Sensor-mesh-based system with application on sleep study

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Abstract. The process of restoring our body and brain from fatigue is directly depending on the quality of sleep. It can be determined from the report of the sleep study results. Classification of sleep stages is the first step of this study and this includes the measurement of biovital data and its further processing.

In this work, the sleep analysis system is based on a hardware sensor net, namely a grid of 24 pressure sensors, supporting sleep phase recognition. In comparison to the leading standard, which is polysomnography, the proposed approach is a non-invasive system. It recognises respiration and body movement with only one type of low-cost pressure sensors forming a mesh architecture. The nodes implement as a series of pressure sensors connected to a low-power and performant microcontroller. All nodes are connected via a system wide bus with address arbitration. The embedded processor is the mesh network endpoint that enables network configuration, storing and pre-processing of the data, external data access and visualization.

The system was tested by executing experiments recording the sleep of different healthy young subjects. The results obtained have indicated the potential to detect breathing rate and body movement. A major difference of this system in comparison to other approaches is the innovative way to place the sensors under the mattress. This characteristic facilitates the continuous using of the system without any influence on the common sleep process.

Keywords: movement detection, respiration rate, sleep study, FSR sensor.

1 Introduction

The importance of sleep in human life should never be undervalued. Our daily routine can be positively or negatively influenced by the quality of sleep. Studies show that the recommended sleep duration varies based on personal body attributes and even more – on the age group. However, the amount of sleep alone does not guarantee the good quality of a rest [1]. The identification of the sleep stages and their durations, which present sleep cycles, is also necessary for the accurate evaluation of the quality of sleep.

Sleep can be categorized into stages, which can be ascertained by processing the various electrophysiological signals during sleep. The examples of these signals would be Electroencephalography (EEG), Electromyography (EMG) and Electrooculography (EOG). The brain and muscle activity as well as the eye movements can be captured separately using these measurements [2]. Following the method determined by Rechtschaffen and Kales (R-K) [3] the obtained signals are being analysed to identify, which one of the six sleep stages the body is in.

Rapid Eye Movement (REM) and Non-Rapid Eye Movement (NREM) are the two main categories of sleep stages. About 25% of the sleep typically occurs in the REM stage, while the remaining 75% occurs in the NREM [4]. REM, also known as the dream stage, is the stage where skeletal muscle activity is actively inhibited. The intention of this inhibition is preventing the physical manifestation of activities or movements being executed in the dream. The eye muscles during this phase are engaged in rapid movements under the lids, which causes the name of this sleep stage [5]. NREM can be split in four stages of sleep. The first NREM stage can be described as the transition between being awake and sleep. In other words, it is the stage, where the process of falling asleep occurs. A person in this stage of sleep is still a bit in aware of his or her surrounding and can easily be awakened by sounds or other outside influences. This phase usually lasts about 5-10 minutes [6]. When the second NREM stage is attained, the subject is really sleeping, what means a transition from falling asleep to real sleep is completed. There are some characteristics typical for this stage: a person becomes less conscious of the surrounding, breathing and heart rate become more regular and the body temperature drops. Healthy people spend approximately 50 percent of their sleep in this stage [4]. NREM 1 and NREM 2 conjunct are also known as light sleep. The combination of NREM 3 and NREM 4 is also called deep sleep. Starting in NREM 3 in the brain the delta waves or extremely slow waves appear to be switching with some faster waves. In this stage, core body temperature decreases even more than in NREM 2, heart rate slows down and the blood pressure drops down. During NREM 4 stage only delta waves are produced by the brain. When a person wakes up during these stages (NREM 3-4), the first feelings can be groggy and disoriented [7]. These stages form a sleep cycle that for healthy adults continues 90-120 minutes and then repeats again [8].

Sleep is definitely not a waste of time. Research has demonstrated that the brain remains active during the process of sleep. Very important role in brain process such as memory consolidation and brain detoxification is played by sleep. During the person is sleeping, the brainstem, hippocampus, thalamus and cortex help to consolidate different kinds of memorial [9]. Moreover, during sleep, the glymphatic system detoxifies the brain from toxins that were built up while consuming energy during the day [10]. Understanding how do we sleep and analysing the individual human sleep patterns, can help to intervene and improve the quality of the sleep and consequential the life quality. The lack of sleep can result in many health issues such as migraine, insomnia, hypersomnia and in worst case scenario even death.

Nowadays sleep can be analysed with help of electrophysiological signals in sleep laboratories. Unfortunately, the sleep environment in sleep laboratories is very different from home and feeling being sleeping like at home cannot be reached. This makes it therefore even more difficult to obtain results equal to home-sleeping with high accuracy. In addition, continuous monitoring can be easier executed in home environment. Another important aspect to be taken into account is expense factor. Sleep study in sleep laboratory requires high financial and human resources. Respiration and heart rate, but also body movements are important in determining sleep behavior [11]. Furthermore, monitoring body movement in addition to breathing during sleep can support the detection of apnoea and myoclonic [12]. The aim of this work is to develop an efficient system for collecting information about movement and respiration of a person while sleeping and without any additional physical contact to a person's body such as wearable sensors.

2 State of the art

Sleep study and sleep stage classification as its part have different methods of measurements and further data processing. The most widely used method for measuring sleep patterns is Polysomnography (PSG) [13]. PSG includes: Electroencephalography (EEG), Electrocardiography (ECG), Electrooculography (EOG), Electromyogram (EMG). Some other measurements could also be executed as a part of a PSG session, like e.g. video recording.

There are also other methods used in sleep monitoring apart from PSG. One of researches focused on the current state of the art on this field is [14]. Not only the comparison of presented on the market commercial devices with their properties and application fields was executed, but also the short overview of current researches on the topic of health monitoring systems using sensors on beds or cushion was presented in this paper.

Some methods are based on the use of motion sensors, which measure the body movement – actigraphy [15]. Actigraphy can be worn on the wrist or the hip to record sleep and wake behavior [16]. Actigraphy signals can be analysed with much more details, if they are recorded with a high sampling rate [17]. Then it is possible to derive even respiration from actigraphy recording. In most cases an actigraphy-method, pushes data to a computer after some period of time or even offline. Some other proposing studies work with wearable devices and read time data [18]. The continuous wearing of the devices could provoke the feeling of being permanently in an uncomfortable environment, resulting that these methods have limitations in being used long-term. Combinations of methods are also presented in research. An example is the combination of actigraphy and respiration data [19]. The mentioned sleep monitoring methods cannot provide all data in comparison to PSG as described by R-K Method, but they could provide enough information to diagnose sleeping disorders and classify the sleep stages.

Identifying of some 'non-conventional' sleep stages, such as the pre-wake stage, are also a topic of research [20]. This is important for quantifying drowsiness before and after sleep as well as during the sleep phase. Here, the patient suddenly wakes up. The continuous analysis of everyday behavior is very helpful in such cases for detecting symptoms that might indicate sleep disease syndromes or other health issues.

However, using the established method PSG can be very uncomfortable for long-term observation of the patient, and, it is costly and difficult to setup for non-experts. This is one of reasons of a new research trend using non-invasive sleep study systems. Some of examples of sensors used are: video motion system, radar sensors [21], optical fiber sensors, piezoelectric sensors, load cells and pressure sensors (e.g. resistive) [22]. Piezo resistive, capacitive, piezoelectric or optoelectronic principles are applied to detect pressure. Another type of pressure sensors is the Force Sensing Resistor (FSR) [23] that was used in several researches on sleep analysis. Comparing to the piezoresistive sensors that cannot hold up the value under long-term use, FSR keeps the output value stable. It consists of polymer thick film and interdigitating electrodes; FSR has a resistance value that changes according to the applied force. The typical range of applied force recognized by FSR is from 0.01 kg to 10 kg. The deviation of the measured values is not more than ±2% in this range. The durability test showed that even under high temperature such as 170 °C and a force test applying 5.44 kg over ~1.5 cm^2, the value of the resistance remains in the tolerance range of FSR sensor. In the most of researches, FSR sensor was used over the mattress.

These FSR sensors can recognize sleep postures. One of researches [24] has not only classified in total eight positions, but also has proven a precision of up to 97%. Here, the project goal was to analyse the posture of bedbound patients for the avoiding of ulcers. Because of the high requirements of the system, this research is for categorizing postures. The algorithms for continually detecting bed posture has been developed with the low-cost pressure mat, consisting of pressure sensors.

Not only movements during the sleep, but also changes in respiration and heart rate are important for the indirect classification of sleep stages. [25] demonstrates that pressure sensors can also be used to analyse sleep states; there are used to observe the respiration and body movements. For the respiration signal validation, such parameter as Respiratory Rate (RR) was defined that results in a parameter the Respiration per Minute (RPM) and the number of apnoea, occurred during the measurement period. This number is used for calculation of the apnea-hypopnea index. Furthermore, RR can also be used in calculating of sleep depth and sleep cycles [26]. The dynamics of RR in terms of statistical properties can be exploited in addition [27]. Using the analysis of short-term and long-term correlation as defined by the random walk theory allows the distinction between NREM and REM sleep stages.

The ECG itself, heart rate and heart rate variability can be used to analyse and detect sleep stages [28]. Sleep stages differ in terms of statistical properties of inter-beat intervals of the heart [29]. This had been done successfully and not only sleep stages could be detected but also sleep disorders could be recognized [28]. Some specific sleep disorders are recognized with a very high reliability such as sleep apnoea [30]. For this identification both, heart rate interval analysis and ECG wave morphology such as R-wave amplitude are combined to achieve a high accuracy. Other disorders are certainly more difficult to identify, such as insomnia.

FSR sensors were also used in [31] for measurement of respiration rate and body movements during sleep. 28 commercial FSR sensors are included in the system and a wireless network is built using ZigBee. The real-time communication between FSR and computer is ensured. The developed for this system software contains seven views: (1) the value of sensors using color, (2-4) the output signals from the FSR, (5-7) the average value of fields 2-4. Moreover, this research shows a good result in detecting body movement and respiration rate.

3 System architecture

3.1 Evolution of a system design

The system design of the mesh sensor network described in our approach started with the first version of the system [32] but soon have been revised in both hardware and software architecture. Previous hardware architecture was based on a series of off-the-shelf microcontroller boards which didn't provide many ADC pins but were easy to use and served well as a proof of concept implementation. They were interconnected using an I2C bus with resistor series based address arbitration - addresses were assigned depending on the voltage measured at daisy-chained voltage divider. An Intel Edison board (trademark of Intel) was used as a mesh network endpoint, which served as a communication relay from the mesh network to external service, which recorded data and served as a visualization and analysis tool. The benefit of such system design was simplicity of implementation of each of the components but system as a whole required many hand-soldered boards and wires to connect sensors to sensor nodes. A large number of sensor nodes and an external computing unit was required to collect and process measurement data. To address these issues, a new system architecture was proposed - off-the-shelf microcontroller boards would be replaced with custom PCBs, which would enable the connection of a larger number of sensors. Hand soldered board functionalities could be transferred to a PCB needed as an external computational unit and local data storage and processing has been enhanced. The implementation of proposed changes resulted in a system that is more cost-efficient, easier to install and manage, and it does not require external devices while retaining the feature of large scale integration via an API.

A sensor mesh design is well-suited in this scenario, in case a system requires a large number of sensors, which can be accessed from a single point. When connecting sensors to nodes, a time and processor power consuming task of AD conversion is delegated from an endpoint to the external processors. Now, a horizontal system scaling can be implemented. Attention has to be payed to how this is done. Too granular scaling requires a high bandwidth for the communication channel and increases latency. In contrast to that a conglomerated system requires more complex microcontrollers providing more pins and a higher computational power to process data. The best approach is to tune the system granularity according to the hardware structure of the solution. In this case, a node is placed between two rows of sensors. It supports up to eight sensors in a row and up to 16 in total.

The planned coverage requires three nodes, while total bed coverage requires only six nodes. In comparison to the previous system that required 20 boards. The nodes are still communicating with the endpoint via single I2C but address arbitration is now implemented digitally. Again, this allows easier system scaling and eliminates the need for voltage divider resistor boards. The development platform used to collect measurements now consists of two nodes, each connected to 12 sensors and an endpoint like shown in Figure 1.

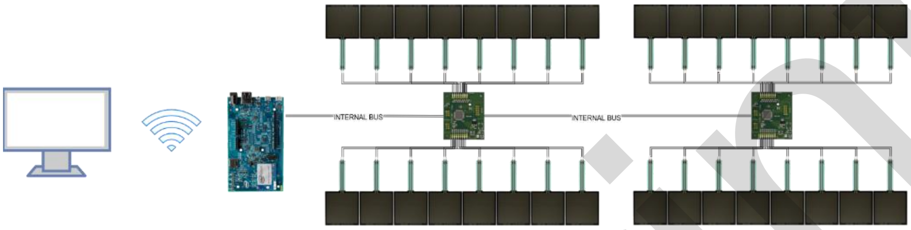

Fig. 1. A new sensor-bed system hardware architecture

3.2 Sensor node implementation

A node is implemented as a small and simple PCB. It features an ATMEL SAMD 21 microcontroller based on 32-bit ARM architecture. The benefit of this exact microcontroller is the large number of 16-bit resolution AD pins and the compatibility with a lot of widely-used frameworks and tools. The node PCB uses resistors required for measuring pressure, internal bus connectors for easy interconnection to other boards, a low noise voltage regulator, programming connector, reset button and micro-USB connector. The sensor connector consists of two pins - ground and voltage input pin. 8 pin pairs are located on each side and they are directly attached to the sensors. Programming and debug connector has a cortex debug pinout and is used to flash firmware images and debug. There are two system bus connectors so that boards can be easily chained together. Power is supplied over a system bus or a micro-USB connector and can be connected only on one node. Figure 2 shows board implementation.

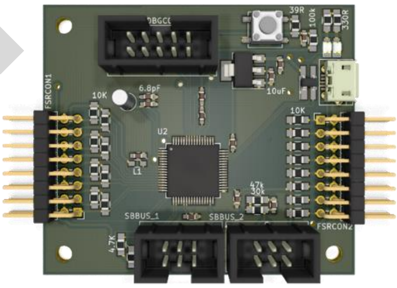

Fig. 2. Node PCB design

The firmware is based on ARM mbed framework and is written in C++. In regular intervals, the node measures voltage value on sensor pins and saves that data in a local buffer. Sample rate can be increased to improve the time resolution or reduced to save power. When a request arrives via a system bus, the microcontroller processes the request and returns the latest measurements. The node can also change its bus address or work with the endpoint to update addresses of other nodes in case the right request is received. The bus itself is based around I2C communication while two pins are reserved for location sense in and sense out. This architecture allows fully digital address arbitration that starts broadcasting from the endpoint node: all nodes reset their addresses and wait for a high signal on sense input pin. When this happens, the node takes the offered address and responds to the bus. After that, the endpoint instructs that node to rise its sense output pin high so that the next node can catch the address. This arbitration algorithm allows users to place boards in any order and for their sensor mesh network.

3.3 Data collection

The data collection is done on the endpoint node. Periodically, an endpoint queries the network for the latest data. Received from sensor values are being stored along their timestamps and node locations in a local database. For the beginning, a relational database was chosen as it offers an easy and fault tolerant option for storing data but it turned out to be a bottleneck: the data storage took longer than the sensors' readouts. Nonetheless, it enabled a systematic access to collected data directly on the endpoint. A custom RESTful API was implemented to allow both external services and a visualization interface to read stored data. The API serves JSON messages and it serves information on current system setup and sensor values; as well as previous values determined by either number of reading and/or timestamp.

The implemented data visualization utilizes the aforementioned API to display a live histogram of current sensor values, historic values for sensors on each node and the heat map of the system. The real-time histogram helps users to detect sensor issues during operation. Past values are available for each sensor, while the heath map shows the 'birds-eye' view of the bed at given point in time.

4 Results

Finally, it was important to prove the system architecture for movement and breathing detection. Therefore, a test-system was setup and several experiments have been executed for its evaluation.

24 sensors were connected to the system under the chest area of the mattress. In a first step, experiments were executed with three test persons in different age groups. Two male and one female persons have participated in study. In total, about two hours were spent in bed by each; simulating sleep in different positions have been recorded.

As sensors are placed like a mesh with about 5cm distance to each other, the signals have differences in amplitudes and they have recorded movements of different parts of body with varying intensity. For simple and clear visualisation at Figure 3, signals from only three sensors are presented. The signal from each sensor is represented with different colour and this visualizes the change of its pressure value over the time.

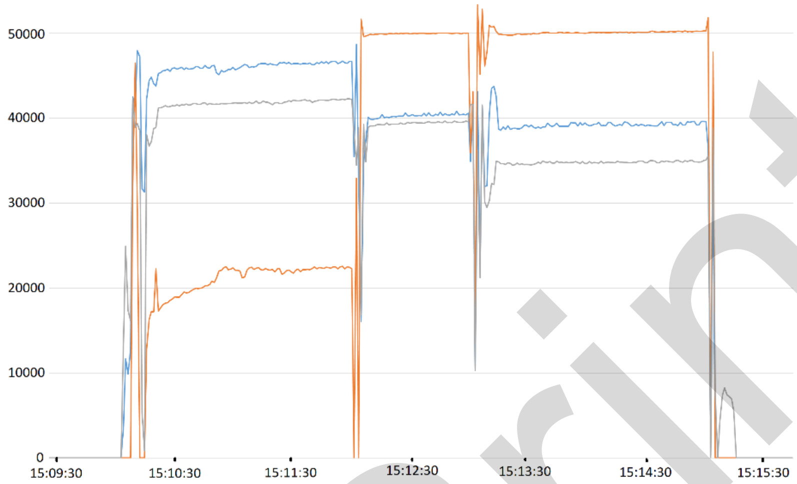

Fig. 3. Signals from 3 sensors

The distance between sensors represented by the blue and orange line is the maximal one, used in experiment. These two sensors were place on opposite vertices of a rectangular sensor mesh. From this figure, it is possible to draw the conclusion that in spite of distances between sensors, all of them can record the signal with a sufficiently high sensitivity for recognizing significant movements.

Figure 4 presents data from just one sensor, placed as the top left element of the sensor mesh. It recorded 7 minutes of an experiment with first sitting on the bed, then lying on it, changing the position and finally getting out of the bed.

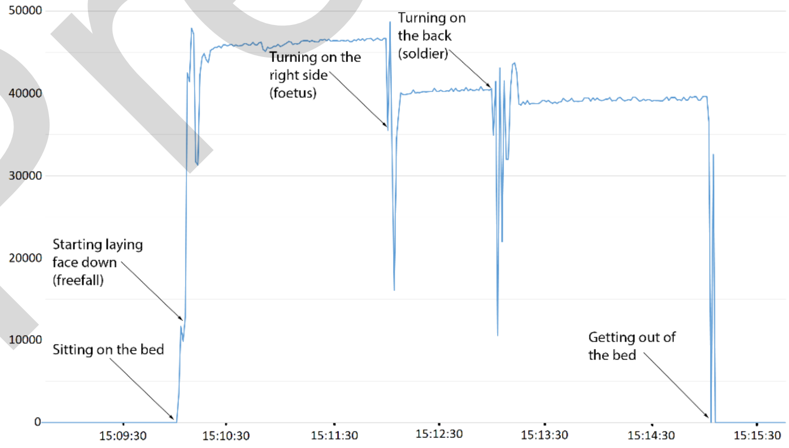

Fig. 4. Test sleep-simulating flow

All movements are clearly recognizable and also the periodical signal can be slightly seen. Figure 5 shows the zoomed-in representation of this periodical signal. It is necessary to mention, that the frequency of signal recording was equal to 1Hz. This is the main reason, why the periodical signal seems to be not very clear and why it is not possible to recognize exact peaks.

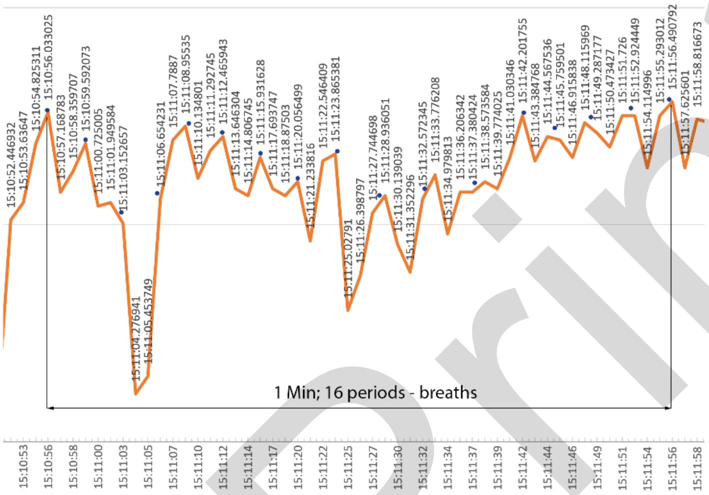

Fig. 5. Zoomed in graph with breathing peaks

As a reference device for evaluating the respiratory rate recognition we used a Zephyr BioHarness - chest belt sensor [33]. Participants have used this device during the test and it shows that the device and the sensors are synchronized with inaccuracy < 0.5s. For respiration rate recognition applied in a sleep study, this is accurate enough, because the data processing will be done for 30s intervals. Figure 6 shows, the Zephyr BioHarness as a reference, zooming on the breathing signal from for the same period, as in Figure 5.

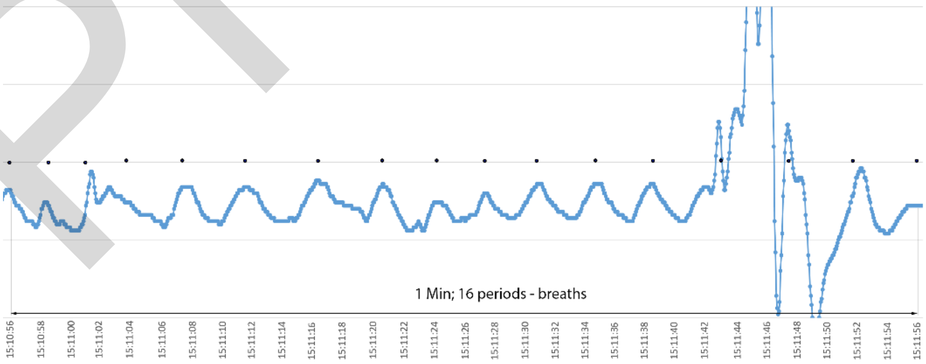

Fig. 6. Reference zoomed in breathing graph from Zephyr BioHarness

The Zephyr BioHarness system uses a different type of sensors and signal processing methods, anf therefore, the visualisations of signals shows some differences. The placement of sensors and distance to the measured object – human chest is playing an important role for the recorded and represented signals. Nevertheless, on both graphs, from the sensor bed system and from the chest belt device, the same amount of 16 periods between peaks can be recognized. Of course movement/speaking/etc. should be taken into account to recognize and classify some rare sleep disorders like parasomnias with sleep walking, talking during sleep, or sleep terrors. Therefore, it is not always possible to clearly detect all peaks on a respiration graph, but even with the inaccuracy of 1-2 breaths per minute it could be acceptable for most cases of sleep studies; as breathing rate variability and not respiration rate itself is more important for the conclusions about quality of sleep or its disorders.

5 Conclusion and future work

The proposed low-cost system enables measurement of different biovital parameters relevant in sleep phase analysis. The system architecture is composed of a grid of pressure sensors integrated in a common bed. It does not provoke any form of discomfort during sleep since the sensors are placed below the mattress and there no sensors are attached to the body. Body movements and respiration signals could be obtained with help of the sensors. As a consequence, the system seems suitable for sleep analysis providing data related to respiration rate and body movements.

Evaluating the system work with the reference device has confirmed that even with a frequency of 1Hz, a breathing rate can be recognized. As next step, a long-time experiment with over the night monitoring will be executed and results will be evaluated. In parallel, work on higher scan frequencies have been already started, This may open the possibility to improve the results and enable heart rate recognition. An intermediate step will be the connection to a sleep stage classification algorithm [2] for performing an experiment at a sleep laboratory, where the results can be evaluated in cooperation with sleep medicine experts. The algorithms will include an analysis of high resolution actigraphy recordings in order to derive respiration as shown in previous studies [17]. The algorithms will make use of the dynamics behavior of respiratory rate [27] and of heart rate dynamics [29]. Combining different features from respiratory rate, heart rate and ECG will improve the analysis further to predict sleep stages and sleep disorders [28].

6 References

1. M. Hirshkowitz, K. Whiton, S. M. Albert, C. Alessi, O. Bruni, L. DonCarlos, N. Hazen, J. Herman, E. S. Katz, L. Kheirandish-Gozal, D. N. Neubauer, A. E. O'Donnell, M. Oha-yon, J. Peever, R. Rawding, R. C. Sachdeva, B. Setters, M. V. Vitiello, J. C. Ware, P., "National Sleep Foundation's sleep time duration recommendations: methodology and results summary," Sleep Health, pp. 40-43, 24 09 2014.

2. A. Klein, O. R. Velicu, R. Seepold, "Sleep stages classification using vital signals recordings," Intelligent Solutions in Embedded Systems, pp. 47 - 50, INSPEC: 15655487, 2015.
3. A. Rechtschaffen, A. Kales, "A Manual of Standardized Terminology, Techniques and Scoring System for Sleep Stages of Human Subjects," U.S. Department of Health, Education, and Welfare, pp. 1-12, 1968.
4. Sleep Foundation, "What Happens When You Sleep?" [Online]. Available: https://sleepfoundation.org/how-sleep-works/what-happens-when-you-sleep. [Accessed 04 12 2017].
5. Sleep Foundation, "How Sleep Affects Brain Function," healthination, 2012. [Online]. Available: https://sleepfoundation.org/video-library. [Accessed 03 12 2017].
6. VeryWell, "The Four Stages of Sleep (NREM and REM Sleep Cycles)," [Online]. Available: https://www.verywell.com/the-four-stages-of-sleep-2795920. [Accessed 28 11 2017].
7. National Institute of Neurological Disorders and Stroke, "Brain Basics: Understanding Sleep," [Online]. Available: http://www.ninds.nih.gov/disorders/brain_basics/understanding_sleep.htm. [Accessed 05 12 2017].
8. Sleep Sync, "What normally happens during a typical sleep cycle?" [Online]. Available: http://sleepsync.com/. [Accessed 01 12 2017].
9. J. Born, I. Wilhelm, "System consolidation of memory during sleep," Psychological Research, pp. 192-203, DOI 10.1007/s00426-011-0335-6, ISSN 1430-2772, 2012.
10. National Institutes of Health, "How Sleep Clears the Brain," [Online]. Available: http://www.nih.gov/news-events/nih-research-matters/how-sleep-clears-brain. [Accessed 02 12 2017].
11. A. Muzet, "Dynamics of body movements in normal sleep," Sleep, pp. 232-234, 1988.
12. Y. Nishida, T. Hori, T. Sato, S. Hirai, "The surrounding sensor approach - application to sleep apnea syndrome diagnosis based on image processing," Systems, Man, and Cybernetics, 1999. IEEE SMC '99 Conference Proceedings. 1999 IEEE International Conference on, pp. 382 - 388 vol.6, ISBN: 0-7803-5731-0, 1999.
13. M. L. Blood, R. L. Sack, D. C. Percy,"A comparison of sleep detection by wrist actigraphy, behavioural response, and polysomnography," Sleep, vol. 20, no. 6, pp. 388-395, 1997.
14. S. Orcioni, M. Conti, M. Gaiduk, R. Seepold, N. Martínez Madrid, “A review of health monitoring systems using sensors on beds or cushion”, Proceedings of international workshop “Smart Future Living Bodensee”, Konstanz, tbp, 2017.
15. J. Hedner, G. Pillar, S. D. Pittman, D. Zou, L. Grote, D. P. White, "A novel adaptive wrist actigraphy algorithm for sleep-wake assessment in sleep apnea patients," Sleep, vol. 27, no. 8, pp. 1560-1566, 2004.
16. Zinkhan M, Berger K, Hense S, Nagel M, Obst A, Koch B, Penzel T, Fietze I, Ahrens W, Young P, Happe S, Kantelhardt JW, Kluttig A, Schmidt-Pokrzywniak A, Pillmann F, Stang A. Agreement of different methods for assessing sleep characteristics: a comparison of two actigraphs, wrist and hip placement, and self-report with polysomnography. Sleep Med 2014; 15: 1107-1114
17. Wohlfahrt P, Kantelhardt JW, Zinkhan M, Schumann AY, Penzel T, Fietze I, Pillmann F, Stang A. Transitions in effective scaling behavior of accelerometric time series across sleep and wake. EPL 2013; 103: 68002
18. O.R. Velicu, N. Martínez Madrid, R. Seepold, "Experimental sleep phases monitoring," IEEE EMBS International Conference BHI, pp. 625-628, ISBN: 978-1-5090-2455-1, 2016.
19. X. Long, P. Fonseca, J. Foussier, R. Haakma, R. Aarts, "Sleep and wake classification with actigraphy and respiratory effort using dynamic warping," IEEE Journal of Biomedical and Health Information, pp. 1272 - 1284, ISSN: 2168-2194, 04 10 2013.

20. M. Baran Pouyan, M. Nourani, M. Pompeo, "Sleep state classification using pressure sensor mats," 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 1207 - 1210, ISSN: 1094-687X, 26 08 2015.
21. O'Hare E, Flanagan D, Penzel T, Garcia C, Frohberg D, Heneghan C. A comparison of radio-frequency biomotion sensors and actigraphy versus polysomnography for the assessment of sleep in normal subjects. Sleep Breath 2015; 19: 91-98
22. Wikipedia, the free encyclopaedia, "Pressure Sensor," [Online]. Available: https://en.wikipedia.org/wiki/Pressure_sensor. [Accessed 29 11 2017].
23. S. I. Yaniger, "Force Sensing Resistors: A Review of The Technology," pp. 666-668 DOI 10.1109/ELECTR.1991.718294, 04 1991.
24. M. Baran Pouyan, S. Ostadabbas, M. Farshbaf, R. Yousefi, M. Nourani, M. D. M. Pompeo, "Continuous eight-posture classification for bed-bound patients," 6th International Conference on Biomedical Engineering and Informatics, pp. 121-126, ISSN: 1948-2914, 12 2013.
25. E. J. Pino, A. D. de la Paz, P. Aqueveque, J. A. P. Chavez, A. A. Moran, "Contact pressure monitoring device for sleep studies," 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 4160-4163, Electronic ISBN: 978- 1-4577-0216-7, 26 09 2013.
26. N. Burioka, G. Corńelissen, F. Halberg, D.T. Kaplan, H. Suyama, T. Sako, "Approximate entropy of human respiratory movement during eye-closed waking and different sleep stages," CHEST Journal, vol. 123, no. 1, pp. 80-86, doi:10.1378/chest.123.5.1323, 2003.
27. Rostig S, Kantelhardt JW, Penzel T, Cassel W, Peter JH, Vogelmeier C, Becker HF. Non-random variability of respiration during sleep in healthy humans. Sleep 2005; 28: 411-417
28. Penzel T, Kantelhardt JW, Bartsch RP, Riedl M, Kraemer JF, Wessel N, Garcia C, Glos M, Fietze I, Schöbel C. Modulations of Heart Rate, ECG, and Cardio-Respiratory Coupling Observed in Polysomnography. Front Physiol 2016; 7: 460. doi:10.3389/fphys.2016.00460
29. Penzel T, Kantelhardt JW, Grote L, Peter JH, Bunde A. Comparison of Detrended Fluctuation Analysis and Spectral Analysis for Heart Rate Variability in Sleep and Sleep Apnea. IEEE Trans. Biomed. Eng. 50: 1143-1151 (2003)
30. Penzel T, McNames J, de Chazal P, Raymond B, Murray A, Moody G. Systematic comparison of different algorithms for apnoea detection based on electrocardiogram recordings. Med. and Biol. Eng. and Comput. 40: 402-407 (2002).
31. S. Lokavee, T. Puntheeranurak, T. Kerdcharoen, N. Watthanwisuth, A. Tuantranont, "Sensor pillow and bed sheet system: Unconstrained monitoring of respiration rate and posture movements during sleep," IEEE International Conference on Systems, Man, and Cybernetics (SMC), Seoul, pp. 1564-1568, Electronic ISBN: 978-1-4673-1714-6, 2012.
32. Gaiduk M., Kuhn I., Seepold R., Ortega J.A., Madrid N.M. A Sensor Grid for Pressure and Movement Detection Supporting Sleep Phase Analysis. In: Rojas I., Ortuño F. (eds) Bioinformatics and Biomedical Engineering. IWBBIO 2017. Lecture Notes in Computer Science, Vol 10209. Springer, Cham, 2017.
33. Kim, J.-H., Roberge, R., Powell, J. B., Shafer, A. B., & Williams, W. J. (2013). Measurement Accuracy of Heart Rate and Respiratory Rate during Graded Exercise and Sustained Exercise in the Heat Using the Zephyr BioHarness^{TM}. *International Journal of Sports Medicine*, *34*(6), 497–501. http://doi.org/10.1055/s-0032-1327661