

UNIVERSITY OF ZAGREB  
FACULTY OF ELECTRICAL ENGINEERING AND COMPUTING  
and  
UNIVERSITY OF APPLIED SCIENCES KONSTANZ

MASTER THESIS No. 1536

# Enhancement of sensor mesh functionality with application on sleep tracking

Bruno Vunderl

Konstanz, August 2017

# Master thesis

Conclusion of Master Degree

**Master of Science in Computing (M. Sc.)**

at the

University of Zagreb  
Faculty of Electrical Engineering and Computing

and

Hochschule Konstanz  
Technik, Wirtschaft und Gestaltung

Topic: **Enhancement of sensor mesh functionality with application on sleep tracking**

Master candidate: Bruno Vunderl, Havidiceva 22, 10010 Zagreb

First supervisor: Prof. Ralf Seepold  
Second supervisor: Prof. dr. sc. Mario Kovač

Issue date: 10.3.2017.  
Submission date: DD.MM.YYYY

Zagreb, 6 March 2017

## MASTER THESIS ASSIGNMENT No. 1536

Student: **Bruno Vunderl (0036455534)**  
Study: Computing  
Profile: Computer Engineering

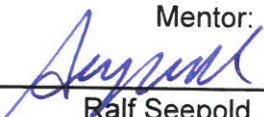
Title: **Enhancement of Sensor Mesh Functionality with Application on Sleep Tracking**

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.

Issue date: 10 March 2017  
Submission date: 29 June 2017

Mentor:



Ralf Seepold, PhD

Committee Chair:

Full Professor Mario Kovač, PhD  
(co-mentor)

Committee Secretary:

Full Professor Danko Basch, PhD

Full Professor Mario Kovač, PhD

# Contents

<b>Contents</b>	<b>1</b>
<b>1 Introduction</b>	<b>2</b>
1.1 Motivation . . . . .	2
1.2 Technology and current consumer market trends . . . . .	3
1.3 A poll on perceived influence of sleep and usage of sleep tracking devices	5
1.4 Goal and scope . . . . .	5
1.5 Thesis outline . . . . .	6
<b>2 Evolution of system design</b>	<b>7</b>
2.1 Devices and technology . . . . .	7
2.2 Test environment . . . . .	8
2.3 Results so far . . . . .	8
<b>3 Sensor nodes</b>	<b>9</b>
3.1 Functionality overview . . . . .	9
3.2 Component selection and compatibility . . . . .	9
3.3 PCB design . . . . .	9
3.4 Prototype production . . . . .	9
3.5 Installation and integration . . . . .	9
<b>4 Endpoint node</b>	<b>10</b>
4.1 System setup . . . . .	10
4.2 Communication with sensor network . . . . .	10
4.3 Data acquisition routine . . . . .	10
<b>5 Data collection and display</b>	<b>11</b>
5.1 Functionalities and usage . . . . .	11
5.2 API interface . . . . .	11
5.3 User interface . . . . .	11
<b>6 Testing and results</b>	<b>12</b>
<b>7 Conclusion</b>	<b>13</b>
<b>Symbols, Units and Abbreviations</b>	<b>I</b>
<b>List of Figures</b>	<b>II</b>
<b>List of Tables</b>	<b>III</b>
<b>Bibliography</b>	<b>IV</b>
<b>Abstract</b>	<b>VI</b>

# 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 waves<sup>1</sup> 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

---

<sup>1</sup>High 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.

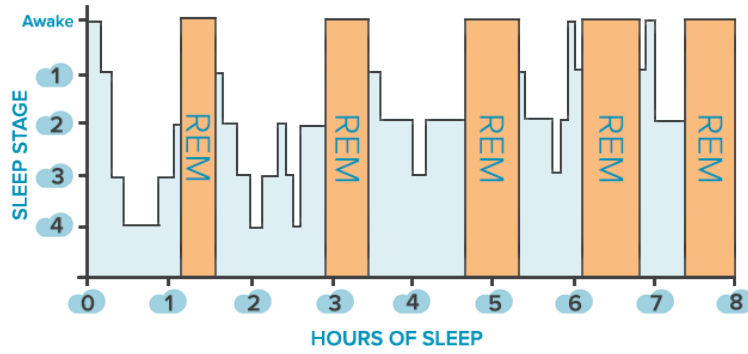


Figure 1.1: Sleep phases during typical 8 hour sleep.

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-party<sup>2</sup> 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].

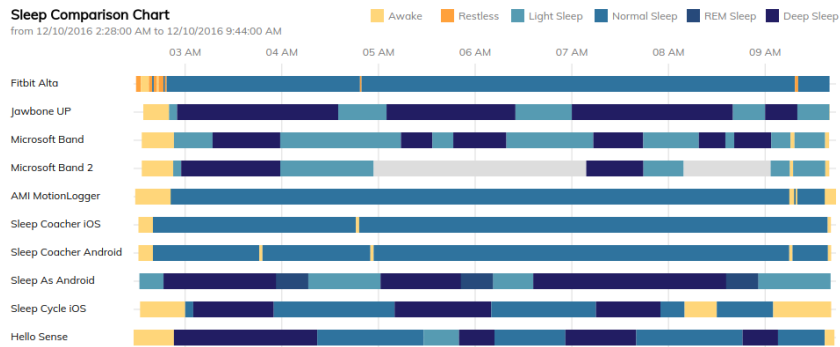


Figure 1.2: Sleep detection comparison between consumer devices

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 actigraphy<sup>3</sup> 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

<sup>2</sup>Not provided by the original manufacturer

<sup>3</sup>a 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 environment<sup>4</sup> and external conditions<sup>5</sup> 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

---

<sup>4</sup>eg. bed quality, sleeping garments

<sup>5</sup>eg. 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. Piezoelectric film sensor were placed on a rodent cage and signals were used for recognition of breathing and movement[6]. In same way, sleep and awakening was recorded in humans using load cells placed under bed supports[7]. Subjects were also recorded using infrared cameras and this method provided 19% better recognition of small movements than actigraphy done with a wrist worn device[8]. Plastic optical fiber (POF) sensors were also used to recognize breathing patterns and detect apnea[9]. In another research, a group of researchers conducted experiment in which they placed two 24Gigahertz (GHz) radars under the bed in a nursing home and found out that it is possible to accurately recognize the hearth rate[10]. Using pressure sensitive e-textile it is possible to classify a sleep stage as awake, NREM or REM[11]. And using pneumatic pressure sensors placed in a sealed air-cushion that is placed under the bed it is possible to measure hearth beat, respiration, snoring and movement[16].

### 2.1 Devices and technology

Current setup is based on work of Prof. Dr. Ralf Seepold, Raína Kuhn, Daniel Scherz and Maxime Guyot at UC-Lab[12][13].

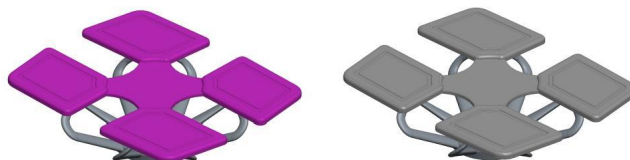


Figure 2.1: Base plates in the bed.

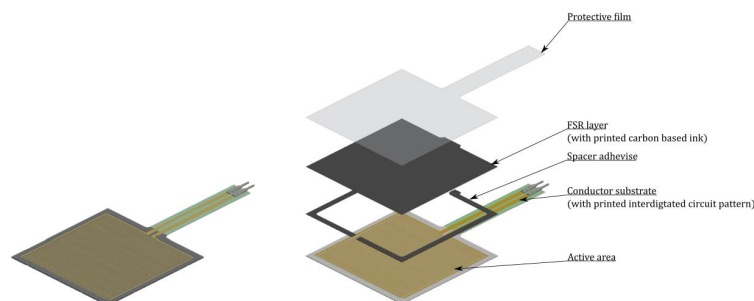


Figure 2.2: Layout of sensors in a bed.

## 2.2 Test environment

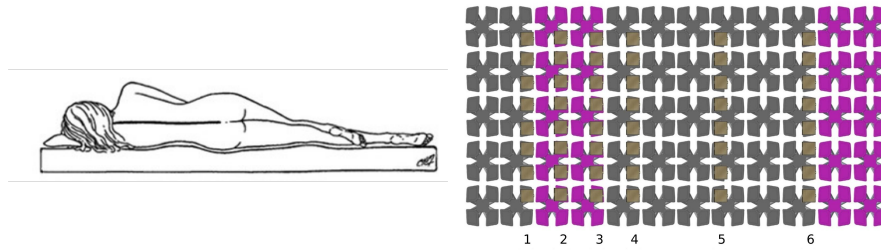


Figure 2.3: Sensor arrangement in bed compared to sleep position.

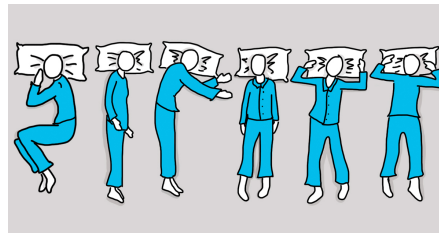


Figure 2.4: Different sleep positions.

## 2.3 Results so far

## 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

### 4.1 System setup

### 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

Lorem ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore magna aliquyam erat, sed diam voluptua. At vero eos et accusam et justo duo dolores et ea rebum. Stet clita kasd gubergren, no sea takimata sanctus est Lorem ipsum dolor sit amet. Lorem ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore magna aliquyam erat, sed diam voluptua. At vero eos et accusam et justo duo dolores et ea rebum. Stet clita kasd gubergren, no sea takimata sanctus est Lorem ipsum dolor sit amet.



# 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

**GHz** Gigahertz

# List of Figures

1.1	Sleep phases during typical 8 hour sleep. . . . .	3
1.2	Sleep detection comparison between consumer devices . . . . .	4
2.1	Base plates in the bed. . . . .	7
2.2	Layout of sensors in a bed. . . . .	7
2.3	Sensor arrangement in bed compared to sleep position. . . . .	8
2.4	Different sleep positions. . . . .	8

## List of Tables

# Bibliography

- [1] National Sleep Foundation. (2015) National Sleep Foundation recommends new sleep times. [Online]. Available: <https://sleepfoundation.org/press-release/national-sleep-foundation-recommends-new-sleep-times>
- [2] J. J. Pilcher and A. I. Huffcutt, “Effects of sleep deprivation on performance: A meta-analysis,” *Sleep*, vol. 19, no. 4, p. 318, 1996. [Online]. Available: <http://dx.doi.org/10.1093/sleep/19.4.318>
- [3] D. J. Buysse, C. F. Reynolds, T. H. Monk, S. R. Berman, and D. J. Kupfer, “The pittsburgh sleep quality index: A new instrument for psychiatric practice and research,” *Psychiatry Research*, vol. 28, no. 2, pp. 193–213, 1989. [Online]. Available: [https://doi.org/10.1016/0165-1781\(89\)90047-4](https://doi.org/10.1016/0165-1781(89)90047-4)
- [4] D. C. Winter. (2014) Personal sleep monitors: Do they work? [Online]. Available: [http://www.huffingtonpost.com/dr-christopher-winter/sleep-tips\\_b\\_4792760.html](http://www.huffingtonpost.com/dr-christopher-winter/sleep-tips_b_4792760.html)
- [5] J. Yoon. (2017) Comparing 10 sleep trackers. [Online]. Available: <http://sleep.cs.brown.edu/comparison/>
- [6] A. E. Flores, J. E. Flores, H. Deshpande, J. A. Picazo, X. Xie, P. Franken, H. C. Heller, D. A. Grahn, and B. F. O’Hara, “Pattern recognition of sleep in rodents using piezoelectric signals generated by gross body movements,” *IEEE Transactions on Biomedical Engineering*, vol. 54, no. 2, pp. 225 – 233, 2007. [Online]. Available: <https://doi.org/10.1109/TBME.2006.886938>
- [7] D. Austin, Z. T. Beattie, T. Riley, A. M. Adami, C. C. Hagen, and T. L. Hayes, “Unobtrusive classification of sleep and wakefulness using load cells under the bed,” pp. 5254–5257, Aug 2012.
- [8] A. Heinrich, X. Aubert, and G. de Haan, “Body movement analysis during sleep based on video motion estimation,” *2013 IEEE 15th International Conference on e-Health Networking, Applications Services (Healthcom)*. [Online]. Available: <https://doi.org/10.1109/HealthCom.2013.6720735>
- [9] S. Mitachi, D. Shiroishi, M. Nakagawa, and K. Satoh, “Development of a sleep apnea syndrome sensor using optical fibers,” *Lasers and Electro-Optics Society, 2007. LEOS 2007. The 20th Annual Meeting of the IEEE*. [Online]. Available: <https://doi.org/10.1109/LEOS.2007.4382393>
- [10] M. Kagawa, Y. Yoshida, M. Kubota, A. Kurita, and T. Matsui, “Non-contact heart rate monitoring method for elderly people in bed with random body motions using 24 ghz dual radars located beneath the mattress in clinical settings,” *Journal of Medical Engineering & Technology*, vol. 36, no. 7, pp. 344–350, 2012. [Online]. Available: <http://dx.doi.org/10.3109/03091902.2012.697533>

- [11] L. Samy, M. C. Huang, J. J. Liu, W. Xu, and M. Sarrafzadeh, “Unobtrusive sleep stage identification using a pressure-sensitive bed sheet,” *IEEE Sensors Journal*, vol. 14, no. 7, pp. 2092–2101, July 2014.
- [12] R. Kuhn, “A sensor grid for pressure and movement detection supporting sleep phase analysis,” Master’s thesis, HTWG Konstanz, 2016.
- [13] M. Guyot, “Optimization of the sensor grid for pressure and movement detection supporting sleep phase analysis.”
- [14] The Harris Poll. (2015) Wearable tech familiarity and consideration on the rise. [Online]. Available: <http://www.theharrispoll.com/business/Wearable-Tech.html>
- [15] Sleepjunkies. (2017) The ultimate guide to sleep tracking. [Online]. Available: <https://sleepjunkies.com/features/the-ultimate-guide-to-sleep-tracking/>
- [16] K. Watanabe, T. Watanabe, H. Watanabe, H. Ando, T. Ishikawa, and K. Kobayashi, “Noninvasive measurement of heartbeat, respiration, snoring and body movements of a subject in bed via a pneumatic method,” *IEEE Transactions on Biomedical Engineering*, vol. 52, no. 12, pp. 2100–2107, Dec 2005.

# 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