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Enhancement of sensor mesh functionality with application on sleep tracking

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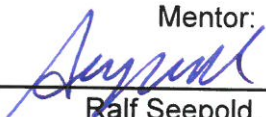
Title: **Enhancement of Sensor Mesh Functionality with Application on Sleep Tracking**

Description:

The focus of this project is enhancement of functionality, reliability and sensor accuracy of an intelligent bed that monitors human sleep. The scope of the project includes the implementation of an application layer protocol and network communication between the embedded system in the bed and remote server. Furthermore, the implementation possibilities of data preprocessing, filtering, and automatic sleep analysis are explored and tested. The system is tested and evaluated in the Ubiquitous Computing Laboratory at the Hochschule Konstanz University of Applied Sciences.

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1 Introduction

To help readers get better acquainted with the topic, introduction is divided into four sections. First section covers general motivation and relevance of the project. Next section describes state of technology, market and consumer trends at the time this thesis was published. The following section lays out project goals and defines the scope they will be tackled on while in the last section, project structure is outlined so that readers can easily navigate through this thesis body.

1.1 Motivation

Sleep is seemingly a trivial thing - from the moment that they are born, all humans have a need to sleep. It is a natural function in the same way breathing and other vital body functions are. Having slept for adequate time and with good quality tends to make people feel good and have more energy performing their daily tasks. When a person did not sleep well or did not sleep enough it will usually negatively reflect both on their body and their behaviour. National Sleep Foundation along with multi-disciplinary expert panel recommends sleep time for each age group ranging from 14 to 17 hours daily for newborns to between 7 and 8 hours for older adults[1]. Sleep deprivation effects motor and cognitive abilities as well as mood but these effects can also occur in cases of bad sleep quality regardless of the sleep duration[2]. That same sleep quality is influenced by many factors ranging from physical ones such as sleeping environment and position to subjective ones such as emotional state and dreams. As clear separation of these factors is rarely possible, most of the researches relied on the isolation of influences comparing results between large control and influenced groups. Sleep quality is then usually determined by questionnaires and data analysis which result in quantitative results such as Pittsburgh Sleep Quality Index[3].

To accurately and consistently determine sleep quality, sleep is divided into 4 stages. First stage is called N1 and is a transition between awakesness and sleep. Person is still conscious and aware of surroundings. Duration of this stage is usually between 5 and 10 minutes. The second stage is called N2 and is categorized by a steady breathing and hearth rate as well as with a drop in body temperature. This stage occurs multiple times during sleep and totals for around 50% of the time spent sleeping. Together these categories can be classified as light sleep. Stages N3 and N4 can be categorized as a deep sleep as it becomes harder to wake up a person from these stages. They can be recognized by further temperature drop, lower blood pressure and by delta waves¹ emitted by the brain. Sleep state can also be categorized as Non-Rapid Eye Movement (NREM) or Rapid Eye Movement (REM). REM phase usually occurs only after an initial stage of deep sleep. It is a phase in which dreams occur whilst eyes move

¹High amplitude brain waves with a frequency of oscillation between 0.5 and 4 Hz.

quickly in different directions with heart and breathing rate becoming irregular. To prevent a person from waking up, muscles and senses below the neck become inactive. REM phases alternate with light and deep sleep stages and tend to become longer with each alternation. Adults with a healthy sleep habits spend 20% of time asleep in a REM phase while this percentage becomes lower with age. Typical alternation of sleep stages during sleep is shown in 1.1.

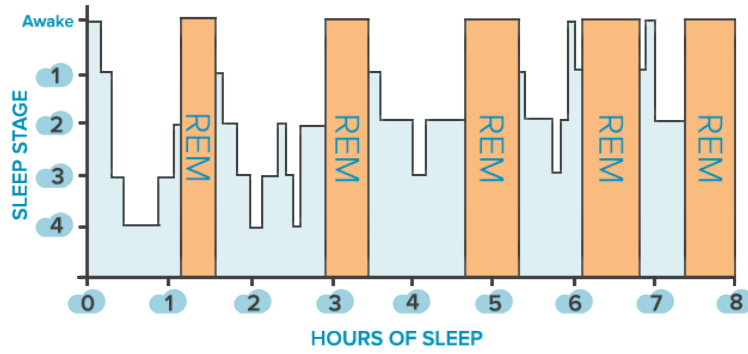


Figure 1.1: Sleep phases during typical 8 hour sleep.

As it is impossible to track these sleep phases personally, a variety of measurement devices is used in a study called Photoplethysmography (PPG). This study involves continuous or periodical measurement of physical parameters. Electrophysiological measurements are done with the help of Electroencephalography (EEG), Electromyography (EMG) and Electrooculography (EOG). Drawback of using these methods is requirement of complex equipment, knowledge to evaluate the results and controlled environment which is why these measurements are usually done only for clinical or research purposes. But simple sleep monitoring can be done using much simpler processes - with heart rate, body movement and position tracking. Unlike before mentioned method these measurements can be done unobtrusively and in home environment. Improving the process and accuracy of these methods and improving correlation of collected results to the real sleep parameters may lead to much easier diagnosis of sleep disorders. Furthermore, availability and accessibility of this technology will encourage larger number of people to monitor their sleep performance which may lead to better mood, efficiency of executing daily tasks and sport results. This thesis will primarily focus on proposing a non-obtrusive way to track both sleep time and quality with a proposal of technology and measuring methods.

1.2 Technology and current consumer market trends

In the recent years, the market for sleep and fitness tracking devices has been expanding with the support of almost all major smartphone manufacturers. Some new brands specializing in the making of such devices have also emerged and have been steadily gaining the market share. Most of the devices that are currently used for consumer sleep tracking are actually multifunctional devices such as smart watches, armbands and rings. Beside sleep, they usually track physical activity, pulse and show time or provide some other information. Smart watches are additionally customizable as they usually

allow for installation of third-party² applications. This versatility makes such devices very attractive to the customer regardless of sleep tracking and monitoring quality built into the devices. To paint a better picture, in 2014 Dr. C. Winter compared a few of the most popular sleep tracking armbands to the polysomnogram[4]. His results are showing that most of the devices, regardless of their cost, were able to distinguish between awakeness and sleep which allowed them to measure the time spent sleeping. Unfortunately, they were not able to separate REM, N1, N2 and N3 sleep phases or estimate the time spent dreaming. Some devices provided estimate if a person was in a deep or light sleep but the results were mostly inaccurate. In late 2016 J. Yoon tested newer iteration of the consumer devices and the results(1.2) show improvement of the deep or light sleep phase detection but devices are still not accurate enough to guess the real sleep phase with an acceptable degree of certainty[5].

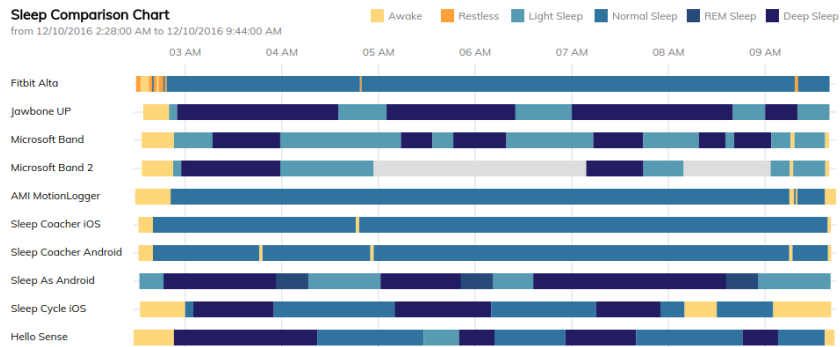


Figure 1.2: Sleep detection comparison between consumer devices

The reason for inaccuracy of consumer on-body sleep tracking devices is the underlying technology. Microelectromechanical systems (MEMS) sensors are used for movement tracking for actigraphy³ and simple photo sensors are used for PPG which gives an estimate of pulse frequency. Most of the devices are designed in such a way that they are non-obtrusive, small, easy to use and nice looking. This means that batteries powering sleep monitoring devices must be small and device usage should be minimized to maximize the battery life. This is achieved through the use of low power microcontrollers, through updating movement sensor data in an interrupt routine which wakes up the microprocessor when a movement occurs and through minimizing the number of readings done by the PPG sensor. This, of course results with the inability of devices to categorize sleep phases with acceptable certainty and most manufacturers categorize sleep as just light or deep.

Contactless consumer devices that are specialized for sleep tracking and monitoring are newest to the market. They are using sound to detect breathing and body movement through the night. Depending on the product they can also measure light for easier start of sleep detection. Since smartphones also have microphones and light sensors, multiple applications which analyse the sleep are also present on the market. This method is favorable in some cases because it eliminates the need for a device touching the subject. But what it gains in practicality, this method lacks in accuracy as sound and light sensors are easily disturbed by the events present around the sleep environment. This

²Not provided by the original manufacturer

³a non-invasive method of monitoring rest and activity cycles where a device worn by subject records movements

method has also a problem of distinguishing multiple sound sources eg. multiple people sleeping in the same room.

1.3 A poll on perceived influence of sleep and usage of sleep tracking devices

Young adults are an age group with the most early adopters of new technologies. In general and due to the lifestyle, they are likely to have suffered from short term or long term sleep deprivation. Getting the best sleep quality with the minimal time spent sleeping can be a beneficial factor to the outcome of the exams and handling of stressful tasks. A poll was conducted between peer students at the University of Zagreb with a goal to analyse the perceived influence of sleep and usage of sleep tracking devices in that group. It should be taken into consideration that the total number of poll participants is *12345125* and they are localized both geographically and by social group. Therefore the results will be compared to other polls and researches which include more data in both quantity and diversity. In case that no data on the subject was found, a result from this poll will be used but this will be noted in the text.

Conducted poll results show that majority of students are on average getting ***7 hours*** of sleep daily which is quite close to the ***result*** determined by the NSF[1]. For relative majority of ***PERCENT*** this amount of sleep is adequate to their needs. To get a perception what influences their sleep, they were asked if sleep duration, sleep environment⁴ and external conditions⁵ influence their sleep quality. The results show that much bigger percent of participants perceives that sleeping environment and external conditions impact the quality of sleep compared to pure duration of the sleep. A vast majority of poll participants (***PERCENT***) indicated that they would like to have an insight into their sleep but most of the participants indicated that they are not certain if that data would actually improve their sleep quality.

PERCENT of participants are familiar with sleep tracking devices and only ***PERCENT*** have used a non obtrusive sleep tracking device. Out of all poll participants, only one has tested its quality of sleep using clinical methods such as EEG, EMG or EOG. As widely available sleep trackers are still quite new to the market, all of the participants owning a sleep tracking device have been in a possession of it for less then a year. Also, all of the participants that own a sleep tracking device indicate that they check their sleep quality on a weekly basic or more frequently and that data received from the sleep tracking devices has helped them improve their sleep quality. A majority of ***PERCENT*** of that group indicates that they would like to have an even more precise and detailed device to track their sleep.

1.4 Goal and scope

This thesis will try to describe a novel implementation which will track sleep for both clinical and consumer purposes improving on the quality of tracking and simplicity of use over the currently available solutions. Proposed solution is based on a pressure

⁴eg. bed quality, sleeping garments

⁵eg. temperature, humidity, pressure, noise levels, moon phases

sensor mesh network which is placed under the mattress and which tracks the movement and vital signs of the sleepers. It continues on the previous work done at Ubiquitous Computing Laboratory (UC-Lab) at Hochschule Konstanz für Technik Wirtschaft und Gestaltung (HTWG) and enhances it by providing system architecture, hardware and software required to achieve a goal of precise contactless sleep tracking. Thesis also proposes an interface that can be used to collect and analyse acquired data and will serve as a stepping stone for the future research.

Hardware is designed in such a way that it allows an easy installation and so that all of the components are widely available and easily replaceable. Thesis describes design decisions in detail with the proposal of future improvements in terms of features, reliability and precision. Embedded software setup is based on open-source solutions which are not tied to a specific platform which means that an end product may use the same software albeit possible changes in hardware. Application software provides user interface for analysis of data but also provides an Application Programming Interface (API) which allows other services to access the data in a standardized way. Together the whole system will allow recording, tracking and analysis of sleep data and will be tested in a suitable environment.

In this scope, reader will be acquainted with the process of design and implementation of such a system. Problems regarding communication between sensor nodes, endpoint data collection and graphical data display will be described in detail. Thesis will also present and give an insight into the results of how system functions. Possibilities for implementation of preprocessing, filtering and automatic sleep analysis will also be presented. What will not be in focus of this thesis however are the medical aspects of sleep recognition and sleep stage classification. They will be considered and reviewed, as they are critical to the functional aspect of the project, but they remain to be described and analysed in a future research to which this thesis will hopefully serve as a technological foundation.

1.5 Thesis outline

Before the new system design is proposed a current one found at UC-Lab will be presented and reviewed. Current system design decisions will be shown along with the implementation based details in chapter 2. Focus in chapter 3 will be on implementation of a mesh network nodes that will serve the purpose of data collection from the sensors. It will present design considerations and decisions that led to the final product. Details on an embedded system serving as an endpoint will be described in the chapter 4. In it a part of application software which takes care of communication between the endpoint and sensor nodes will also be described. In chapter 5 it will be shown how data is stored and displayed and how it can be used by other services. Measurement results will be shown in the chapter 6 after which a conclusion will be drawn in chapter 7.

2 Evolution of system design

To track sleep unobtrusively, multiple techniques and sensor types have been tested and evaluated by other researchers. Placing load cells under the bed supports allowed researchers to determine the precise time when subject fell asleep and when subject woke up[6]. Infrared camera recording of subjects sleeping allowed precise recognition of small movements even under the blanket [7]. Another research group used Plastic optical fiber (POF) sensors to recognize breathing patterns and detect apnea[8]. The same results were also achieved using pneumatic pressure sensors placed in a sealed air-cushion under the mattress[9]. In yet another research, a group of researchers conducted experiment in which they placed two $24GHz$ radars under the bed and found out that it is even possible to accurately recognize hearth rate[10].

But one of the recently most popular methods of unobtrusive sleep tracking is much simpler and more affordable than others. It is called pressure sensing and involves continuous measurement of pressure from under the subject. This thesis picks up on the work of Prof. Dr. Ralf Seepold, Raína Kuhn, Daniel Scherz and Maxime Guyot at UC-Lab[11][12] who have successfully used pressure sensors to determine position, detect movement and track vital signs during sleep.

2.1 Devices and technology

To achieve a good sleep tracking from pressure readings under the bed, an appropriate environment has to be selected. Environment consists of an adequate bed frame, a mattress and of base-plates which hold the mattress in the frame of the bed. Bed frame is of a regular size - $90 * 200cm$ which accommodates vast majority of people. Because of good pressure propagation mattress should not be too firm or too tight. Therefore mattress of uniform hardness level 2 has been selected.

To hold the mattress in place, a grid of pressure-disks is used. They are critical part of the system as they have to absorb the pressure from the mattress. Also, they are a point where pressure measurement can be done. To provide a better granularity, a pressure-disks provided by ErgoProTech and depicted in Figure 2.1 was used. They were placed 3cm from each other and under the whole area of the mattress according to the manufacturers usage recommendation. This ensures adequate support across the mattress. For selected mattress size, base-plate grid consists of 12 rows and 5 columns totaling in 60 pressure-disks. Pressure-disks are made of semi-elastic polymer and consist of 4 connected rectangular pads. These pads are supported by 4 double arms anchored at the same point where the whole structure is connected to the bed frame. There are multiple hardness levels of base plates and they are differentiated by the color of the rectangular pads. Firmer base plates are grey while more elastic ones are purple. More about placement of pressure-disks can be found in section 2.2

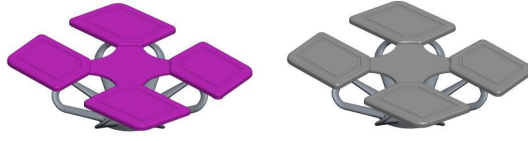


Figure 2.1: Base plates in the bed.

There are multiple types of pressure sensors that could be used for the purpose of this project[13]. Potentiometric pressure sensors are very crude due to their construction and often have reliability and hysteresis issues. Inductive pressure sensors require Alternating Current (AC) excitation of coils and consequentially signal filtering and demodulation. Piezoelectric and piezoresistive pressure sensors measure change of pressure using piezoelectric effect. Capacitive pressure sensors use a small diaphragm as a capacitor plate. When pressure is applied, diaphragm deflects and capacitance changes. Change may or may not be linear and usually is on the order of a few **pF!** (**pF!**) while total capacitance of the sensor is between 50 and 100pF. This means that it may be hard to precisely measure the values and this method may also suffer from environmental effects and Printed Circuit Board (PCB) or protoboard design. Force sensing resistor (FSR) is a type of material whose resistance changes when a pressure is applied. Advantages of FSR sensors over other pressure sensor are possibility of detecting static pressure, its flexibility, thinness and inexpensiveness. Multiple other researches were made used the same type of sensor and have proven its reliability and accuracy when used in a sensor grid[14][15][16]. Therefore, this type of sensors was selected for use in this specific project.

So how does the FSR sensor work? FSR is a Polymer Thick Film (PTF) device which exhibits a decrease in resistance with an increase of the force applied to the active surface[17]. At 'zero force', conductive ink is separated from the active area by spacer adhesive and in that case FSR sensor has the highest possible resistance. When pressure is applied to sensor, conductive layer is pushed down on the active area which results in a decrease of resistance. Construction of FSR sensor is provided in 2.2. For a hemispherical sensor with a diameter of 12.7mm (model 402) sensibility starts just below 20g and extends to around 10kg when saturation occurs. Passing a threshold at 20g, resistance changes from greater than 100k Ω to 10k Ω . After that resistance falls logarithmically with an increase of force as seen in 2.2. For consistent results application manual[17] suggests using a firm, flat and smooth mounting surface and use of a rubber spring to spread the pressure over the whole sensor. Also, an appropriate sensor size and shape is to be used.

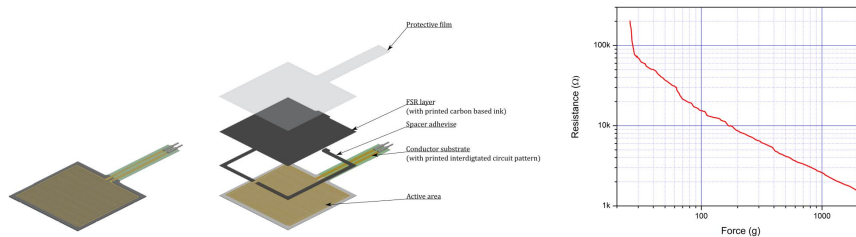


Figure 2.2: FSR sensor construction and resistance characteristics.

There are 4 different types of standard of-the-shelf sensors[17] and their sizes and shapes are shown in Table 2.1. Models 400 and 402 also have short-tailed variants which feature shorter connection between FSR pads and pins found at the end of the lead wires. These same models have a small pressure sensing surface and are not as well suitable for this project. Models 406 and 408 have much larger contact surface area, which means that a more consistent distribution of pressure is possible. Model 406 is perfect for use in areas that require good position resolution such as scapular area. On the other hand, type 408 can be used in crural region.


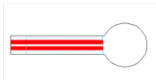


Part number	Description	Part image
Model 400	0,2" circle	
Model 402	0.5" circle	
Model 406	1.5" square	
Model 408	24" strip	

Table 2.1: Standard shapes and sizes of FSR sensors offered by Interlink Electronics.

To get a reading of sensor resistance (R_{fsr}), a sensor is connected in a series with a fixed value reference resistor (R_{ref}). Then, an input voltage (V) is applied to the circuit. Voltage drop (V_{fsr}) is measured on the FSR sensor leads. Pressure applied to sensor is in a reciprocal correlation to the R_{fsr} because FSR has a maximal resistance when there is no external force pressuring its surface as seen in Figure 2.2. The same graph is also sampled for force-resistance pairs which are used for reference resistor selection. R_{fsr} needs to be selected in such a way that it has best resolution for force between $0kg$ and $1.6kg$. These weight values were selected based on R. Kuhns calculation[11]. She took an average weight of a person and mattress and calculated an estimate of how much weight each of the disk springs carry. Equation 2.1 describes the relation between V_{fsr} and R_{fsr} when a R_{ref} has a fixed value. Multiple standard resistor values were put into the equation and at resistance of $10k\Omega$ change gradient was highest. Therefore, $10k\Omega$ resistor was used as R_{ref} .

$$V_{fsr} = \frac{V * R_{ref}}{R_{fsr} + R_{ref}} \quad (2.1)$$

Initial sensitivity tests that were conducted by R. Kuhn and M. Guyot showed that additional layer should be added on top of the FSR sensors to help with pressure absorption. In Figure 2.2 it is clearly visible that adhesive spacer layer creates a non-sensitive frame around the active sensor area. When sensor surface was directly exposed to the mattress, adhesive absorbed most of the pressure as it was not as elastic as active area. This was solved by using felt¹ gliders. This greatly improved the sensitivity and the results can be seen in Figure 2.3.

¹textile material that is produced by matting, condensing and pressing fibers together.

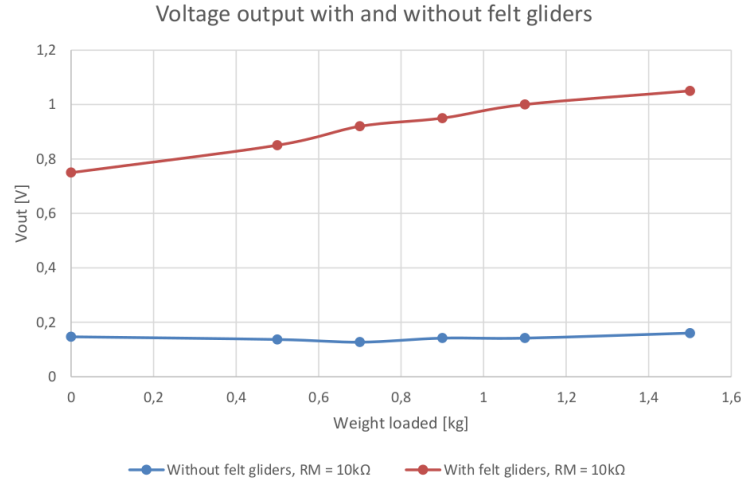


Figure 2.3: Comparison of pressure with and without felt gliders.

To convert voltage to a digital value Analog to Digital Conversion (ADC) was done with a help of a microcontroller. Sensors were connected to the Trinket Pro 5V microcontroller development board[18]. This board features ATmega328P microcontroller with integrated ADC functionality[19]. From a myriad of different boards this one was chosen because it can be programmed as Arduino Pro Mini but features 8 analog input pins. Unfortunately, two of the analog pins share functionality with Inter-Integrated Circuit (I2C) protocol and 1 was used for board identification. This means that 1 board could support up to 5 sensors. To get collect readings from multiple devices already mentioned I2C protocol was used. A device that takes the readings from the pressure sensors and can communicate with the rest of the system will be called a node in the rest of the thesis.

But it would be quite impractical to connect a PC to each an every node to collect data so the system was designed with a new device as an endpoint. This device communicates as I2C master device with the nodes and allows easier communication between user and nodes. For purpose of an endpoint, Intel Edison System On a Module (SOM) was used. It features Intel Atom Central Processing Unit (CPU) and Intel Quark 32-bit microcontroller[20]. Both have x86 architecture and use x86 instruction set. But what is more important, Intel Edison has 4GB Embedded Multimedia Card (EMMC) storage as well as integrated *Bluetooth* and *Wi-Fi*. This features allow storing larger amount of collected sensor readings and easier interaction with the system.

2.2 Test environment

If a sensor grid would have 8 rows with 8 sensors, it would require at least 13 boards. As all of the boards were communicating using I2C protocol, they required addresses that were in accordance with their physical position. This would either require a different firmware for every board or some smarter alternative in which every board would automatically select different I2C address in an orderly way. The solution that was proposed was using same-value resistors in a series. Depending on the voltage difference between adjacent board identification resistor and ground an I2C address was chosen. Although

this solution was easy to implement, it had used up one ADC pin that could have been used for sensor connection. Since Trinket Pro does not have a prototyping holes, 5 reference resistors for sensor reading and 1 for position identification had to be added. Reference resistors were soldered as a part of the wires and isolated using heat-shrink tube while position identification resistor was soldered onto a piece of perforated board and connected between two Trinkets.

If all of the An ideal sensor positioning and distribution would result in 100% coverage of the sleeping area. If type 406 sensors would be used, this would require use of 1272 sensor units

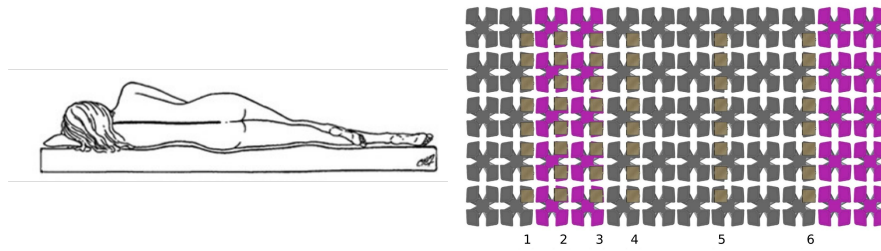


Figure 2.4: Sensor arrangement in bed compared to sleep position.

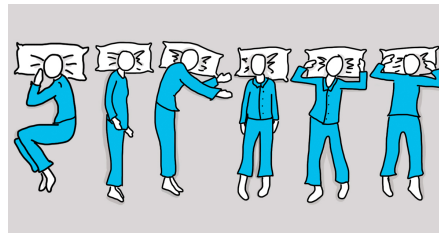


Figure 2.5: Different sleep positions.

2.3 Results so far

2.4 A new architecture

3 Sensor nodes

3.1 Functionality overview

3.2 Component selection and compatibility

3.3 PCB design

3.4 Prototype production

3.5 Installation and integration

4 Endpoint node

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4.2 Communication with sensor network

4.3 Data acquisition routine

5 Data collection and display

5.1 Functionalities and usage

5.2 API interface

5.3 User interface

6 Testing and results

7 Conclusion

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Symbols, Units and Abbreviations

EEG Electroencephalography

EOG Electrooculography

EMG Electromyography

MEMS Microelectromechanical systems

PPG Photoplethysmography

UC-Lab Ubiquitous Computing Laboratory

HTWG Hochschule Konstanz für Technik Wirtschaft und Gestaltung

API Application Programming Interface

NREM Non-Rapid Eye Movement

REM Rapid Eye Movement

POF Plastic optical fiber

PCB Printed Circuit Board

AC Alternating Current

FSR Force sensing resistor

PTF Polymer Thick Film

ADC Analog to Digital Conversion

I2C Inter-Integrated Circuit

SOM System On a Module

CPU Central Processing Unit

EMMC Embedded Multimedia Card

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Enhancement of sensor mesh functionality with application on sleep tracking

Abstract

The focus of this project is enhancement of functionality, reliability and sensor accuracy of an intelligent bed that monitors human sleep. The scope of the project includes the implementation of an application layer protocol and network communication between the embedded system in the bed and remote server. Furthermore, the implementation possibilities of data preprocessing, filtering, and automatic sleep analysis are explored and tested. The system is tested and evaluated in the Ubiquitous Computing Laboratory at the Hochschule Konstanz University of Applied Sciences.

Keywords: sleep tracking, embedded systems, sensor meshes, sleep analysis

Primjena senzorskih mreža na praćenje ljudskog sna

Sažetak

Tema projekta je unaprjeđenje funkcionalnosti, pouzdanosti i preciznosti rada inteligentnog kreveta koji prati ljudski san. U sklopu projekta implementira se aplikacijski sloj te ostvaruje mrežna komunikacija između ugradbenog sustava u krevetu i udaljenog računalnog servera. Nadalje, rad istražuje i testira implementaciju preprocesiranja podataka, izrade podatkovnih filtera i automatske obrade i analize podataka o snu. Sustav se testira i evaluira u Laboratoriju za sveprisutno računarstvo pri Hochschule Konstanz University of Applied Sciences.

Ključne riječi: praćenje sna, ugradbeni sustavi, mreže senzora, analiza sna