A Sensor Grid for Pressure and Movement Detection Supporting Sleep Phase Analysis

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Abstract. Sleep quality and in general, behavior in bed can be detected using a sleep state analysis. These results can help a subject to regulate sleep and recognize different sleeping disorders. In this work, a sensor grid for pressure and movement detection supporting sleep phase analysis is proposed. In comparison to the leading standard measuring system, which is Polysomnography (PSG), the system proposed in this project is a non-invasive sleep monitoring device. For continuous analysis or home use, the PSG or wearable Actigraphy devices tends to be uncomfortable. Besides this fact, they are also very expensive. The system represented in this work classifies respiration and body movement with only one type of sensor and also in a non-invasive way. The sensor used is a pressure sensor. This sensor is low cost and can be used for commercial proposes. The system was tested by carrying out an experiment that recorded the sleep process of a subject. These recordings showed the potential for classification of breathing rate and body movements. Although previous researches show the use of pressure sensors in recognizing posture and breathing, they have been mostly used by positioning the sensors between the mattress and bedsheet. This project however, shows an innovative way to position the sensors under the mattress.

Keywords: Sensor grid · Movement detection · Sleep phase · Force resistor sensor

1 Introduction

The average human spends about one third of his or her life sleeping [1]. Depending on how the sleep designated hours are expended, our daily routine can be either positively or negatively influenced. Studies show that the recommended sleep duration varies based on age group. However, the amount of sleep alone does not assure the possibility of a good quality rest [2]. In order to accurately evaluate the quality of sleep, it is necessary to identify the sleep stages and their durations, which present sleep cycles. There exists a difference between falling asleep and being asleep. As a result, sleep can be categorized into stages, which can be ascertained by the use of various electrophysiological signals during sleep. The electrophysiological signals can be for example Electroencephalography (EEG), Electromyography (EMG) and Electrooculography (EOG), which enable the brain and muscle activity as well as the eye movements to be captured severally [3]. The recorded signals follow the method determined by Rechtschaffen and Kales (R-K) [4] to identify which one of the six sleep stage the body is in.

Rapid Eye Movement (REM) and Non-Rapid Eye Movement (NREM) are the two main categories of sleep. About 25% of the sleep typically occurs in the REM stage, while the remaining 75% occur in the NREM [5]. REM, also known as the dream stage, is the stage where the muscles are shut down with the exception of the eye muscles, with the intention of preventing the physical manifestation of activities or movements being executed in the dream. The eye muscles during this phase are engaged in random movements under the lids, which explicates the name [6]. NREM comprises of four stages of sleep. The first NREM stage, known also as light sleep, is regarded as the transition between being awake and sleep. In other words, it entails the process of falling asleep. The person in this stage of sleep is still a bit conscious of his or her surrounding and can easily be awakened by sounds. This phase usually lasts between 5–10 min [7]. When the second NREM stage is reached, the subject is really sleeping, what means transition from falling asleep to sleep. The person not only becomes less conscious of his or her surrounding, but also breathing and heart rate become more regular and the body temperature drops. People spend approximately 50 percent of their sleep in this stage [5]. Last but not least are the third and fourth sleep stages. The N3-4 is also called deep sleep. Starting in N3 the delta waves or extremely slow waves appear to be switching with some faster waves. In this stage our temperature decreases even more, heart rate and the blood pressure slow down. By N4 stage the brain only produces delta waves. When a subject wake up in the stages N3-4, the first feelings can be groggy and disoriented [8]. These stages form a path that is repeated every 90–120 min [9].

Sleep is not a waste of time. As a matter of fact, research has shown that during the process of sleep, the brain remains active. Sleep also aids and plays a very important role in brain process such as memory consolidation and brain detoxification. During sleep, the brainstem, hippocampus, thalamus and cortex helps to consolidate different kinds of memorial [10]. Furthermore, during sleep, the glymphatic system detoxifies the brain from toxins that are built up while consuming energy during the day [11]. Understanding how we sleep and analyzing the individual sleep patterns, can help to improve life quality. Sleep is of uttermost importance, as a lack thereof can result in so many health issues such as migraine, insomnia and in worst case scenario even death.

Having a good night of sleep is important. Nowadays there are a lot of sleep laboratories where sleep can be analyzed with help of electrophysiological signals. Unfortunately, it is not possible to simulate the sleep environment in such a way that patients feel totally at home This makes it therefore even more difficult to obtain valid results, that are high in accuracy. Not only respiration and heart rate, but also body movements are important in determining sleep behaviour [12]. Besides that, monitoring body movement additionally to breathing during sleep can aid the detection of apnea and myoclonic [13] The aim of this work is to find an efficient way to collect information about movement of a patient while he sleeps without any physical impairments such as wearable sensors. This information should aid the analysis of the quality of sleep.

2 State of the Art

Currently there are different methods used for the sleep stages classification. Polysomnography (PSG) [14] is widely used for measuring sleep patterns. PSG includes data such as EEG, that collects the brain activity. Electrocardiography (ECG) is a method that recognizes and measures the small electrical differences caused by the heart muscle on the skin, which results in the electrical activity of the heart over time. Whereas Electrooculography (EOG) recognizes and measures the standing potential that exists between the back and the front of the human eye. These measurements permit the determination of the sleep stage and the behavior of the eyes like REM and NREM. Muscle activity can be recorded through Electromyogram (EMG).

Apart from PSG, there are other methods used in monitoring sleep. Methods like actigraphy involve the use of worn motion sensors, that measure the body motion [15]. The normal actigraphy method send the read data after some period of time on a computer. New studies have shown a new way to work with wearable devices and read real time data [16]. The demand for the continuous wearing of the devices makes the patient uncomfortable, resulting in the practice of these methods being difficult for long term use. They are in general not long term monitoring devices and can only be put into service in designated environments like sleep laboratories. It also remains uncertain if the patient exhibits the same sleep pattern as exhibited in the laboratory while asleep at home. Combinations of methods are also found in several research papers. An example is the combination of actigraphy and respiratory data [17]. The newest sleep monitoring methods in comparison to PSG cannot provide all data as described by R-K Method, but provide enough to classify the sleep stages and diagnose sleeping disorders.

Apart from the conventional sleep stages, research has also been done to identify new stages such as the pre-wake stage [18]. In this stage, the patient suddenly wakes up. An everyday sleep behavior analysis is in such cases very helpful in detecting any symptoms that might point towards sleep disease syndromes and other health issues. Systems such as PSG when used in such a case for the sleep analysis can be very uncomfortable. For this reason, amongst others, there is a trend of new research using non-invasive sleep analysis systems. Examples of such sensors used for this kind of analyses are; piezoelectric signals, video motion system, optical fiber sensors, radar sensors, load cells, textile recording system, pneumatic method and pressure sensor. Pressure sensor as the name implies, works as a transducer for the pressure [19]. Piezoresistive, capacitive, piezoelectric or optoelectronic technologies are examples of sensors that follow this principle. Another important pressure sensor is the Force Sensing Resistor (FSR) [20], which is also used in several sleep studies. Unlike the piezoresistive sensors that cannot hold up the value under long term use, FSR keeps the value stable. Consisting of polymer thick film technology and interdigitating electrodes, FSR has a resistance value that changes according to the applied force. 0.01 kg to 10 kg is the typical range of applied force recognized by FSR. In this range the deviation of the measured values is not more than $\pm 2\%$. As a result of the characteristics of FSR, the durability test showed that even under high temperature such as 170 °C and a force test applying 5.44 kg over ca. 1.5 cm^2, using a 3 mm thick 45 shore with a rubber foot, the value of the resistance still remains in the tolerance range of FSR. Most publications have used FSR sensor between the mattress and the bed sheet to analyze the sleeping posture of the subject while asleep. Developing a pressure sensing bed system, that can automatically provide information about a patient to the caregivers so that the risk of bedsore can be avoided, was one of goals of a study about pressure sensing beds [21].

Further research [22] not only classified 2 more positions, giving a total of 8 position, but also has proven a precision of up to 97%. The goal is to analyze the posture of bedbound patients, so that ulcers can be avoided. As a result of the high requirements of the system, this research has a proposal not only to fill in as one of the until now categorized posture detection system. With a low cost pressure mat, built with pressure sensors, the algorithms for continually detecting bed posture has been developed.

In classifying the sleep state, not only the sleep movements, but also respiration and heart rate are important. A research [23] shows that pressure sensors can also be used to analyze sleep states. This research uses the pressure sensor to observe the respiration signal and body movements. For the respiration signal validation, such parameters as Respiratory Rate (RR) was defined, which is the result of the Respiration Per Minute (RPM) and the number of apneas. This number is used to calculate the apnea hypopnea index. RR can also be used in calculating sleep depth and sleep cycles (SC) [24].

Another research [25] also used the FSR sensor to detect respiration rate and posture movements during sleep. The system contains 28 commercial FSR sensors and a wireless network is built with ZigBee. The communication between FSR and computer occurs in real time. The monitoring software for this project was programmed with LabView. The software contains seven views: (1) the value of using color sensors, (2–4) the output signal from the FSR, (6–7) the average value of field 2–4. A real movement or pressure is acknowledged when more than 10% of the value in a FSR sensor has changed. Moreover, this research shows a good result in detecting BM and RR.

3 System Architecture and Movement Detection Method

Knowing that the system is placed in bed to detect movements in order to support sleep analysis, the system does not present any risk to human health. There is no discomfort, inconvenience, molestation and disturbance incurred by the usage of this system. No skin breakage, no contact with mucosa or any internal body cavity beyond a natural or artificial body orifice. These are some of the characteristics included in the definition of a non-invasive system [26]. The furniture chosen is a bed. It is part of the system and consists of a mattress, bed frame, a slatted frame. The bed frame has an open structure, so that changing the sensors and checking the system does not prove any difficulty. This bed frame has a bed surface of 90 × 200 cm. The mattress has a hardness degree between 1 and 2 to ensure, that the exerted pressure goes straight to the slatted frame.

The sensor used to detect the body movement is an inexpensive rugged force sensor. It is flat, flexible and the force range covers the range pressure of the lying body. An array containing points of pressure detection is built with the sensors. The sensor network consists of n sensors. In order to transfer the data acquired in the sensors, a communication channel is necessary. The sensors' only duty is to receive the data resulting from the body. For this reason, a peripheral component is connected to each sensor so that the data can be read and sent to the main component. To control and synchronize the communication between the main component and the peripheral components, a bidirectional communication system is needed. This bidirectional communication ensures that the main component can send a message to the peripheral components requesting data. This data includes important information like physical position and sensor value.

The implementation of it can be done with a master/slave structure. If the implementation is done by one channel, it is important that not all the peripheral components use the channel at the same instant. The system suggests a master/slave communication, but once the channel communication can receive the data information as described, and can be synchronized, then another technology can be used. As already described, each place where the sensor can be plugged has an ID. This information is very important and the current value of the sensor as well. Moreover, to transfer the information to the main component, the peripheral component must implement the communication protocol in order for the data transfer to be accomplished. Furthermore, the sensor has as an already described interface that is adequate for qualitative force. For this reason, the peripheral component needs an analog input channel, so that the sensor value can be read. If some problem exists with the peripheral component, it should be able to send a signal.

The last component to be described is the main component of the system, which has the task of controlling the complete structure, synchronizing the sensor values, saving the data and sending the data to be analyzed. The idea proposed in this work is an open embedded system. The main component has an integrated system with a microelectronic control used for performing complex tasks, but does not have a user interface. This is the primary definition of the main component. The main component is an open embedded system containing at least a microcontroller with 32-bit and multicore systems that permits the execution of more complex tasks. This is in contrast to the depth embedded system that only has an 8-bit microcontroller and can only execute one kind of task. The main component constraints are the following: limited space, compact and small, no user interface, headless structure and diskless. Following characteristics are important: an instant on with a short boot time, fast power off, non-stop (24/7), and long lifetime system. The main component has Integrated Firmware Image (IFWI) which initiates the boot process, the operation system, root file system and application. It is responsible for the administration of all peripheral component and sending the data out for analysis. Furthermore, the main component determines the protocol for the communication channel and requests the data from the peripheral component.

Aimed towards increasing elasticity and snugness, disk-springs are placed upon the bed frame. The smaller sized disk-springs were chosen intentionally as they are flexible and ensure better distribution of the body weight. The disk-springs are arranged next to each other with the maximum distance between the ends not being more than 3 cm.

The chosen sensor to implement was the FSR 406 from Interlink Electronics.

The chosen hardware to connect the FSR sensor into the system was Trinket Pro 5 V [29], however any other hardware that fits the requirements of the system can be used. A maximum of four sensors can be connected to each Trinket Pro.

Figure 1 shows the overview of the system and the concept of the layout. An extra identification wire consisted of a series circuit of resistors was built, to give the Trinket Pro an ID that can categorize the physical position. The resistor value only influences the current value of a circuit. The system's voltage value stays the same and is divided proportionally as long as the resistance has the same value. If the resistors are not equal in value, the voltage will be divided differently. In order to achieve the best measurement results, FSR sensor has to be adjusted with the right series resistance. Its value depends on the working range of the system. FSR sensor decreases in resistance with the increasing in force applied to the sensor-surface. This applied force is converted into the signal. To define the working range, it is important to determine each of the ranges the force applied to the surface of FSR sensor has.

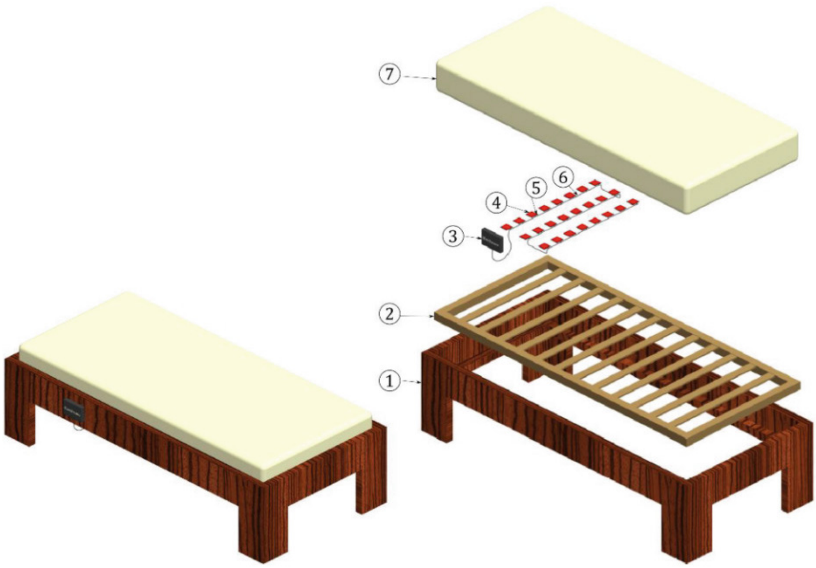

Fig. 1. Overview of the model design system: (1) bed frame, (2) slatted frame, (3) main component, (4) sensors, (5) peripheral component, (6) communication channel, (7) mattress. [28]

Figure 2 shows a hardware overview of the project. It contains 3 main components: Trinket Pro, FSR sensor and Intel Edison. The Intel Edison is the main component of the system. Intel Edison is described as a System-On-Module (SOM), which is used for Internet of Things (IoT) and wearable computing. Intel Edison is based on the dual-core Intel Quark System-on-a-Chip (SoC). A research [30] evaluated some of the important human's body-dimensions. In this research at least 50% of the average case for the dimensions of the human body were put into consideration, a height of 172 cm and a hip area of about 36. The average weight of a human lies between 60–80 kg [31].

To determine the pressure over each FSR sensor, the force applied through the average human $(70\,\text{kg})$ and the mattress $(10\,\text{kg})$ was calculated using the Eq. 1, so that the total force applied is $F = 80.00\,\text{kg} * 9.81\,\text{m/s}^2 = 784.8\,\text{N}$. To calculate the force applied over an area, the average area was calculated with Eq. 2. The total area of human

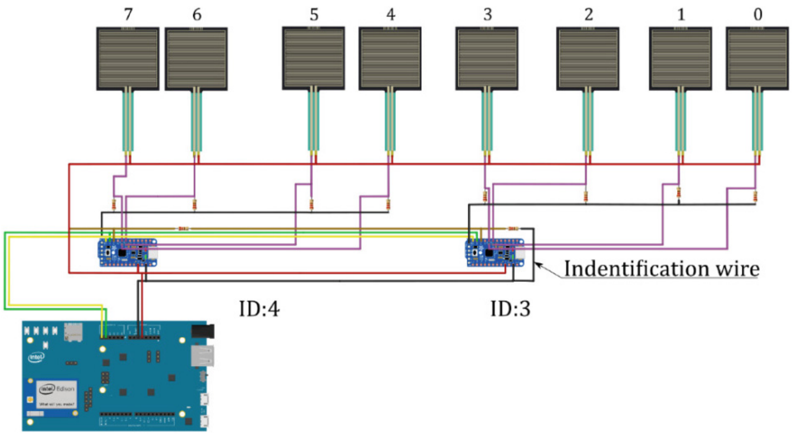

Fig. 2. Hardware system overview

body (Ahb) is $(Ahb = 1720\,\text{mm} * 360\,\text{mm} = 617121\,\text{mm}^2$. Equation 3 was used to calculate the surface pressure (Sp), which results is equal to $0.001271712\,\text{N/mm}^2$. This surface pressure is exerted over the disk-spring. Each disk-spring has cover area of $24500\,\text{mm}^2$ (calculated with Eq. 4), this covered area is the total of the height and width of one disk spring and the half of the area between two disk springs. This area is calculated differently in order to obtain the height and width. The pressure exerted of the area of the disk-spring (Ads), is calculated with Eq. 5. The applied force for a disk-spring Fds, is $Fds = 0.001271712\,\text{N/mm}^2 * 24500\,\text{mm}^2 = 31.15693681\,\text{N}$. The weight over each disk-spring is 3.176038411 kg. Each spring has four pressure recording point, so that the total pressure over a disk-spring can be dived into four. The result is the amount of pressure over one sensor, which is equal 0.80 kg.

$$F = m * g \tag{1}$$

$$Ahb = height * hip \tag{2}$$

$$Sp = \frac{\text{F}}{\text{A}_{\text{hb}}} \tag{3}$$

$$A_{sd} = h * w \tag{4}$$

$$d_s = S_p * A_{ds} \tag{5}$$

As an example based on the graph in Fig. 3, if the system requires a force range of 800–1000 N, the measuring resistor (RM) should be chosen as 10 kΩ or 3 kΩ, because the gradient of this function is the highest in this range.

Figure 4 shows a measured sensor curve with no outlier, where the gradient in the working range is high enough to use it as a calculation base to determine the right RM.

Knowing the Eq. 6 and the Parameters *RM*, *V+* and *Vout* it is now possible to calculate the *RFSR* curve. The result can be seen in Fig. 5.

$$V_{out} = \frac{\mathrm{R_M} * \mathrm{V_+}}{\mathrm{R_M} + \mathrm{R_{FSR}}} \quad (6)$$

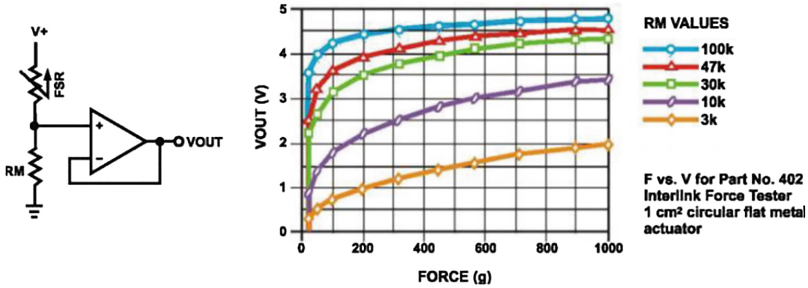

Fig. 3. Voltage divider and FSR curve depended on RM values [32]

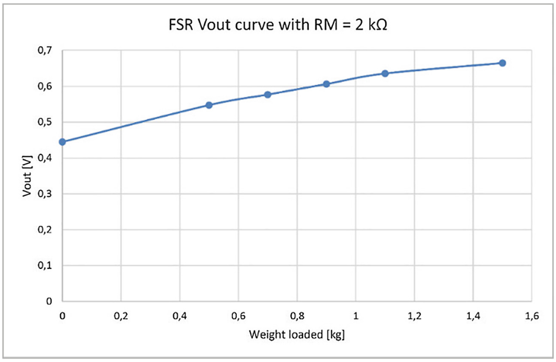

Fig. 4. FSR V_{out} curve with RM = 2 kΩ

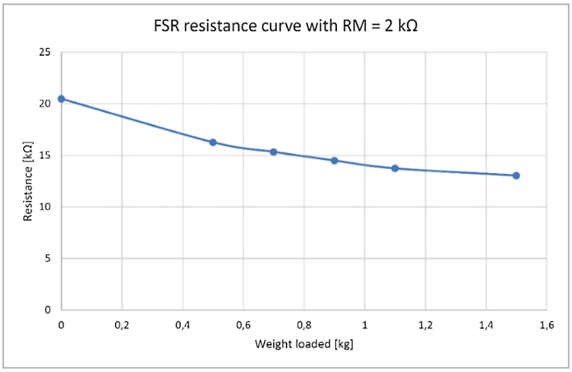

Fig. 5. FSR resistance curve with RM = 2 kΩ

4 Application of System and Results

The sleep test has been carried out with different types of resistance in the Ubiquitous Computing Laboratory. The candidate for the study is a 31-year-old male in good health and with a normal Body-Mass-Index. 20 min of his afternoon nap was recorded in order to be analyzed. Despite the fact that he carries out very little movement during sleep, at least three movements can be identified on the Fig. 6 below.

The first movement happened as he fell asleep. Between 15:44 and 15:45 the candidate scratched his nose. The second movement was very subtle, it was the moment he woke up between 16:59 and 16:00, the third movement shows the time the candidate got out of bed. Compared to the first and second movements where the body does not get up from bed, the last movement showed radical differences in value.

The respiration can be recognized in different times and in different sensors. Previous re-search shows that depending on the subject's position, a particular sensor may be best at recording the subject's respiration movements than others. In this case the left end of the bed was the sensor A7, followed by the A6, A5, A4, A3, A2, A1 and A0 on the end of the bed. All sensors showed recordings of his breathing, but because the subject is lying on his back at the center of the bed, the best rates of breath are in the sensors, A4, A3, A2, A1. To calculate a breathing cycle, it was taken into consideration that an adult breathes between 11–15 times per minute and that inspiration time is shorter than the expiration time [27]. Figure 7 shows four consecutive breathing. By the continuous repetition of the respiration rate cycle, it is assumed that this is the respiration-movement pattern. However, this must be verified by a second device.

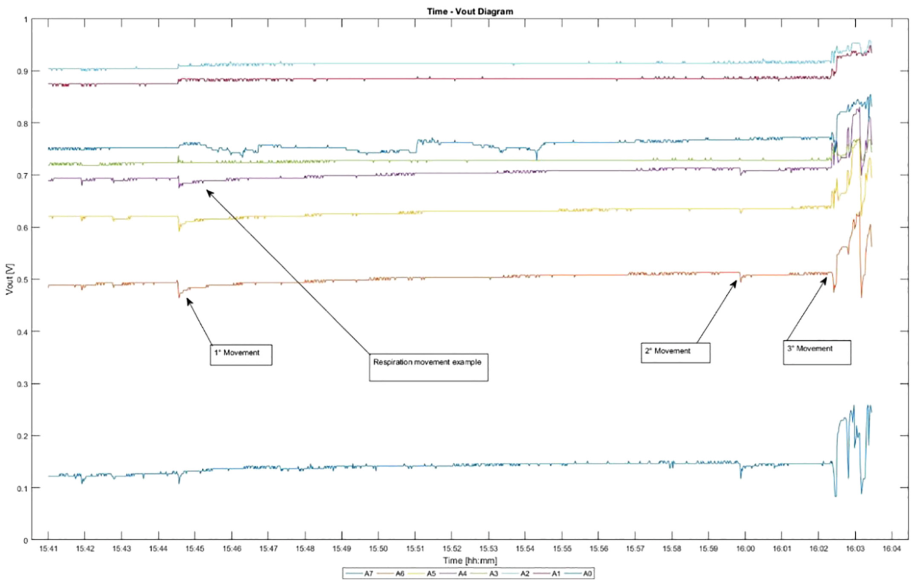

Fig. 6. Time - V_{out} diagram: A7; RM = $0,5\,\mathrm{k}\Omega$; A6; RM = $1\,\mathrm{k}\Omega$; A5; RM = $1,5\,\mathrm{k}\Omega$; A4;\, RM = $2\,\mathrm{k}\Omega$; - without felt gliders. A3; RM = $0,5\,\mathrm{k}\Omega$; A2; RM = $1\,\mathrm{k}\Omega$; A1; RM = $1,5\,\mathrm{k}\Omega$; A0; RM = $2\,\mathrm{k}\Omega$; -with felt gliders

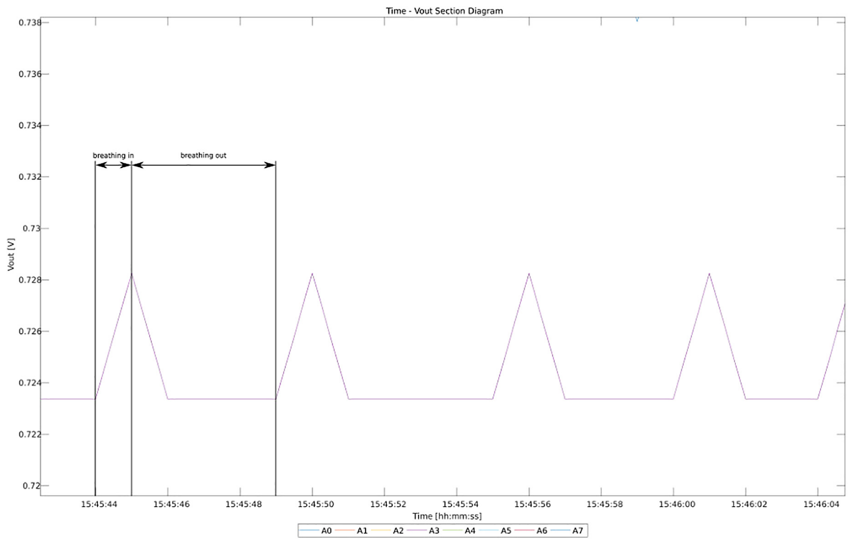

Fig. 7. Time V_{out} section diagram from Fig. 7

5 Conclusion and Future Work

The proposed low-cost sensor grid for pressure and movement detection showed that different parameters for sleep phase analysis can be measured. In addition to that, it proved to be a system that neither come in contact with the subject nor initiates any form of discomfort during sleep. It was demonstrated that FSR sensor is very useful tool in obtaining body movements and respiration signals. This result indicates that the system is well suited for supporting sleep analysis by providing data concerning the following activities carried out during sleep: respiration rate and body movements. The integration of the sensors under the mattress gave a new perspective on how a system is implemented for sleep analysis. At the moment various sleep recordings has been obtained from the same subject and compared using an algorithm. This confirms the extraction of respiration signals and body movements through FSR sensor. Moreover, the system is completely scalable and can be transferred to any bed of the same kind. The designed system shows a promising result with successful validation.

Future work would include a connection to the sleep stage classifier, working with a sleep algorithm [3] that provides a sleep stage classification and a sleep quality analysis. Furthermore, a development with FSR sensor should enable the monitoring of blood pressure and heart rate. To achieve it, further researches of optimal sensor grid topology are necessary. Using the described system as a base for the apnea-recognizing system could be also one of topics for further researches.

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