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

Hohschule Konstanz
Technik, Wirtschaft und Gestaltung

Topic:	**Enhancement of sensor mesh functionality with application on sleep tracking**
Master candidate:	Bruno Vunderl, Havidićeva 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

UNIVERSITY OF ZAGREB
FACULTY OF ELECTRICAL ENGINEERING AND COMPUTING
MASTER THESIS COMMITTEE

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

Full Professor Mario Kovač, PhD
(co-mentor)

Committee Secretary:

Full Professor Danko Basch, PhD

Committee Chair:

Full Professor Mario Kovač, PhD

Contents

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 multidisciplinary 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 awakeness 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[1] 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

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

quickly in different directions with hearth 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.

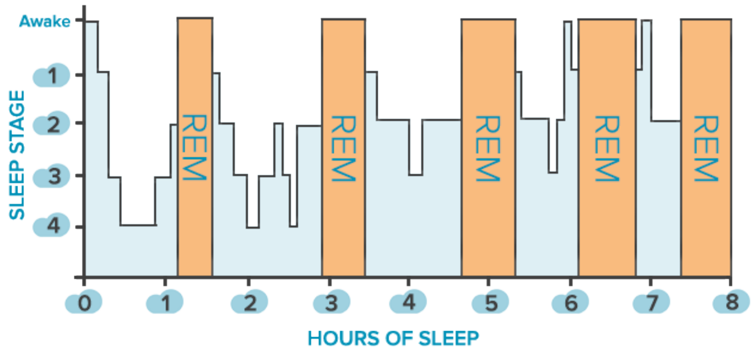


Figure 1.1: Sleep phases during typical 8 hour sleep.

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[2] 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].

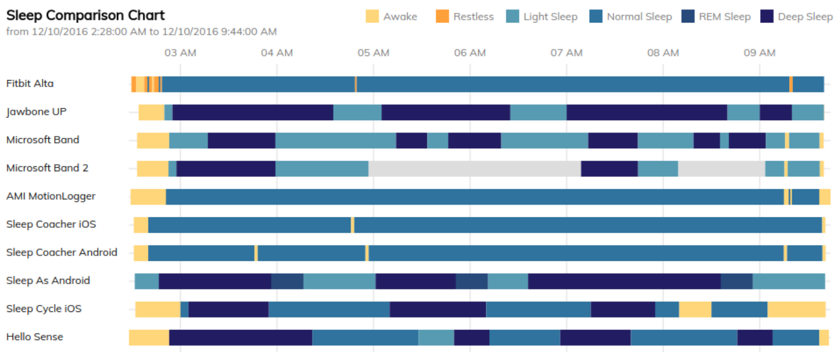


Figure 1.2: Sleep detection comparison between consumer devices

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[3] 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

[2]Not provided by the original manufacturer

[3]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[4] and external conditions[5] 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

[4] eg. bed quality, sleeping garments
[5] 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 and 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 cane 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

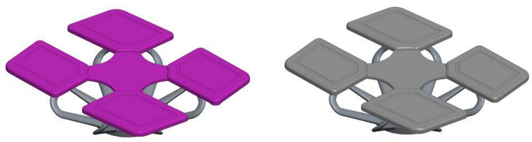


Figure 2.1: Base plates in the bed.

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 realiability 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 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 $100k\Omega$ to $10k\Omega$. 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.

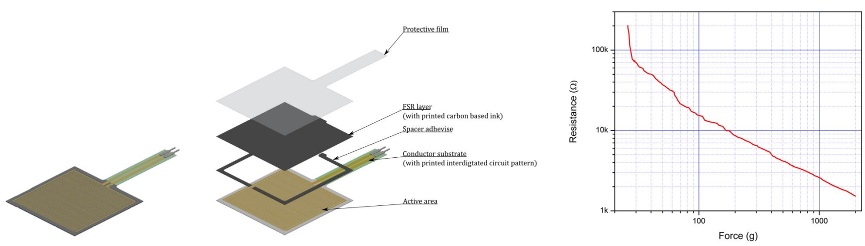


Figure 2.2: FSR sensor construction and resistance characteristics.

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.

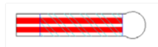
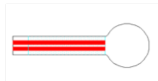
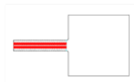
Part number	Description	Part image
Model 400	0,2" circle	
Model 402	0.5" circle	
Model 406	1.5" square	
Model 408	24" strip	

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}.

$$V_{fsr} = \frac{V * R_{ref}}{R_{fsr} + R_{ref}} \tag{2.1}$$

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 felt[1] gliders. This greatly improved the sensitivity and the results can be seen in Figure 2.3.

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

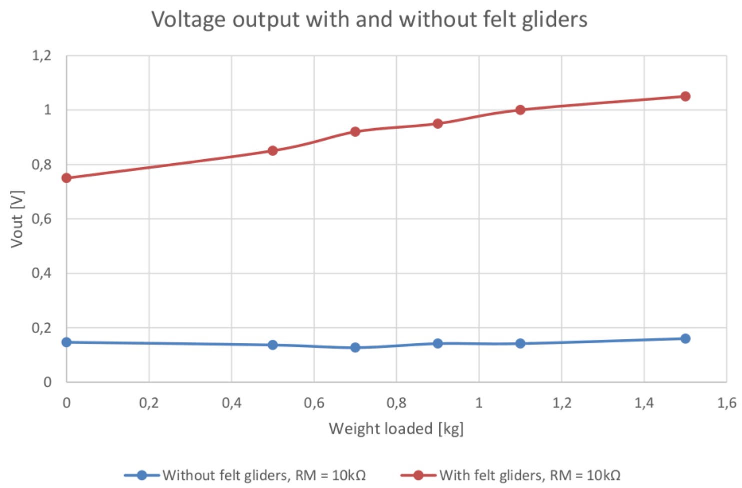


Figure 2.3: Comparison of pressure with and without felt gliders.

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 Personal computer (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 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*. Using Wi-Fi, sensor readings paired with their position were transmitted to locally situated web server. Web server application saved the incoming data into the database and provided API for the client application. Using client application, user was able to calibrate and review sensor data.

2.2 Test environment

To get a better result recognizing sleep position, a sleeping recognition sensor network has to be designed in such a way that it is able to detect all of the most common sleep position. Figure 2.4 shows 6 positions people most often sleep in. From left to right those are fetal position, log position, yearner position, supine position, starfish position and prone position. Fetal, yearner and log position can be left or right depending on the bed side subject is facing. But since there is no difference in weight distribution between left and right log position, it is possible just to classify position as log position. This means that total of 8 different positions can be classified using pressure sensing. Using commercial pressure sensing mat and pattern matching, a research conducted in a clinic has achieved 97% classification accuracy[21] which means that this technique is very reliable. But putting a FSR sensor pad on every possible blade would require 240 sensors and 48 nodes which is not only expensive in terms of hardware cost but also of time used for setting up the system. The easiest way to minimize the complexity would be reducing the number of sensors but it has to be done in such a way that there is no significant classification accuracy loss compared to fully populated base-plate area. Since vertical movement during sleep is rare and all of the major body regions exceed the surface area of a base-plate, the emphasis was placed on horizontal resolution. Pressure sensors were placed on two pads in the same row while the other row was left without pads. This decision reduced the number of required sensors from 240 to 120.

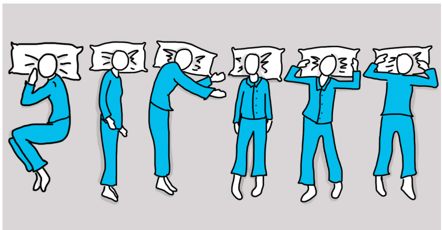


Figure 2.4: Different sleep positions.

To retain the possibility of accurate position recognition but to further minimize the number of sensors used, a look was taken into the weight distribution during supine and log position. In Figure 2.5 we can see that mattress deflects the most in scapular, gluteal and crural regions. Scapular area is especially important because it is the area where respiration and heart rate detection is done. Other areas of the body are not as important to create an accurate picture of the body position and to measure vital signs. Also, at the edge of the bed frame, mattress is transferring a significant amount of pressure to the frame which means that these pads are not very sensitive. As a conclusion 48 sensors were placed in 6 rows as seen in Figure 2.5 and according to M. Guyots[12] sensor layout proposal.

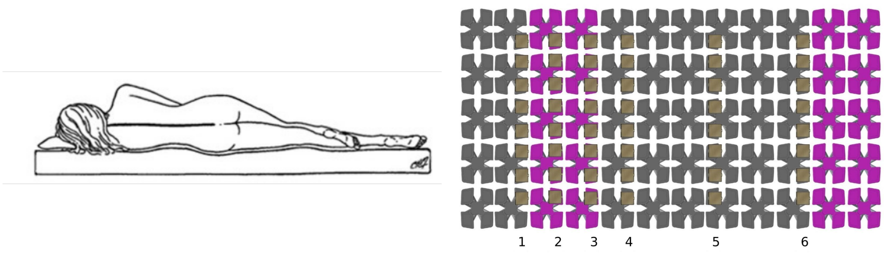


Figure 2.5: Sensor arrangement in bed compared to sleep position.

The described system with 48 sensors required 10 Trinket Pro boards. As all of the boards were communicating using I2C protocol in which each of the slaves has a unique address, addresses had to be distributed in accordance with their physical position. This required either 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 involved using same-value resistors in a series. Depending on the voltage difference between identification resistor and ground, an I2C address was chosen by the microcontroller. 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 prototyping holes, 5 reference resistors for sensor reading and 1 for position identification had to be added. For every reference resistors a perforated electonic prototyping board was cut, a resistor and 3 wires were soldered. Also, position identification resistor was soldered onto a piece of perforated board and connected between two adjacent Trinkets. This means that adding new node with 5 sensors to the system required 6 new small boards to be soldered. Wiring was also something that could be improved with introduction of a signal bus.

2.3 A new architecture

To address this hardware shortcomings a new hardware architecture was proposed. In it sensor nodes were implemented as PCBs which featured all previously additionally soldered resistors. A new method of node position identification was developed without the use of identification resistor and connection between nodes was implemented using standardized connectors and cables. This means that FSR sensors can now be directly connected to the nodes. Proposed solution eliminated a need for perforated boards and use of soldering iron for installation. The total number of nodes was also halved by using microcontrollers with more ADC inputs. This was done to reduce system cost, power consumption and to make installation and modification of development much simpler.

Endpoint was reimagined to integrate data storage and server functionality so no external servers are now needed for a system to serve data to the client. Web based user interface is also implemented on the endpoint so that results can be viewed from a PC or even from a mobile device. But what if there is a need for a service which monitors multiple beds at the same time such as in case of hospital or nursing home? Well, endpoint also serves data over well described API and allows easy readout of data collected from sensor network. A graph depicting a new system architecture is found in Figure 2.6.

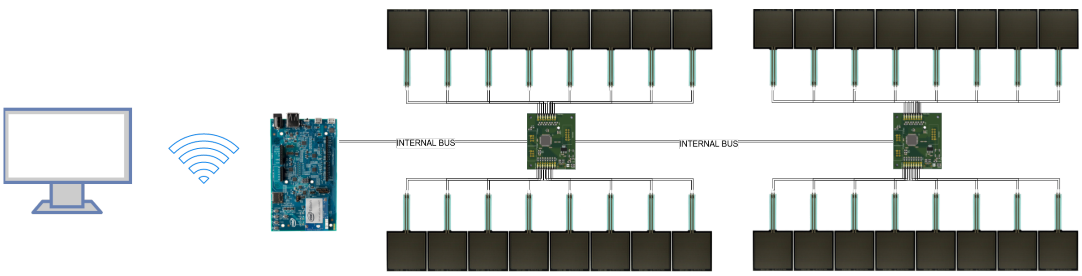


Figure 2.6: A newly implemented system architecture.

3 Sensor nodes

This chapter will describe functionalities of sensor node devices. After that it will describe how electronic parts were chosen. A separate section will include details regarding PCB design while another section will follow the production from first prototype to the production. Finally, it will be shown how the board is installed and integrated into the system.

3.1 Physical design and connections

Most of the required PCB features were already described in the previous chapter - board should allow direct connection of FSR sensors, it should eliminate need for additional perforated boards and it should provide a more robust solution for physical board position detection. Furthermore, it should feature low power consumption and enable connection of at least two rows of 8 pressure sensors. Also it should feature small dimensions because and provide mounting holes so that it doesn't have to be suspended by wires or be taped to the bed. The ideal position for the installation of the board is under the bed base slates. This way it can easily be serviced.

There are 4 variants of pin endings found on FSR sensors. A variant with no leads is used for custom pin endings while solder tabs variant is used for direct soldering to the board. Because of the materials used for construction of the sensor, when heat is applied using standard soldering iron, there is a high possibility of sensor leads melting. This is why a female plug connector option was chosen. Distance between leads is 1/10" and they are compatible with standard PCBconnector pins. Since sensors will be mounted on pressure disks which are found on the upper side of the bed base, while the board is found under the slates, elongation cables are required. In this case, DuPont "jumper" cables will be used and a board connectors have been designed in such a way. Two edges of the board, are populated with 8 two-row connectors. Row on the top is connected to the ADC pins of the microcontroller while the bottom pins are grounded. In front of each of the pin, a reference resistor R_ref is found.

Connector that was used for internal communication bus features 6 wires - 2 wires are used for I2C, 2 are used for power supply and 2 are used for physical position recognition. Because they are interchangeable with DuPont jumper wires and because of toolless cable connector installation, Insulation-displacement connector (IDC) cables and connectors were used[22]. There are two 3x2 internal communication bus connectors on the board so that boards can easily be "daisy-chained". Close to the first connector, two pull-down resistors for I2C bus are situated. For microcontroller programming, the same type of connectors was used. The cortex debug interface consists of 10 pins so a single 5x2 connector was used. Graphic 3.1 shows connectors with positions of pins.

To power the microcontroller and because of debugging possibilities, a type B micro Universal Serial Bus (USB) connector was also added to the board. USB connection

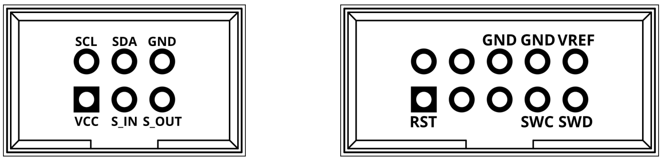


Figure 3.1: Internal communication bus and programming connector layout.

features 2 differential data signals, a $5V$ and ground. Connector additionally has a "on-the-go" identification pin which is left floating because the requirement does not require a board to become USB host. What board implements is a PRTR5V0U2X ElectroStatic Discharge (ESD) diode[23] which helps protect both the host PC and the PCB from electrical stress in form of surge or overvoltage.

3.2 Component selection and compatibility

A most important part of the node circuit is a microcontroller. Main requirement for it was the possibility of connecting 16 ADC devices without the use of additional ADC Integrated Circuits (IC)s. Since other members of UC-Lab have experience with programming Atmel microcontrollers, a choice was between ATxmega 8-bit AVR microcontrollers, 32-bit UC3 AVR microcontrollers and Atmel SMART ARM-based Microcontroller Unit (MCU)s[1]. So let's take a look at a sample microcontroller from each of the categories. *ATxmega64C3* is a 8-bit AVR microcontroller which features 64KB flash program storage and 4KB of Random Access Memory (RAM), 16 pins provide ADC with 12-bit resolution and there is native support for I2C[24]. *AT32UC3C164C* is a 32-bit AVR microcontroller with the same flash size and number of 12-bit ADC inputs but it features 20KB RAM[25]. ATSAMD21J16 is a 32-bit ARM based microcontroller which has 8KB RAM, 20 ADC channels which have programmable gain stage, automatic offset and gain compensation as well as a possibility to oversample the signal to get 16-bit resolution[26]. Considering that this microcontroller is cheaper than both AVR microcontrollers and that it supported by multiple third-party frameworks such as ARM mbed, Arduino and Simba, Atmel SAMD was chosen as a microcontroller family that will be used. Atmel SAMD MCU family microcontrollers have a naming pattern which makes easy to distinguish chips characteristics. An example will be described on is SAMD21J16B-AU. *SAMD* is product family, *21* is product series, *J* stands for pin count (j = 64pins), *16* is for flash memory density (16 = 64KB), *B* is chip variant, *A* is for package type (a = Thin Quad Flat Package (TQFP)) and finally *U* is for package grade (U = -40 - 85°C). A first prototype of the board was developed using *ATSAMD21J18-AU* which is the same as one found in Atmels *SAM D21 Xplained Pro Evaluation Kit* but that processors was out of stock when production boards were to be made. This is why *ATSAMD21J16-AU*, a pin-compatible variant with 64KB instead of 256KB of RAM, was used in production boards. Pin layout of a TQFP package can be seen in Figure 3.2. This pinout is same for all ATSAMD21 microcontrollers with 64-pin TQFP package so even smaller memory versions can be used for the cost-saving.

To power the selected microcontroller a $3.3V$ source is used. Since the most important feature the microcontroller does is analog to digital conversion, it's very important to have a stable and ripple-free Direct Current (DC) power supply. Oscillations in input

[1](abbrev. SAM)

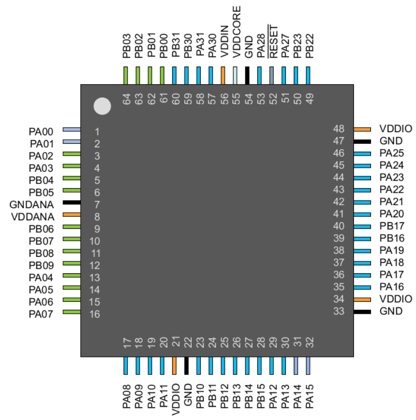


Figure 3.2: AT SAMD 64-pin TQFP package pin layout.

voltage to the microcontroller may lead to inconsistent voltage readings. Switching Mode Power Supply (SMPS) is a very efficient way of DC-DC conversion but it suffers from a constant high and low frequency voltage ripple. Most of high frequency and some of low frequency ripple can be countered by using ferrite beads and capacitors but ripple still remains. Breakout board for Intel Edison, an endpoint used in this project, uses TPS62133 $5V$ step-down SMPS which can supply a maximum of $3A$ of current[27][28]. Out of available $15W$, Intel Edison consumes on average $0.41W$ with Wi-Fi enabled. This means that it is possible to use the same power supply for powering the nodes. To filter out the noise a Low-Droput (LDO) is found on each of the nodes. This is in accordance to the specification for high-performance ADC power supply design provided by Texas Instruments[29]. LDO that was chosen for this project is LD1117 which provides a stable $3.3V$ power supply with $1.1V$ dropout voltage. Input and output voltage lines of the power supply are bridged to the ground with capacitors to filter out the input noise. For debugging a $3.3V$ source can be attached to $VREF$ pin of the programming connector.

3.3 PCB design and production

A PCB was designed in KiCad open-source tool for electronics design automation. First a microcontroller was placed with decoupling capacitors and ferrite bead according to the manual[26]. This ensures low noise during operation. After already described internal bus, programming, sensor connection and micro USB connectors were placed, PCB was populated with 2 status Light emitting diode (LED)s. First LED serves as on/off detection and is directly connected to the V_{cc} while the other one is user programmable and can be used for debugging. Board also has a power supply and a reset button. On 3 edges of the board a $3mm$ diameter holes were placed for easy mounting. The layout of the PCB can be seen in Figure 3.3.

To test the initial design, a board was milled at Department of Electronics at HTWG using LPKF ProtoMat S63 circuit board plotter. Since board design features vias, they had to be filled with copper rivets. Prototype production showed that micro USB pin had switched GND and USB OTG ID pins. This error happened due to difference of pin naming between footprint and schematic during the design. After this issue was fixed a board was sent for production to AISLER. The components were ordered from DigiKey

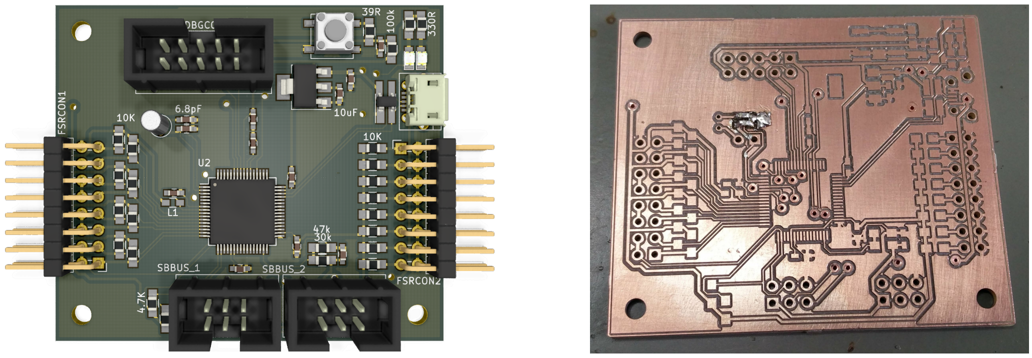


Figure 3.3: 3D view and prototype of printed circuitboard developed for the project.

with already described change from ATSAMD21J18 to ATSAMD21J16. 3 boards were produced and were hand soldered. After production, every board was tested with a sample program reading from each of sensors. The final and assembled board can be seen in Figure 3.4

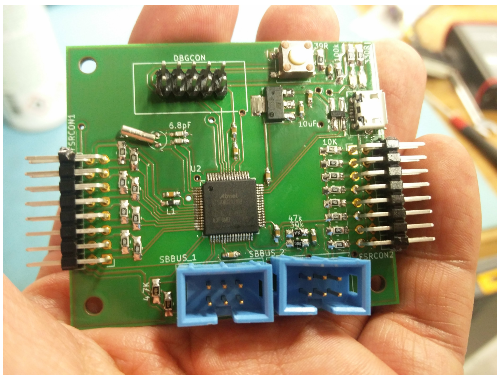


Figure 3.4: Fully populated node circuitboard.

3.4 Development environment

Because of the ARM architecture and Thumb2 instruction set, selected microcontroller supports multiple frameworks and development environments. One of most standardized and widely used frameworks is ARM mbed. It is compatible with almost all ARM microcontroller designs from vendors such as STMicroelectronics, NXP, Renesas, Nordic and Atmel[30]. Through abstraction it allows the same code to work on different devices. Depending on the selected device, application code is linked with platform specific libraries and a hex code output file is generated. This hex file can then be uploaded to the microcontroller using "drag and drop" or using Serial Wire Debug (SWD) interface[31]. In case of this project, mbed framework was used through Platformio open source ecosystem for Internet of Things (IoT) development. This environment integrates in Microsoft's VSCode code editor and allows code compiling, upload and debugging along with other features such as intellisense code competition, unit testing and continuous integration. Although both mbed and Platformio support ATSAMD21J18 and Atmels Xplained Pro development board, they provide no support for ATSAMD21J16 variant of the microcontroller. This is why a new configuration for both had to be made.

First, a new board configuration was added to the Platformio configuration folder found in `~/.platformio/boards`. Then a JavaScript Object Notation (JSON) structured file was created based upon Atmel Xplained Pro board file but maximum ram size and maximum size were changed because of the smaller RAM and flash size. Then a support for a new processor had to be added to the mbed Software development kit (SDK). First a new microcontroller and variant were declared an then microcontroller features were described in `.platformio/packages/framework-mbed/targets/targets.json`. and can be seen in Listing 3.1. Then General Purpose Input Output (GPIO) port mapping of this chip variant is declared in `port_api.c`. Next required change includes modification of load script. Read Only Memory (ROM) is set as rx memory form address 0x00000000 until address 0x00010000 while RAM is of rwx type starting from 0x20000000 and with size of 0x2000. Stack size is defined to be 0x500. After these changes were introduced, Board Support Package (BSP) can be generated using tool tox. After that, a board is visible in Platformio and programs can be compiled for it.

Listing 3.1: Description of mbed features implemented in ATSAMD21J16

```
"SAMD21J16A": {
    "inherits": ["Target"],
    "core": "Cortex-M0+",
    "macros": ["__SAMD21J16A__", "I2C_MASTER_CALLBACK_MODE=true",
        "EXTINT_CALLBACK_MODE=true", "USART_CALLBACK_MODE=true",
       "TC_ASYNC=true"],
    "extra_labels": ["Atmel", "SAM_CortexM0P", "SAMD21"],
    "supported_toolchains": ["GCC_ARM", "ARM", "uARM"],
    "device_has": ["ANALOGIN", "ANALOGOUT", "I2C", "I2CSLAVE", "
       I2C_ASYNCH", "INTERRUPTIN", "PORTIN", "PORTINOUT", "
       PORTOUT", "PWMOUT", "RTC", "SERIAL", "SERIAL_ASYNCH", "
       SERIAL_FC", "SLEEP", "SPI", "SPISLAVE", "SPI_ASYNCH"],
    "release_versions": ["2"],
    "device_name": "ATSAMD21J16A"
}
```

After program has been compiled and linked for the specific microcontroller, the hex file needs to be uploaded to the microcontroller flash storage. Segger JLink programmer is used for this purpose. To automate the upload a custom script and configuration file were written and integrated into the Platformio. Debugger interface using OpenOCD was also setup so that microcontroller could be debugged from the same development environment. A preview found in Figure **TODO FIGURE** shows debugging user interface.

3.5 Software implementation

3.6 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

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

PC Personal computer

IDC Insulation-displacement connector

USB Universal Serial Bus

ESD ElectroStatic Discharge

MCU Microcontroller Unit

IC Integrated Circuits

RAM Random Access Memory

ROM Read Only Memory

TQFP Thin Quad Flat Package

DC Direct Current

LDO Low-Droput

SMPS Switching Mode Power Supply

LED Light emitting diode

SWD Serial Wire Debug

IoT Internet of Things

JSON JavaScript Object Notation

SDK Software development kit

GPIO General Purpose Input Output

BSP Board Support Package

List of Figures

List of Tables

Bibliography

[1] National Sleep Foundation. (2015) National Sleep Foundation recommends new sleep times. [Online]. Available: 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: 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: doi.org/10.1016/0165-1781(89)90047-4

[4] D. C. Winter. (2014) Personal sleep monitors: Do they work? [Online]. Available: www.huffingtonpost.com/dr-christopher-winter/sleep-tips_b_4792760.html

[5] J. Yoon. (2017) Comparing 10 sleep trackers. [Online]. Available: sleep.cs.brown.edu/comparison/

[6] 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. [Online]. Available: dx.doi.org/10.1109/EMBC.2012.6347179

[7] 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: doi.org/10.1109/HealthCom.2013.6720735

[8] 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: doi.org/10.1109/LEOS.2007.4382393

[9] 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. [Online]. Available: dx.doi.org/10.1109/TBME.2005.857637

[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: dx.doi.org/10.3109/03091902.2012.697533

[11] R. Kuhn, "A sensor grid for pressure and movement detection supporting sleep phase analysis," Master's thesis, HTWG Konstanz, 2016.

[12] M. Guyot, "Optimization of the sensor grid for pressure and movement detection supporting sleep phase analysis."

[13] R. E. Bicking. Fundamentals of pressure sensor technology. [Online]. Available: www.sensorsmag.com/components/fundamentals-pressure-sensor-technology

[14] S. Lokavee, W. Suwansathit, V. Tantrakul, and T. Kerdcharoen, "Unconstrained detection of respiration rate and efficiency of sleep with pillow-based sensor array," in *2014 11th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, May 2014, pp. 1–6. [Online]. Available: dx.doi.org/10.1109/ECTICon.2014.6839779

[15] S. Lokavee, N. Watthanawisuth, J. P. Mensing, and T. Kerdcharoen, "Sensor pillow system: Monitoring cardio-respiratory and posture movements during sleep," in *The 4th 2011 Biomedical Engineering International Conference*, Jan 2011, pp. 71–75. [Online]. Available: dx.doi.org/10.1109/BMEiCon.2012.6172021

[16] A. Sundar and C. Das, "Low cost, high precision system for diagnosis of central sleep apnea disorder," in *2015 International Conference on Industrial Instrumentation and Control (ICIC)*, May 2015, pp. 354–359. [Online]. Available: dx.doi.org/10.1109/IIC.2015.7150767

[17] Interlink Electronics, *FSR Integration Guide*. [Online]. Available: interlinkelectronics.com/integration_guides/FSR400Series_IG.zip

[18] Adafruit Industries. (2017) Trinket pro 5v. [Online]. Available: www.adafruit.com/product/2000

[19] Atmel Corporation, *ATmega48A/PA/88A/PA/168A/PA/328/P datasheet*. [Online]. Available: www.atmel.com/images/Atmel-8271-8-bit-AVR-Microcontroller-ATmega48A-48PA-88A-88PA-168A-168PA-328-328P_datasheet_Complete.pdf

[20] Intel Corporation, *Intel Edison Compute Module, Hardware Guide*, 2016. [Online]. Available: www.intel.com/content/dam/support/us/en/documents/edison/sb/edison-module_HG_331189.pdf

[21] M. B. Pouyan, S. Ostadabbas, M. Farshbaf, R. Yousefi, M. Nourani, and M. D. M. Pompeo, "Continuous eight-posture classification for bed-bound patients," in *2013 6th International Conference on Biomedical Engineering and Informatics*, Dec 2013, pp. 121–126. [Online]. Available: dx.doi.org/10.1109/BMEI.2013.6746919

[22] Wikipedia, the free encyclopedia. Insulation-displacement connector. [Online]. Available: en.wikipedia.org/wiki/Insulation-displacement_connector

[23] NXP B.V., *PRTR5V0U2X*, 2008. [Online]. Available: assets.nexperia.com/documents/data-sheet/PRTR5V0U2X.pdf

[24] Atmel Corporation, *8-bit Atmel XMEGA C Microcontroller*, 2014. [Online]. Available: ww1.microchip.com/downloads/en/DeviceDoc/Atmel-8465-8-and-16-bit-AVR-Microcontrollers-XMEGA-C_Manual.pdf

[25] ——, *32-bit AVR Microcontroller*. [Online]. Available: ww1.microchip.com/downloads/en/DeviceDoc/doc32117.pdf

[26] Microchip Technology Inc., *32-bit ARM-Based Microcontrollers*, 2017. [Online]. Available: ww1.microchip.com/downloads/en/DeviceDoc/40001882A.pdf

[27] Intel, *Edison breakout board schematic*, 2014. [Online]. Available: www.intel.com/content/dam/support/us/en/documents/edison/sb/mini_edison_breakout_hvm_8_26.pdf

[28] Texas Instruments Inc., *TPS6213x 3V to 17V, 3A Step-Down Converter In 3x3 QFN Package*, 2017. [Online]. Available: www.ti.com/lit/ds/symlink/tps62133.pdf

[29] X. Ramus, "Minimum power specifications for high-performance adc power-supply designs," 2016. [Online]. Available: www.ti.com/lit/wp/slyy086/slyy086.pdf

[30] Atmel Corporation, *mbed compatible boards and platforms*, 2017. [Online]. Available: developer.mbed.org/platforms/

[31] Silicon Laboratories Inc. (2017) Programming internal flash over the serial wire debug interface. [Online]. Available: www.silabs.com/documents/public/application-notes/an0062.pdf

[32] The Harris Poll. (2015) Wearable tech familiarity and consideration on the rise. [Online]. Available: www.theharrispoll.com/business/Wearable-Tech.html

[33] Sleepjunkies. (2017) The ultimate guide to sleep tracking. [Online]. Available: sleepjunkies.com/features/the-ultimate-guide-to-sleep-tracking/

[34] 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: doi.org/10.1109/TBME.2006.886938

[35] 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. [Online]. Available: dx.doi.org/10.1109/JSEN.2013.2293917

[36] Interlink Electronics, Inc., *FSR 400 Series Data Sheet*. [Online]. Available: www.interlinkelectronics.com/datasheets/Datasheet_FSR.pdf

[37] S. RibariÄĞ, *GraÄŚa raÄĐunala.* Algebra, 2011.

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