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Ángel Serrano Alarcón and Andrei Boiko

Designing a Sensor Interface for Cardiorespiratory Measurement in Sleep Monitoring

Mostafa Haghi[1] [0000-0001-8966-0176], Ralf Seepold[1] [0000-0002-5192-2537] and Natividad Martínez Madrid[2] [0000-0003-1965-9481]

Abstract. Sleep is essential to existence, much like air, water, and food, as we spend nearly one-third of our time sleeping. Poor sleep quality or disturbed sleep causes daytime solemnity, which worsens daytime activities' mental and physical qualities and raises the risk of accidents. With advancements in sensor and communication technology, sleep monitoring is moving out of specialized clinics and into our everyday homes. It is possible to extract data from traditional overnight polysomnographic recordings using more basic tools and straightforward techniques. Ballistocardiogram is an unobtrusive, non-invasive, simple, and low-cost technique for measuring cardiorespiratory parameters. In this work, we present a sensor board interface to facilitate the communication between force sensitive resistor sensor and an embedded system to provide a high-performing prototype with an efficient signal-to-noise ratio. We have utilized a multi-physical-layer approach to locate each layer on top of another, yet supporting a low-cost, compact design with easy deployment under the bed frame.

Keywords -- Cardiorespiratory Parameters, Unobtrusive Measurement, Sleep Monitoring.

I. Introduction

According to the United Nations' 2030 agenda for sustainable development goal (SDG) and the World Health Organization's (WHO) 13th general program of work, the aim should be ensuring healthy lives and promoting well-being for all people of all ages as well as setting three interconnected strategic priorities to (i) achieving universal health coverage, (ii) addressing health emergencies, and (iii) promoting healthier populations. Thus, the young and the elderly, the healthy and the disease-affected, should benefit [1,2].

On the one hand, according to statistics, individuals spend up to 80% of their time in indoor spaces such as home, of which we spend almost one-third of our lifetime asleep [3]. On the other hand, homes are the major indoor and private spaces, and with the recent advances in sensors technology, the trend of shifting toward the smart medical home has shown promising output [4].

Integrating inexpensive medical and non-medical sensors and devices in smart homes and combining signal and bio-signal processing using analytical software via artificial intelligence (AI)-based techniques may contribute to an early and valid diagnosis [4].

With advancements in sensor and communication technology, sleep monitoring is moving out of specialized clinics and into our everyday homes. It is possible to extract data from traditional overnight polysomnographic (PSG) recordings using more basic tools and more straightforward techniques. Laboratory PSG, which primarily defines brain states based on electroencephalogram (EEG), is the gold standard of sleep monitoring [5,6].

With the emerging sensor technologies, advances in transforming this private space into a diagnostic space are at hand. This concept is in line with the paradigms of shifting the: (i) subject-to-device in a hospital → device-to-subject in a point of perception, and (ii) diagnosis of symptoms → preventive medicine. This supports the idea of "an accurate forecast for a specific individual longest before the predicted event". Such an approach provides unobtrusive, continuous, and long-term data acquisition for real-time monitoring [4].

Sleep is essential to existence, much like air, water, and food, as we spend nearly one-third of our time sleeping. Poor sleep quality or disturbed sleep causes daytime solemnity, which worsens daytime activities' mental and physical qualities and raises the risk of accidents [7].

The most prevalent sleep disorders are insomnia (the inability to fall asleep) and sleep breathing disorders (repeatedly interrupting normal breathing during sleeping). Other common sleep-related disorders include parasomnias, narcolepsy, periodic limb movement syndrome, and REM sleep disorder. Additionally, it is commonly known that sleep problems make it more likely for healthy people to have multiple chronic diseases at once [8].

Movement analysis and cardio-respiration measurement are the concerns that yield insight into the physiological and health status of the subject as well as the sleep assessment. With improving the sensitivity and availability of the sensors such as force sensitive resistors (FSR), piezoelectric, pressure sensors, and fiber Bragg grating (FBG), unobtrusive, non-invasive, and low-cost monitoring is at hand [9].

[1] HTWG Konstanz, Alfred-Wachtel-Str. 8, 78462 Konstanz, Germany
{mostafa.haghi, ralf.seepold}@htwg-konstanz.de
[2] Reutlingen University, Alteburgstr. 150, 72762 Reutlingen, Germany
natividad.martinez@reutlingen-university.de

The ballistocardiogram (BCG) is a technique measuring the body recoils when the heart pumps blood into the veins. Modern technical developments have greatly streamlined the measurement and evaluation of these signals and opened up new vistas for their clinical application. Every time the heart beats, the blood moves along the vascular tree, causing changes in the body's micro movements. These changes are then maintained by the body's overall momentum. The BCG is the recording of these motions and is understood to comprise motions in all three axes. It can be quantified as a displacement, velocity, or acceleration signal [10].

The transverse BCG indicates anteroposterior (or dorso-ventral) vibrations, where-as the longitudinal BCG measures the head-to-foot deflections of the body. Longitudinal BCG measurements were the main focus of the initial bed- and table-based BCG systems because they were thought to constitute the biggest projection of the 3D forces brought on by cardiac ejection [11,12].

The FSR sensors, which transduce changes in pressure exerted on its active area in-to changes in its electrical resistance, have been extensively applied in monitoring cardiac activity and respiration measurement at home with the focus of research activities [13].

However, designing and implementing a device that is low-cost, easy to deploy, and high performing remains a concern.

In this work, we design and implement a board interface that facilitates the communication between the FSR sensors and the embedded system for measuring cardiorespiratory during sleep. The prototype is in an efficient form factor, compact, low-cost, extendable, and does not need any technical guidance for deployment, is battery-powered, and operates out of the box.

The rest of this work is presented as follows: in Section 2, materials and methods, including the technical description and approach, are provided. In Section 3, the results are presented briefly, and the advantages of the prototype are highlighted. The work is concluded with the take-home messages and future outlook in Section 4.

II. Materials and Methods

LTspice (Analog device, Wilmington, MA 01887, USA) has been used to simulate the electronic circuit, electrical check, adjust the gain, and tune the boundaries of the filters. Besides, we have used the Easyeda tool to design the hardware layout and a two-layer printed circuit board (PCB) performed in JLCPCB library [14].

A. Electronic Design: Components Selection, Gain, and Filter

Using LT3042, a high-performance, low-dropout linear regulator featuring ultralow noise and ultra-high power supply rejection ratio (PSRR) architecture for powering noise-sensitive radio frequency (RF) applications, we have secured the first level of the circuit.

An instrumentation amplifier (INA) provides a large gain for very low-level signals, often at high noise levels. Therefore, the first level of the circuit is followed by AD8221, a high-performing INA. INA is a particular type of differential input amplifier; its primary focus is to provide differential gain and a high common-mode rejection ratio (CMRR). AD8221 offers a wide power supply range of ±2.3 V to ±18 V, high input and low output impedance, low offset (25µV maximum input), and low noise, i.e., 8 nV/√Hz, @ 1kHz, maximum input voltage noise and 0.25 µV p-p input noise (0.1 Hz to 10Hz). There are three main features for selecting this INA:

(i) The gain can be set by one external resistor,
(ii) The input stage is fitted with buffer amplifiers,
(iii) The output stage is a traditional difference amplifier.

We have adjusted the gain to 100 and filtered the signals with a frequency of greater than 50Hz. However, it could be further adjusted.

B. Form Factor: Deployment, Portability, and Applicability

We have developed a prototype composed of two layers – but extendable, (i) battery-powered embedded system and (ii) an interface board, which links the FSR sensor(s) to the embedded system. We have utilized the multi-physical-layer (MPL) approach. It benefits from the extendable height rather than the x-y plane. Thus, the implemented prototype is in 3D, with extended height and maintaining the x-y dimensions. The interface board is stuck on the top of the embedded system via the board-to-board connectors, yet the top layer supports the extension for sticking further board interface for additional sensor(s).

We have shared the power source and inter-integrated circuit (IIC) bus between the boards and preserved the pins for connecting the sensors to the ADC pins of the embedded system, i.e., Raspberry Pi 4B.

The prototype resulted in a compact and out of box functional hardware design that could be readily deployed under the bed frame. It could be assembled, moved, and adjusted from one bed frame to another, yet compatible with the requirements and does not need re-adjustment nor technical instruction for the assembly (Figure 1).

C. Cost: Efficient and End-User Affordability

The total cost of the device, including the interfacing board, the electronic components, Raspberry Pi 4B, and sensors, remains restricted to 180 Euros, of which the costs of the interfacing board plus electronics components integrated into, is approximately 50 Euros.

III. Results and Discussion

We have designed and implemented a board interface between the measuring FSR sensor(s) and an embedded system to acquire, pre-process, and transmit the data over the wire.

The system consists of a battery-powered embedded system (Raspberry Pi 4B), a board interface, and FSR sensors. The approach used is the multi-physical layer (MLP) utilizing the board-to-board connections in the z direction. This would contribute to the portability of the system and easy deployment via maintaining the x-y dimension fixed and expanding the height. Consequently, the approach improves the form factor leading to a compact system.

The sensor-board-Raspberry Pi 4B communication is through IIC, which have been originally designed for on-board, short-range communications for efficient multi-sensor deployment supporting high frequency and avoiding the sampling rate drop. The layout design led to removing all wire-based communications between the board and the embedded system in order to preserve this goal and achieve the sampling rate in the range of 250-300Hz. This enables the system to use the data without violating the Nyquist rule for phonocardiogram (PCG) analysis

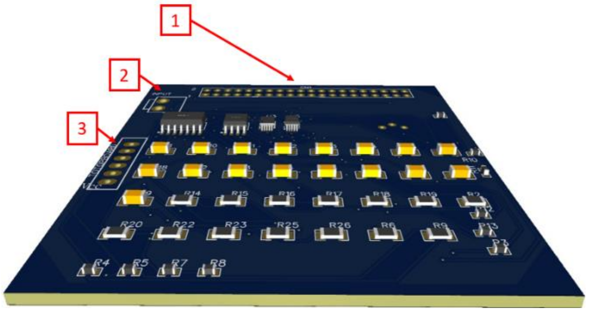

Fig. 1. The sensor board interfaces in two-layer. (1) the shared pins with the Raspberry Pi 4B, (2) the input to the FSR sensor, and (3) the ADC shared pins between the boards.

The sensor board dimension is 70.6 mm × 66.1 mm, which is smaller than the Raspberry Pi 4B with a length dimension of 85.6 mm. The sensor board interface is located on top of the Raspberry Pi 4B through the integrative pins. The total height of the system consists of Raspberry Pi 4B, and board interface is limited to 25 mm.

In addition to sharing the power pins and IIC bus between the two layers, the potential of direct communication between the additional interface board and the embedded system has been anticipated by preserving the sharing ADC pins with each sensor. Thus, the board is expandable up to four board interfaces in the z-direction, extending the height of the whole system up to 55 mm, yet, representing a small box in the dimension of 85.6 mm × 66.1 mm × 55 mm (Figure 2).

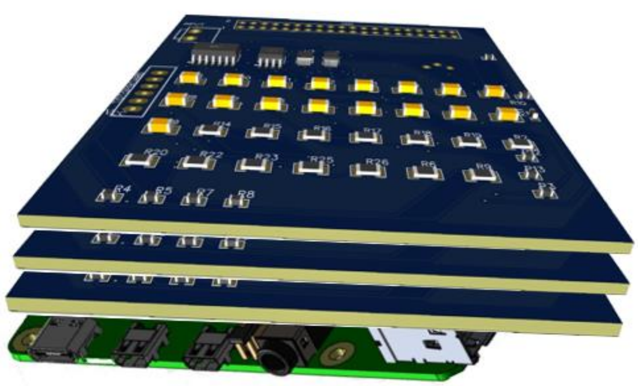

Fig. 2. A schematic of the MPL approach. The battery-powered Raspberry Pi 4B is at the bottom with three additional sensor board interfaces. The approach preserves a compact form factor for easy deployment under the bed frame.

We have already tested the board with one FSR sensor deployed under the mattress and on the bed frame, collecting the data from five subjects in four positions (supine, prone, left, and right shoulder), each for 60 seconds.

The results show that the signal amplitude and signal-to-noise (SNR) have been significantly improved while the form factor of the prototype has shrunk and further advanced.

IV. Conclusion

Using the prototype implemented in this work can facilitate the unobtrusive monitoring of cardiorespiratory parameters using FSR sensors. The prototype supports a low-cost and easy deployment of the sensors under the bed frame for cardiac and respiratory activity measurement, improving the signal quality, sampling rate of up to 300Hz, and a compact and extendable version for further studies.

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