, they cancel each other and the sensor produces a zero-output at (d).

Commercially available PIR motion detector circuits produce binary outputs. However, it is possible to capture a continuous-time analog signal representing the amplitude of the voltage signal which corresponds to the transient behavior of the circuit. We use a circuit, which we developed for flickering flame detection [17], to capture an analog output signal from the PIR sensor and it is shown in Fig. 3. The circuit consists of four operational amplifiers (op amps), U1A, U1B, U1C and U1D. U1A and U1B constitute a two stage amplifier circuit whereas U1C and U1D couple behaves as a comparator. The very-low amplitude raw output at the 2nd pin of the PIR sensor is amplified through the two stage amplifier circuit. The amplified signal at the output of U1B is fed into the comparator structure which outputs a binary signal, either 0 V or 5 V in standard motion detectors. Instead of using the binary output in the original version of the PIR sensor read-out circuit, the analog output signal at the output of the 2nd op amp U1B is captured.

The analog output signal is digitized using a microcontroller with a sampling rate of 20 Hz and transferred to a general-purpose laptop computer for further processing. A typical respiratory rate for a healthy adult at rest is 12–20 breaths per minute. Average resting respiratory rates vary with age. Infants take 30–60 breaths per minute. Therefore even a 2 Hz sampling frequency is enough for digitization of the analog sensor signal due to Shannon's sampling theorem. However a higher sampling rate (20 Hz) is selected for digitization. A typical differential PIR sensor signal due to a human breathing at a 1 m distance from the sensor is shown in Fig. 4. It is clear from the figure that the signal is almost periodic.

2.2. Vibration sensor

Vibration sensors are usually based on accelerometers which are used to detect seismic activity, vibrations in mechanical systems and machines, buildings, and they are also used in