Embedded system for non-obtrusive sleep apnea detection*

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***Abstract*— This document presents a new complete standalone system for a recognition of sleep apnea using signals from the pressure sensors placed under the mattress. The developed hardware part of the system is tuned to filter and to amplify the signal. Its software part performs more accurate signal filtering and identification of apnea events. The overall achieved accuracy of the recognition of apnea occurrence is 91%, with the average measured recognition delay of about 15 seconds, which confirms the suitability of the proposed method for future employment. The main aim of the presented approach is the support of the healthcare system with the cost-efficient tool for recognition of sleep apnea in the home environment.**

***Clinical Relevance*— This approach can be used for continuous non-obtrusive apnea monitoring in the home environment.**

I. Introduction

Humans spend a big part of everyday sleeping. Sleep is unavoidable for the normal functioning of the human organism. To restore our body and brain for daily life, it has to be healthy. However, for healthy sleep, not only the duration of sleep is essential, but its quality [1].

The usual approach for the analysis of sleep behavior is a study in the sleep laboratory. In this case, the overnight polysomnography (PSG) according to the guidelines of the American Academy of Sleep Medicine (AASM) is applied [2], which is very accurate but time and cost consuming procedure. PSG is a golden standard for a sleep study, which includes attaching several sensors to the human body for the measurement, among other things of EEG, ECG, EMG, and EOG signals [3].

Another critical point is that traditional PSG study is typically executed in a sleep laboratory and not in a home environment. Therefore, the continuous observation of a patient at home is almost not possible to organize. For this reason, cost-efficient systems for use in the home environment could support sleep experts in analyzing a sleep quality, even if the accuracy of measurements in a home environment cannot achieve the level of PSG in a sleep laboratory. In [4], a review of actual health monitoring systems using sensors on bed or cushion was done.

Sleep apnea is one of the sleep disorders, which is present by 3% to nearly 50% of the population, depending on sex and age [5,6]. It has different effects on our everyday life; for example, the daytime sleepiness was reported by about 25% of patients with obstructive sleep apnea (OSA) [7]. Fatigue or unrestful sleep was indicated by a higher amount of persons [7].

II. State of the Art

Recognition of OSA is a topic of several scientific publications. Different approaches are presented in the following shortlisting of actual research on this topic.

The sound was analyzed in [8] to recognize the OSA/events. It was processed using Voice Activity Detection (VAD) algorithm, which has measured the energy of the acoustic signal during the breathing and holding the breath. The accuracy of about 97% for the silence phases lasting 15s or longer in the quiet environment using the professional microphone was achieved in the experiment with 50 participating persons.

In [9], the signal from bio-radar placed about 2,5 m from the test persons was used as the input of the system. The wavelet information entropy spectrum is a base for the algorithm implementation. The achieved accuracy for ten participating test subjects was equal to 93,1% comparing to the Polysomnography measurements. In a further research of the same group, they have applied the developed algorithm on the PSG respiratory recordings instead of bio/radar and achieved an accuracy of 96,1% for the detection of apnea events [10].

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Another approach based on the continuous wavelet transform is described in [11]. One of the advantages of this method is a changing wavelet-filter type, which can improve the quality of results depending on different input data. The ECG data of 60 subjects (40 with OSA and 20 without) from MIT databases were used for the training and evaluation of the proposed algorithm. Finally, the accuracy of 86.67% was reached by the researchers.

Further review article [12] presents the list of actual methods for the detection of OSA. Different classes of approaches are described in this paper: based on ECG, based on respiration, based on sound, based on pulse oximetry and based on combined methods.

Notwithstanding that a high amount of researches is existing, the development of a non-obtrusive low-cost system with the possibility of comfortable every day and long-term home use with reliable results is still an actual topic. This is because the available systems have different disadvantages (obtrusive, low accuracy, high costs, not applicable to the home environment, etc.). Furthermore, a combination of hardware and software parts can assure stable and accurate results. In contrast, software systems without hardware components can only process the data obtained and preprocessed by external hardware, which can lead to the loss of accuracy if the signal was previously filtered. Besides, there is no available hardware for obtaining the signal in a non-obtrusive way placing the sensors under the mattress. Therefore, the aim of the proposed in this manuscript approach is to develop an accurate, low-cost embedded system for non-obtrusive sleep apnea detection containing both software and hardware parts.

III. Methodology

One of the development aims was that the described system should work standalone. This means that it includes both hardware and software parts to guarantee that all processes starting from the data acquisition and finishing with the getting OSA detection results can be entirely done within the system without using external hardware. It is one of the unique features of the proposed system, which, together with high accuracy, non-obtrusive, and low cost, should make it suitable for use in the home environment. A signal should be obtained, not depending on the position of the lying person, which necessitates the use of several sensors. These requirements have led to the choice of described in this paragraph approach.

A. Hardware

The hardware part of the system consists of the following elements:

- Computational Unit (Raspberry Pi)
- Analog/Digital Converter
- Amplifier and Filtering Circuit
- Sensors (Force Sensitive Resistors – FSR pressure sensors)
- Cable management

As a prototyping platform, Raspberry Pi 3B was chosen because of its sufficient computational power, small size, low price, and low power consumption. All software processing is running on this device's autonomy. Local Web server is also running on a computational unit for connecting external devices for getting the results of system work.

The analog/digital converter should have a sufficient resolution (at least 14 bit) and support the I^2C interface, which is used in the described system. Another critical point is the availability of 4 channels, which is enough for the aims of the described system. After determining the requirements, the ADS1115 was selected as the analog/digital converter to be used.

An original circuit was developed for the hardware filtering and amplifying the signals obtained from pressure sensors. A passive high-pass filter is used to filter out the frequencies lower than 0,25 Hz so that breathing signals can pass through the filter. A hardware low-pass filter is also implemented in the circuit board to cut all frequencies higher than 10.5 Hz. The amplifying part of the developed circuit board magnifies the signal with the gain factor of 91.

Resistive pressure sensors FSR 406 are used in the proposed system for converting the pressure in an electrical signal.

Figure 1 shows the hardware component structure.

All described above hardware parts of the system due to their small dimensions can be easily placed under the bed structure. Pressure sensors can be placed under the mattress on the bed frame. For this reason, no sensors need to have contact with the body of the user, and all system parts can be hidden

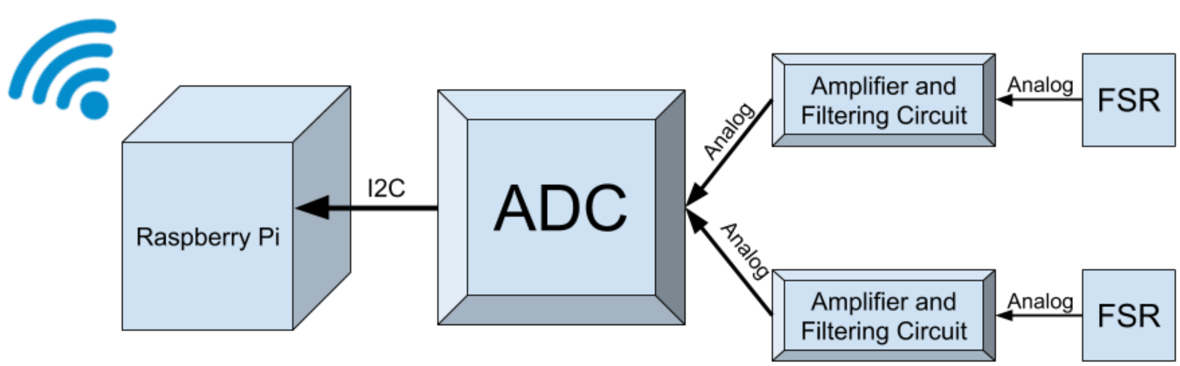

Figure 1. System structure

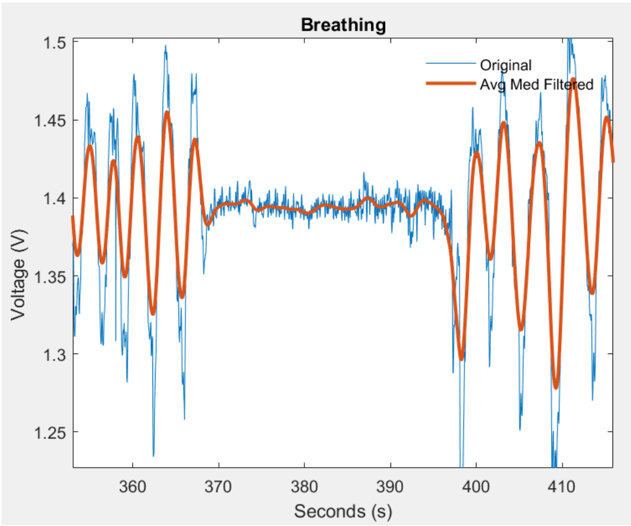

Figure 2. Signal before and after SW-filtering

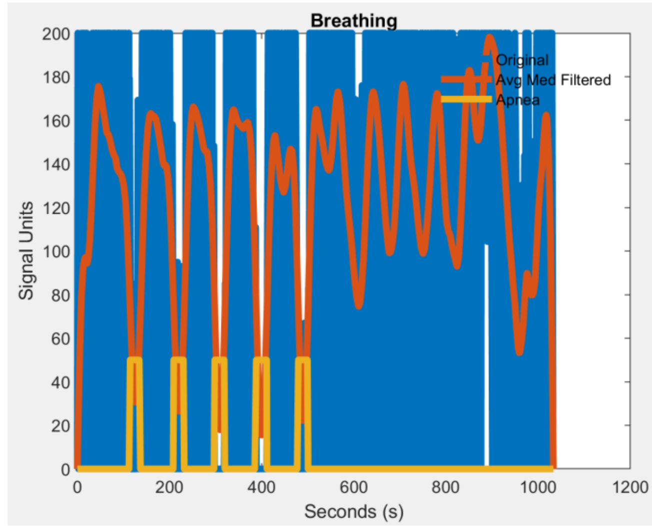

Figure 3. Recognition of apnea events

under the bed. The total retail price of all hardware components is about 85 €.

B. Software

The second central part of the described system is the software for signal processing and visualization of the data preprocessed by hardware. Firstly, the developed software stores obtained from sensors data in a .csv file with a frequency of 25 Hz. As the ADC has four channels, up to 4 signals can be stored in the file for every measurement. The actual timestamp of every signal value is also stored for possible future synchronization with other devices.

Storing the raw data is essential for the flexibility of the system in the case, if other from proposed in this work, signal processing should be applied.

After storing the data, a median filter is applied to remove spikes from the signal. Then, a low-pass filter with a cut-off frequency of 1 Hz has been applied. Different frequencies from 0,7 to 2 Hz were tested with the best results obtained with 1 Hz cut-off.

As soon as the signal is filtered, the algorithm of recognition of apnea events is being applied. For that, firstly, a baseline was found (applying the filter with a big window size); after that, some more filtering (rolling mean filter with the window size of 30 samples) was executed. The next step was to calculate the instantaneous signal power (in this project, we have computed roots of instant power), taking the detected in the previous step baseline for zero. After that, all signal values higher than individually calculated for every signal threshold ("upper threshold") were set to this threshold level to remove the movement signal. Finally, one more iteration of a rolling mean filter with a long window was applied. After the calculation of the individual for each signal threshold ("lower threshold") based on calculated signal power, all values below it are marked as an apnea event.

IV. Results

For the evaluation of system work, a study with 20 (10 males and 10 females) participants was executed. The weight range of the test person was (45–90) kg, and height from 156 cm to 183 cm. The experimental procedures involving human subjects described in this paper have been carried out following the principles outlined in the Helsinki Declaration of 1975, as revised in 2000.

The described system was placed under the bed frame with two sensors placed under the mattress on the bed frame. Participants had to stay 10 minutes in bed, simulating five times the apnea event. Timestamps of simulated apnea were noticed in an experiment protocol, and additionally, a physiological monitor Zephyr BioHarness 3 [13] was used as a reference device.

Figure 2 shows a zoomed-in apnea event recorded by the system before filtering. It is seen when the person stops breathing and then starting breathing again.

Figure 3 represents the recognition of five apnea events (yellow line) for one test person.

A total amount of 100 apnea events with a length of 30 seconds was simulated. The recognition rate of apnea events achieved in this study was equal to 91%, with the average delay of recognition of about 15 seconds, which is due to the fact, that shorter breathing pauses were excluded from recognition to reduce the amount of false-positive recognitions.

V. Conclusion

The achieved so far results (91% of accuracy) confirms the potential of the proposed approach. The level of accuracy is similar to the State of the Art; however, the presented system is based on a new approach and has several significant advantages. The developed prototype includes both software and hardware parts and can be easily placed under the bed. The system is non-obtrusive and can work standalone; the connection to external devices is possible and implemented wirelessly. In this study, only simulated apneas were considered, which is a limitation of the experiment. In addition to apnea recognition, this system could be extended for the general monitoring of respiration. For that, additional filter methods like, for example, continuous wavelet transform, should be applied. The work on this extension is currently being done in our research group. Furthermore, the proposed approach could be used as a part of a system for a sleep study, for example, combining it with the algorithms presented in [14, 15].

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