Sensors Of Intelligent Sleep Systems

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Declaration

I hereby declare and confirm that this thesis is entirely the result of my own original work. Where other sources of information have been used, they have been indicated as such and properly acknowledged. I further declare that this or similar work has not been submitted for credit elsewhere.

Hagenberg, April 28, 2018

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Contents

Abstract

Existing consumer products that are targeted at measuring human vital functionalities, classifying them and presenting them to the user are mostly not capable of actively assisting in improving the quality of sleep. They rather give hints as to how changing behaviour and sleep schedule might help at doing so. Four different of such systems are tested and reviewed. Futhermore the products are disassembled to get insight into the methods of measurement and data processing that are used in these systems.

Possible measurement methods are then analyzed and classified for suitability in a sleep system based on various characteristics such as contactlessness and accuracy. While none of the analyzed systems are directly integrated into the mattress itself this approach enables control over hardness and temperature. Possible actuator concepts that provide these features are reviewed in order to categorize their usability within a sleep system.

A system concept is developed based the gathered information about what is required to achieve the goal of improving the overall quality of sleep through the usage of a combination of sensors and actuators. Hardware analysis and a limited prototypical construction of the system is implemented through collaboration with two other thesis authors for a data analytics backend and a mobile application as user interface.

Features of the prototypical implementation include configuration and setup of a ballistocardiographic sensor and its calibration to a specific environment to provide the highest quality measurement results possible. Another implemented feature is compressing the measured data and sending it to the backend where sleep phases analysis is performed. While not being implemented the outlines for the implementation of temperature sensor, hardness regulator and heater are defined.

Furthermore the hardware systems control infrastructer is set up with wireless network hosting, remote access, server scripts and asynchronous serial communication between the hardware systems modules. Its applicable features and their usage, such as tracking, persisting and transmission of data, are described. Having tracked and persisted measurement data it may then be visualized thorugh data analytics software.

Kurzfassung

Existierende Produkte, die darauf ausgelegt sind, menschliche Vitaldaten zu messen, diese zu klassifizieren und sie dem Benutzer oder der Benutzerin zu präsentieren, sind zu meist nicht in der Lage, die Qualität des Schlafs aktiv zu verbessern. Stattdessen zeigen die Systeme Hinweise bezüglich Änderungen von Verhalten und Schlarythmus an, um dieses Ziel zu erreichen. Vier dieser Systeme werden getestet und überprüft. Zudem werden die Produkte demontiert, um Einblick in die Messmethodiken und Datenverarbeitungsprozesse zu erlangen.

Mögliche Messmethoden werden basierend auf verschiedenen Eigenschaften wie Kontaktlosigkeit und Genauigkeit auf Eignung in einem Schlafsystem analysiert und klassifiziert. Während keines der analysierten Systeme direkt in die Matratze selbst integriert ist, ermöglicht dieser Ansatz die Kontrolle über Härtegrad und Temperatur. Mögliche Aktorenkonzepte, die diese Funktionen bereitstellen, werden überprüft, um deren Verwendbarkeit in einem Schlafsystem einzuschätzen.

Basierend auf den gewonnenen Erkenntnissen wird ein Systemkonzept entwickelt, um durch die Kombination von Sensoren und Aktoren das Ziel einer Verbesserung der Schlafqualität zu erreichen. Hardware-Analyse und ein bregrenzter prototypischer Aufbau des Systems werden durch Zusammenarbeit mit zwei Bachelorarbeitsautoren für ein Datenanalyse-Backend und eine Handyapplikation als Benutzerschnittstelle durchgeführt.

Zum prototypischen Aufbau gehören die Konfiguration und Einrichtung eines ballistokardiographischen Sensors und dessen Kalibrierung auf dessen spezifische Umgebung, um qualitativ hochwertige Messergebnisse zu erreichen. Ein weiteres implementiertes Feature bietet die Möglichkeit, gemessene Daten zu komprimieren und an das Backend zu übertragen, wo Schlafphasenanalysen durchgeführt werden. Die Implementierung von Temperatursensor, Härtegradregulierung und Heizungselementen wurden nicht durchgeführt, stattdessen wurden die dafür benötigten Anforderungen und Eigenschaften der Komponenten definiert.

Zudem wird die Infrastruktur der Hardware mit Drahtlosnetzwerkhosting, Fernzugriff, Serverscripten und asynchroner serieller Kommunikation zwischen den Komponenten des Systems aufgesetzt. Die anwendbaren Funktionen und deren Verwendung, wie zum Beispiel das Aufnehmen, Speichern und Übertragen von Messdaten, werden beschrieben. Nach der Messung der Daten werden diese anhand von Datenanalyse-Software visualisiert.

Chapter 1

Introduction

The target of the developed mattress system is to provide the user with a higher quality and more recovering sleep. The hardware is one of three parts, the others being the backend implementation [6] and the cross platform mobile application [7] that combined describe the entirety of the system.

1.1 Motivation

The major motivation behind the development of this sleep system is that there are only few and limited systems available that implement actuator functionalities. Even though it is useful for the user to be able to measure, classify and analyze information about the sleep behaviour there is no active assistance in experiencing a higher quality and more recovering sleep. The target of the developed system is therefore to create a system that not only provides information about the sleep but also actively interacts with the user in order to provide a better overall quality sleeping experience.

1.2 Problem Statement

Three out of four of the existing products that are described and tested do not utilize any form of actuators while the one that has actuator implementation solely provides heat regulation. Furthermore the control of the heat is performed manually through the mobile application and can therefore be set only before going to sleep. This form of implementation, while assisting in the users comfort while falling asleep, does not guarantee achieving more recovery during said sleep.

1.3 Outline

The proposition is measuring human vital data that can be classified to give further insight into the quality of the sleep. Furthermore to actively assist in achieving this goal hardness, as well as heat actuators are implemented. To keep track of the current heat level a temperature sensor is required.

Chapter 2

Existing Approaches

Sleep in general is a highly underrated matter in terms of concentration, productivity and health. This statement is even more true for younger people like pupils and students [26]. Teenagers on average require about 9.2 hours of sleep to maximize their ability to concentrate during lectures. But wrongly undervalued sleep is not only a matter of younger people, adults are mostly more aware of the value of sleep but they might have problems with getting enough deep sleep that helps them recover energy because of health issues or stress [26].

To achieve further insight into sleeping habits and recovery rates of sleep certain measurements have to be performed. The most important information that is needed to understand and analyse the recovery rate of sleep are heart beat and respiration rate [16]. Further informations such as relative stroke volume and heart rate variability can also be used to determine more detailed data about a humans sleep [16].

There are already different ways to measure and observe humans vital functionalities. The main problems here are that the sensors used have to work precicely as well as not get in direct contact with the subject that is being observed. These criteria eliminate a lot of common methods of measuring humans vital activities.

2.1 Measurement Methods

The detection of fluctuation in blood pressure can be used to conclude to breathing. This is possible since at the start of the inhaling process the blood preasure is lowered and is increased again when exhaling. This information may also be used as an indicator for health issues [2].

To use this procedure the first step is to get accurate information about the blood pressure. Methods of measurement that can be applied can be found in this section. It will provide an overview of some of the currently existing methods of measurement for vital human body functionalities.

2.1.1 Electrocardiography

Electrocardiography is based on potential differences during cardiac activity set up currents in conductors that are applied to the skin around the heart [24]. Even though the information that can be extracted from this method of measurement is very precise when compared to other techniques it still is not suitable for the usage in a sleep setting. The reason for this is the intrusiveness of the electrodes since they have to be moistened and connected directly to the skin of the subject. Figure 2.1 shows an example use of an electrocardiographic system.

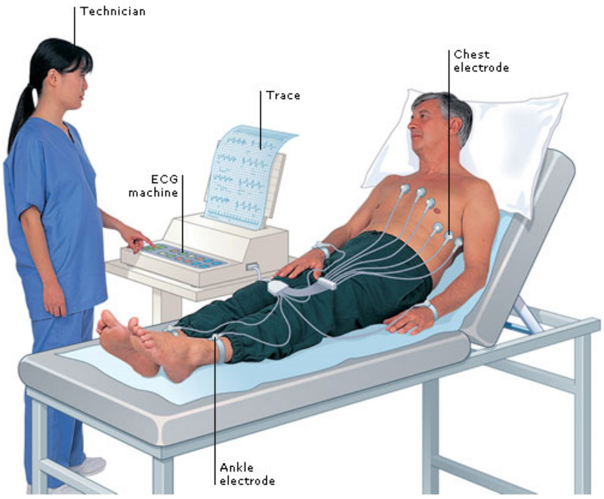

Figure 2.1: ECG (electrocardiography) is used to record the electrical activity of the heart [28].

2.1.2 Reflection of Light

By radiating light with green wave length onto the human skin and measuring the reflections it can be concluded at what rate the heart is beating. This is possible because the blood is absorbing the green light better than the rest of the light spectrum [31]. This method of measurement provides an averagely accurate result for the flow of blood compared to the other measurement systems mentioned in section 2.1.

Examples for this kind of measurement would be a sensor connected to either the arm, fingertip or earlobe. An image of such a sensor can be seen in figure 2.2.

Figure 2.2: Ear-clip heart rate sensor [31].

The disadvantage that makes this method of measurement unusable in a sleep system is that it needs to be directly connected to the human body.

2.1.3 Chest Circomference

By attaching a chest harness and measuring the expanding and retracting phases the breathing cycle can be recorded [9]. This is not a suitable way of measuring breathing since it requires physical body contact. Also this procedure only provides information about the breathing of the subject. This information, while not useless, is not as important for sleep evaluation as heart beat and therefore not suitable to calculate further data from it.

2.1.4 Microphone

While this method of measurement does not provide any information about the heart- or respiration rate of the subject it can still be used to validate sleep data more precisely. This can be achieved by combining it with other vital measurement methods mentioned in this section to conclude to snoring and other respiration related problems. This procedure is not precise enough to measure respiration itself but more the interruption of clear breathing (snoring) [23].

2.1.5 Ballistocardiography

Ballistocardiography (BCG) is a non-invasive method based on the measurent of the body motion generated by the ejection of the blood at each cardiac cycle [4]. One of the biggest challenges with this method of measurement is the lack of understanding of the exact physiologic origin of the BCG waveform, as well as clear guidelines for interpretation of the results, leading to circumspection from the medical community until two centuries ago [4].

The biggest advantage of this method of measurement is that it can be performed entirely without any direct contact with the human body. Indirect contact, for example through a mattress, is enough to get precise enough measurements [22].

Piezoelectric

Piezoelectric elements accumulates electric charge in certain crystalline materials when mechanical stress is applied to their surface [15]. This often also works the other way around, converting electric energy applied to the material into mechanical streching of the element [14].

By utilizing the piezoelectric effect a certain area above or below the mattress can be connected to a fitting crystalline material. This material is then connected to a processing module that digititalizes the signals that are generated by the pressure applied to the sensor. The resulting data can then be filtered and classified to extract heart beat and respiration rate information. Using algorithms this data can then be processed to get insight into the overall vital functionalities of the measured human body [15].

A major draw back of this technology is the life span. This is due to piezoelectric sensor losing its accuracy over time because of degradation of the mechanical and electrical properties of a piezoelectric sensor [21].

This is also the core of most of the used technology in the tested products such as SleepAce (section 2.7.2), SleepExpert (section 2.7.2) and EightSleep (section 2.7.2).

Accelerometer

As stated by Kraft[12] accelerometers work because they are using micromachined capacitive sensing elements. This approach combines the advantages of the simple signal pick-off arangement typically used for analogue accelerometers with those of accelerometers based upon an oversampling technique. The capacitive implmenetation of the accelerometer is low in component count compared to other approaches, but it has still the potential for high-performance [12].

The measured data can then be used to perform more detailed calculations than using the data provided by the methods of measurements in section 2.1.5. In detail it is possible to extract the following information about the human vital functionalities [19].

- Heart Rate
- Respiration Rate
- Relative Stroke Volume
- Simplified Heart Rate Variability

If an accelerometer based ballistocardiography system is calibrated to a certain person it can additionally determine the strength of the signal it receives from the human body. This information can be used to weight certain measurements as less important than other measurements with higher signal strength, since the second measurements are statistically seen more viable and more precise than the first measurement [19].

2.2 Sleep Phases

First of all there is phase one. It is the introduction of sleep. This phase is reached when an awake human is getting sleepy and is therefore slowing down his brain activity and starts to relax his muscles [3].

Second is phase two. This stage is the introduction to sleeping. Brain activities are slowed down more and muscle relaxation continues further. Since this phase is still very light sleep the sleeping person can easily be disturbed and would be wide awake. This phase prepares the brain and body for the upcoming dreams. This is also the stage where (throat) muscle relaxation has extended so far, that people might start snoring at this point [3].

The third and fourth phases, also called "slow wave sleep", are the actual "resting phases". In this state the body and brain are able to regenerate power [3].

Rapid Eye Movement, or "REM", is the only stage in which the human is able to experience dreams. Here the brain is very active since it is processing the dream. During REM the entire human body is paralyzed so that actions can only be "performed" in the dream itself and not in the actual physical enviorment [3].

However these stages do not come once per sleep each. It is more like a circulating process. To better understand what this means please take a look at figure 2.3.

To actually measure and conclude to the different sleep phases knowledge about the current heartbeat and breathing must be existent. From these two sets of data the actual sleep phase can be approximated roughly enough for non medical purposes [25].

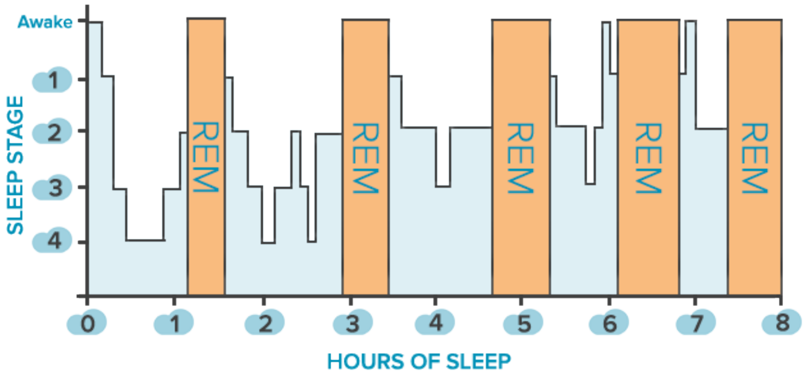

Figure 2.3: The progress of different stages of healthy sleep visualized [32].

2.3 Identification Of Suitable Sensors

This section explains the detailed process of the identification of a suitable sensor and the criteria this sensor has to meet for usage a sleep system environment.

After having identified suitable methods of measurements in section 2.1 one that fits the use-case needs to be selected. For this specific use case the best option can be concluded to be a composition of several sensor components that when combined measure the desired data. For high precision heart- and respiration rate measurements that provide exact information through mattresses either a piezoelectric ballistocardiographic sensor (described in section 2.1.5) or a acceleration based ballistocardiographic (described in section 2.1.5) sensor is required. Since the acceleration based ballistocardiographic sensor provides more precise data and a larger variety of information this sensor is chosen. Since this sensor alone can not provide detailed information about snoring and other breathing related problems a microphone is also added to the sensor composition.

The created combination of acceleration based ballistocardiography sensor and a microphone allows for accurate calculation of sleep phases (described in section 2.2) as well as information about breathing related problems such as snoring. In addition the BCG sensor provides supplementary information that can also be processed into the overall quality of the subject's sleep.

Having acquired this information an acceleration based BCG sensor has to be chosen. The criteria for the system described in chapter 3 were mostly precision and usability. The company Murata[1] produces such a sensor on a solderable printed circuit board (PCB) called SCA10H[2]. Since this board would require a board that matches the pins which would have to be developed first and then reflow-soldered with the chip it is not suitable for prototyping and testing. For these kind of tests the same company developed the SCA11H[3]. This product is a software developer targetted device that utilizes the SCA10H board and adds a WLAN module, an HTTP API server that is hosted on the sensor and a case to it. This enables rapid prototyping and testing of the product.

1 www.murata.com
2 www.murata.com/products/sensor/accel/sca10h_11h/sca10h
3 www.murata.com/en-eu/products/sensor/accel/sca10h_11h/sca11h

Therefore the SCA11H is the sensor of choice. Since the microphone does not have to be accurate the internal microphone of a mobile device will suffice.

2.4 Environment

As previously described in section 2.3 the identification of a suitable sensor is an important step of the development process. The main factors that need to be taken into account are the accuracy and its lifespan so that it does not loose its quality over the time it is used in the system. Especially the way the system is cushioned or padded (section 2.4.1) and the positioning of the sensor (section 2.4.2) is relevant.

2.4.1 Padding

Considering the target scenario of the system is to perform within a soft mattress the ballistic impulses sent out by the heart may be cushioned a lot and can not be received as well as they would be within a non-cushioning environment. If the sensor is used within a hard, solid and impact absorbing enviornment the results of the measurements will be superior. Therefore the sensor needs to be able to measure cushoined impacts.

Another topic that needs to be taken into account is that the system will be able to change its hardness on the surface. As explained previously visco elastic foam may be one of such implementation possibilities (see secion 2.5.1). When utilizing hardness changing mattresses the quality of measurements will vary. The chosen sensor must therefore still be capable of measuring through different levels of hardness without recalibration or other manual configuration processes.

2.4.2 Positioning

Based on the capabilities of the mattress production and on the users comfort the positioning may be limited to certain places within or around the mattress. Therefore the systems sensor must be capable of performing from different positionings. Images of the possible sensor positioning locations and rotations can be found in the project documentation [5].

Placing the sensor module on the side of the bed offers the user the same comfort as be without a sensor module installed. However depending on the quality and configuration of the sensor it may not be able to achieve enough accurate measurements. When installing the sensor module above the mattress, directly below the bed sheet maximum measurement performance is guaranteed but depending on the shape and size of the module it may interfere with the users quality of sleep since the sensor may be felt through the bed sheet. A compromise between comfort and quality of measurement is positioning the sensor module between the mattresses, if multiple mattresses are available on the bed, or within the mattress. The user is not sensing the sensor module and depending on the hardness of the cushion above the sensor it is still capable of providing acceptable measurements. However to implement this system the subjects need to either have multiple mattresses or cut their single mattress open. Placing the sensor below the mattress decreases the sensors performance even more in exchange for a decrease in the possibility of the user feeling the sensor module thorugh the mattress. Also the subjects would not need to have a lot of trouble installing the system compared to cutting the mattress open. This setup however requires an enourmous amount of accuracy on the sensors side.

2.5 Suitable Methods For Setting The Degree Of Hardness And Temperature

Up until this chapter the system would be able to measure precise data and is capable of extracting valuable information about sleeping habits and the subject's recovery. Adding actuators to the system allows it to actively improve the quality of the subject's sleep by for example slightly heating the mattress when the system recognizes that the subject enters a certain sleep phase. Another use-case is the adaption of the mattresses hardness depending on the sleeping position to prevent tensions before they even occur.

2.5.1 Luzern - Viscoelastic Foam

The company "Variowell"[4] developed a mattress that is capable of changing it's hardness as the user prefers.

The project called "Luzern"[34] uses a combination of two viscoelastic foams, a thermo foil and a cold foam base. The viscoelastic foam was originally created by NASA and found it's way into human medical applications. The viscoelatic foams change their hardness based on the temperature that is applied onto them. By modifying the temperature using the thermo foil a wide variety of hard- and softness can be covered. If the viscoelastic foam is getting warmer it gets also softer. Cooling it down makes it harder[34]. Image 2.4 shows this technology.

A side effect of this procedure is that the mattress always has to have a certain warmth to provide the prefered hardness. Thus the user is not able to control the temperature to his liking without disrupting the desired level of hardness.

Another side effect is the high power consumption since it is necessary to keep the warmth applied to the viscoelastic foam during the entire duration of the sleep to keep up the desired level of hardness.

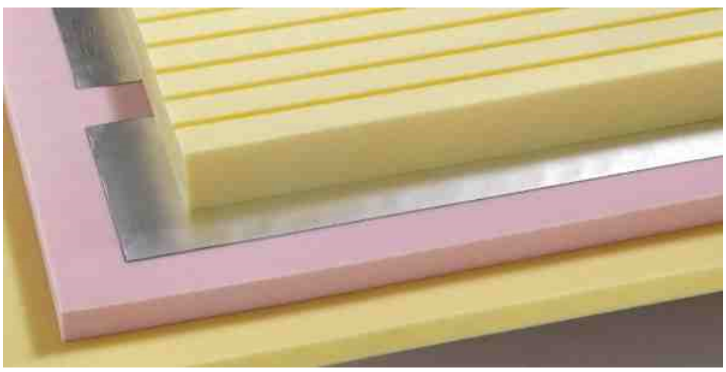

Figure 2.4: Mattress body cut open [34].

[4] www.variowell-development.com

2.5.2 Water Distribution - Adjustable Firmness

A mattress construction in which the firmness of the top surface is selectively adjustable can be achieved by having the body of the mattress provide the primary support for a person lying on top thereof. A removable pillow top covers the mattress body, and is removably fastened thereto along its peripheral edges. A relatively thin fluid inflatable cushion is positioned beneath the removable top such that the pressure in the cushion can be varied to alter the firmness of the mattress top surface [1]. For a concept image take a look at figure 2.5.

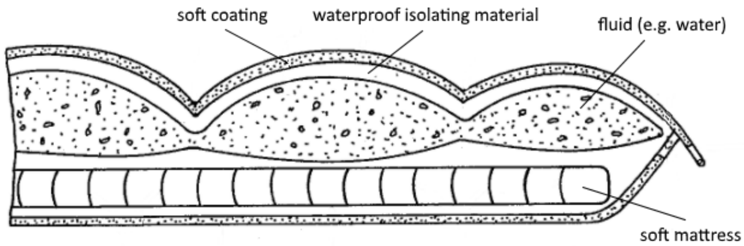

Figure 2.5: Draft of an adjustable firmness mattress based on [1].

2.5.3 Temperature Regulation

Conductive yarns and conductive wires having insulating properties at least on their surfaces are plain-woven as warps and wefts, thus manufacturing a unidirectionally conductive fabric in which neighboring conductive yarns are not electrically in contact with each other. A pair of electrodes is connected to ends of the conductive yarn, and polymeric insulating layers are laminated on both surfaces of the unidirectionally conductive fabric, thus manufacturing an electric heating sheet. Moreover, by forming polymeric covering layers having a thermal fuse function, a temperature-detecting function and a temperature controlling function on the unidirectionally conductive fabrics, highly durable and safe electric heating sheets are manufactured [8].

For further details take a look at figure 2.6.

2.6 Actuators

Actuators perform mechanical actions (e.g. heating) based on control signals. They enable the sleep system to actively interact with the user and assist him directly in improving their sleep.

2.6.1 Hardness

One of the major reasons for low-back pain is unsuitable hardness of the mattress [10].

The hardness of the mattress should also vary throughout the mattress. So that different parts of the body are exposed to different levels of hardness. These sections of

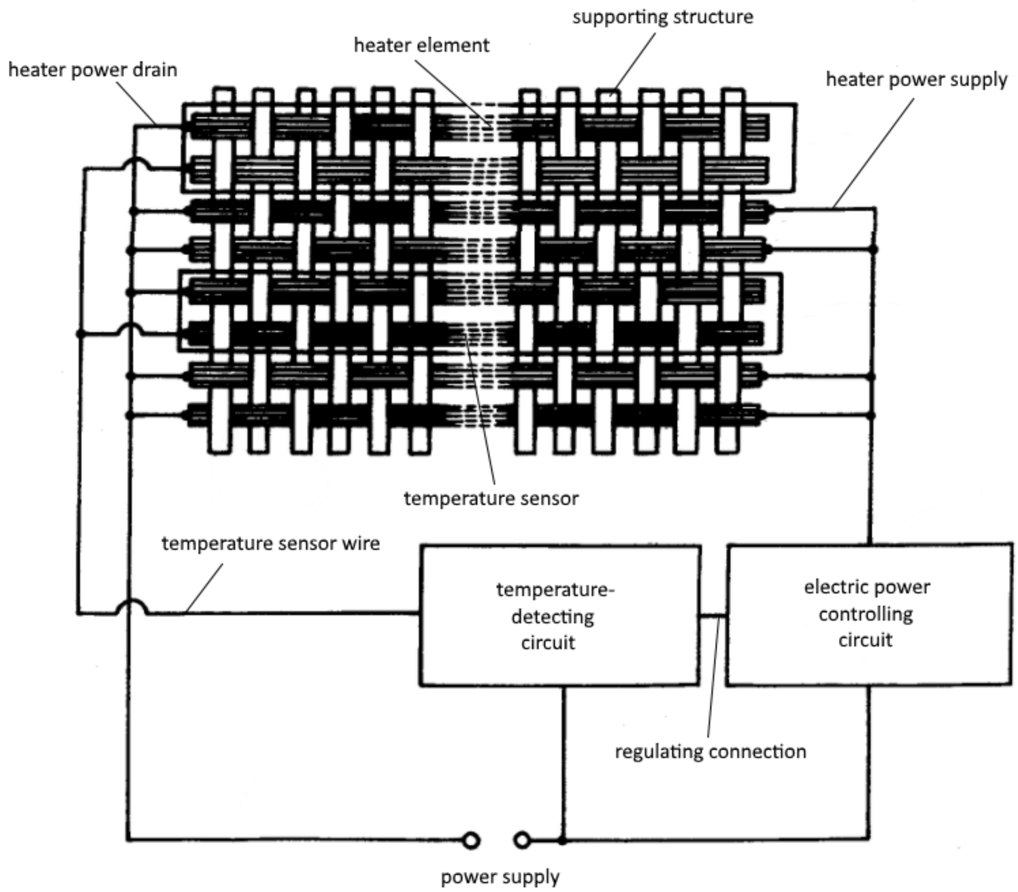

Figure 2.6: Draft of a heat sheet system based on [8].

the body are namely head, upper torso, lower torso and legs [11].

2.6.2 Temperature

Even though regulating the temperature of a sleep system is more of a comfort increasing process a study shows that under certain conditions a constant temperature value is benificial to the users health [13].

2.7 Analysis Of Different Existing Products

The University Of Applied Sciences Upper Austria[5] supplied the project team with several products that are to be tested, taken apart and analysed. The supplied products are listed below.

[5] www.fh-ooe.at/campus-hagenberg

- 2x SleepAce [6]
- 1x SE 80 SleepExpert [7]
- 1x EightSleep [8]
- 1x Withings Aura (sensor module) [9]

2.7.1 Tests

After testing all these systems for about three months the first conclusions could be made. This section also provides a short overview of each products functionality. A quick overview of the performance of the products can be found in table 2.1.

	battery[10]	score[11]	feedback[12]	sleep phases[13]	REM[14]	actuator[15]
SleepAce	x	x	x			
SleepExpert		x	x	x	x	
EightSleep		x	x	x		x

Table 2.1: Conclusion of the tested products.

SleepAce

This product[16] is placed beneath the bedsheet at breast height and does not need to be plugged in to function. To supply it with power it has to be charged every month or two. It is meant to perform completely offline utilizing only bluetooth to push tracked data to a mobile device that has the identically named application installed. To activate it the activator pad must be placed so that the circles align. An image of the product can be seen in figure 2.7.

The app provides the user with multiple screens of information about the sleep. This includes the breathing behaviour, sleep duration, movement in bed and the heartbeat. These informations are shown on a two dimensional graph and are processed into what the manufacturer calls the "Sleep Score". The Sleep score is a number between 0 and 100 that tells the consumer about the overall quality of his sleep.

[6] www.sleepace.com
[7] www.beurer.com/web/at/produkte/schlaf-erholung/schlaf/SE-80-SleepExpert
[8] www.eightsleep.com
[9] www.sleeptrackers.io/withings-aura/
[10] Can function using the interal power supply.
[11] Calculates user feedback consisting of a number between 0 and 100.
[12] Feedback is only recorded, not parsed.
[13] Sleep phases are calculated and presented to the user (see section 2.2).
[14] Sleep phase analysis includes the REM cycle (see section 2.2).
[15] Heat the mattress. Must be activated manually (see section 2.6.2).
[16] www.sleepace.com

Figure 2.7: Image of the product "SleepAce" [33].

The application also allows the user to take notes and answer quick questions about stress level and alcohol consumption. This information does not get processed by the application. It is solely meant to be a check up for the user. The user might then see patterns in his sleep behavior and conclude to furhter actions by him- or herself. Screenshots of the mobile application can be seen in figure 2.8.

To test the product it was placed at breast height between the bedsheet and the mattress. Then the android mobile application[17] was installed on the mobile device (Nexus 5[18] and OnePlus3[19]) that is used to interact with the sensor module. After pairing the mobile device with the sleep sensor module the tracker was ready for usage. The sensor automatically starts tracking as soon as the subject goes to bed and automatically stops when the subjects gets up.

The usability of this product was varying. Since the project team got two different SleepAce sleep trackers two testers were able to test simultaniously. The product has problems keeping the bluetooth connection to the mobile application up and running during the night. The data gathering process might eventually cut off and therefore not provide nether valid, nor usable information. This does however depend on the mobile device that is being used in combination with the product. For example a Nexus 5 mobile device performs better in combination with the product than a OnePlus3 does.

SE 80 SleepExpert

This product[20] is placed beneath the mattress at breast hight and does need to be plugged in to function. It is also meant to perform completely offline utilizing only bluetooth to push tracked data to a mobile device that has the identically named application installed. An image of the product can be seen in figure 2.9.

The app provides the user with multiple screens of information about the sleep. This

[17] play.google.com/store/apps/details?id=com.medicatech.sleepace
[18] www.google.com/nexus/5x/
[19] www.oneplus.net/at/3
[20] www.beurer.com/web/at/produkte/schlaf-erholung/schlaf/SE-80-SleepExpert

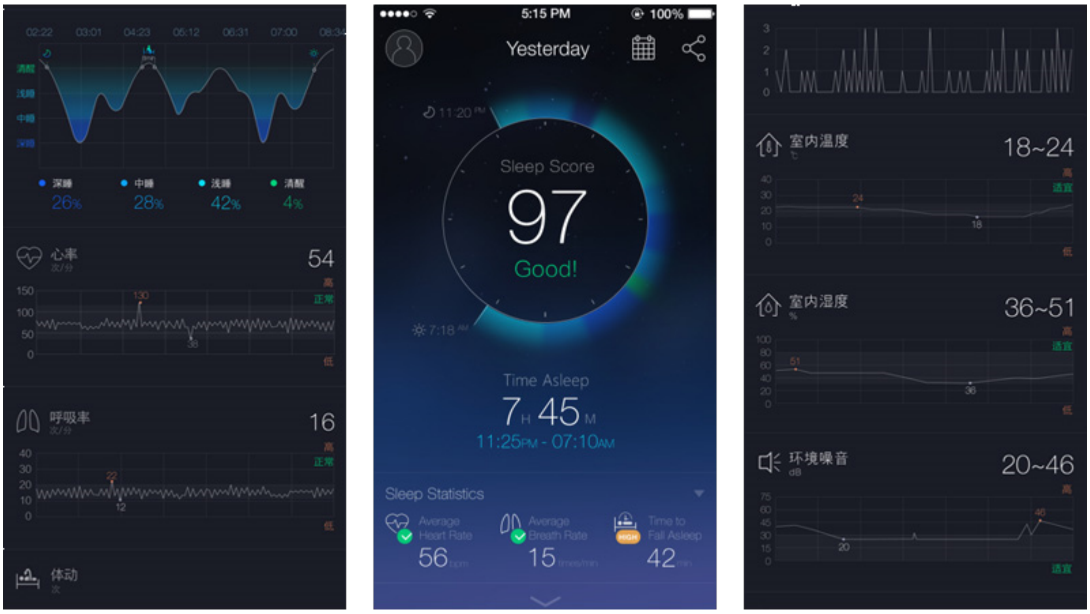

Figure 2.8: Image of the mobile application of the product "SleepAce" [33].

Figure 2.9: Image of the product "SE 80 SleepExpert" [29].

includes the breathing behaviour, sleep duration, movement in bed and the heartbeat. These informations are shown on a two dimensional graph and are processed into what the manufacturer calls the "Sleep Score". The Sleep score is a number between 0 and 100 that tells the consumer about the overall quality of his sleep. This is a similar concept to the one previously described for the product SleepAce (section 2.7.1). The major thing differentiating the two is that the SE 80 Sleep Expert additionally calculates the sleep phases from the gathered data. It then visualizes the sleep phases including REM (see section 2.2) in a two dimensional graph.

The application also allows the user to take notes and answer quick questions about stress level or alcohol consumption. This information does not get processed by the application. It is solely meant to be a check up for the user. The user might then see patterns in his sleep behavior and conclude to furhter actions by him- or herself. Again, this concept is similar the one from SleepAce. Screenshots of the mobile application can be seen in figure 2.10.

Figure 2.10: Image of the mobile application of the product "SE 80 SleepExpert" [29].

The overall experience with this product was very positive. The collected data seem to be accurate and truth representing. There were no connectivity issues between the mobile application and the product itself. However the app does recommend the user to plug in the mobile device during the night to guarantee the successfull transmission of the gathered data to the phone else the application consumes about 70% of the total power an average mobile phone provides. The feature that lets the user see the exact sleep phases of the sleep is also quite useful.

EightSleep

This product[21] is used as a bedsheet beneath the actual bedsheet (figure 2.11). Markings on the top left corner indicate the direction it has to be placed on the mattress. This product does however have a fairly different appraoch than the previously mentioned systems (sections 2.7.1 and 2.7.1) in terms of communication setup. The mattress initially hosts a wireless hotspot that the user may connect to. The mobile application (figure 2.12) then allows the user to configure what wireless lan network the EightSleep should connect to. Additionally the user has to register an account during this process. This is required to use this product. After having performed these setup steps the system reboots and connects to the wireless lan network automatically.

[21] www.eightsleep.com

Figure 2.11: Image of the sleep tracker product "EightSleep" [30].

To synchronize data to the mobile device the mattress has to first push the measured data to the server. After the server finished processing the information the application then fetches the data and presents it to the user. Additionally the application is capable of controlling heat elements that are sewn into the product. Therefore a two way connection is needed, so that the application can at the same time set and read the temperature of the mattress. The heating elements are even at their highest setting not really noticable. Assumingly this feature is more meant to get the bed to the average room temperature when the air in the room itself would be cold.

The application presents the hypngogram (see section 2.2) information in a segmented line that is colored according to the corresponding sleep phase at the time. This gives the user the opportunity to scroll precisely through the sleep data. This approach does however take a long time to analyse the individual sleep data since you have to scroll a lot. Additionally the application calculates a sleep score that is a value between 0 and 100 and represents the overall quality of the sleep. EightSleep is very transparent in the calculation of this sleep score in comparison to the previosly discussed systems. Furthermore the application gives a quick overview of the average data like heart- and respiration rate, percentage of light- and deep sleep phases and bed temperature during the night.

The usability of this product was overall very positive but at times the system would not be able to measure entire sleep cycles and present wrong data to the user. If this occurs the user is left with wrong information that would tell the user that he got up two to ten times during the sleep and that he never fell asleep. Since there is no direct streaming from the EightSleep to the mobile application the user can not check if the system has recognized the subject laying in the bed or not. A big advantage compared to the other tested systems is that this system utilizes at least basic implementation of actuators in terms of temperature control. Also this system is capable of measuring two people, left- and right side of the bed, simultaneously.

Withings Aura

No use case tests could be performed with this product since the project team was not provided with the hub that would be required to do so. The reason for this is that the sole purpose of the product tests and analysis is to get further understanding of how

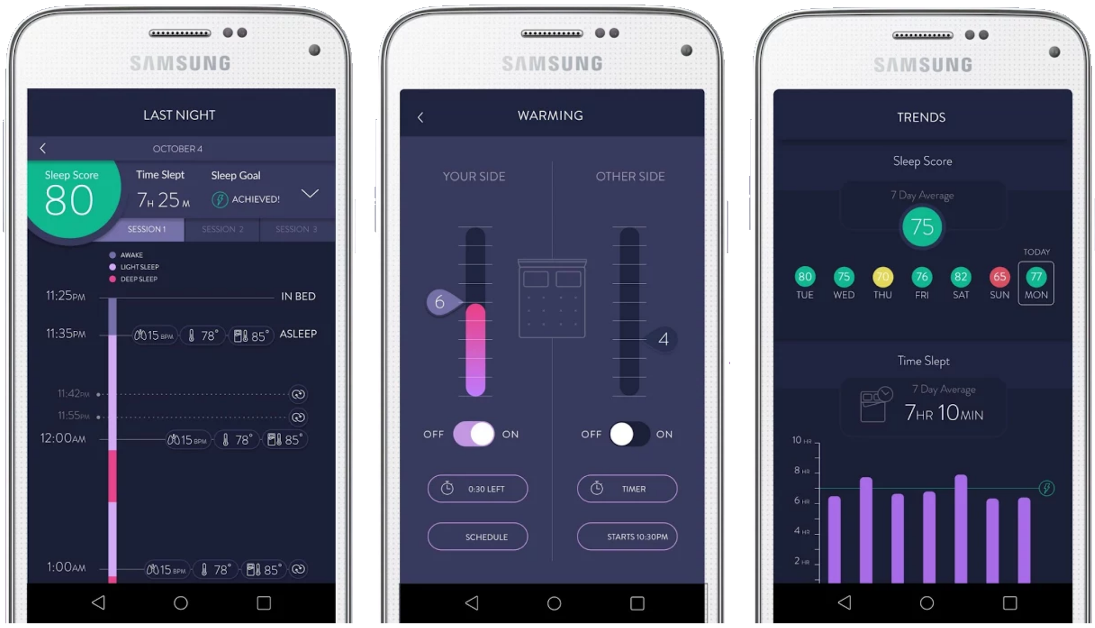

Figure 2.12: Image of the mobile application of the "EightSleep" product [30].

sleep tracking systems currently operate and perform. The provided product (see figure 2.13) is a component that when combined with the corresponding hub can measure a subjects vital data. The Withings Aura analysed in terms of hardware in section 2.7.2.

Figure 2.13: Image of the Aura Withings hub (left) and sensor module (right) [35].

2.7.2 Analysis

All of the products were taken apart and analysed. Especially looking at the hardware components like sensors, analog-digital converters and micro controller units (MCUs). Based on this analysis in combination with the previously performed tests (section 2.7.1) a more thorough insight into the subject of the state-of-the-art in sleep monitoring can be concluded. An overview of the analysis results can be seen in table 2.2. Images of the disassembly process of the systems can be found in the enclosed documents.

	battery[22]	piezo[23]	strip[24]	disc[25]	multi person[26]
SleepAce	x	x	x		
SleepExpert		x		x	
EightSleep		x	x		x

Table 2.2: Conclusion of the tested products.

SleepAce

The sleepace consists of two major components. The sensor strip and the box that contains the PCB and power supply. For an image of the product take a look at figure 2.7.

After seperating the strip from the controller box the box can be furhter disassembled into the following components:

- Cover
- Container with PCB
- Activator

The cover reveals four magnets that help keep the activator in place. The activators inside reveals some user instructions. To take a closer look at the PCB and to analyse how it works it had to be carefully removed from the container. Researching several of the chips that are soldered onto the PCB reveals that this product uses ballistocardiography to gather vital information. SleepAce is powered by a 1600 mAh battery that outputs 3,3 V.

SE 80 SleepExpert

The SE 80 SleepExpert consists of one component. It is a circular box with a comparable small PCB inside. For an image of the product take a look at figure 2.9.

To analyse the SE 80 SleepExpert it has to be taken apart carefully. This can again be done by using a sharp object (e.g. a knife) and carefully unlocking the pins that are hidden below the white top cover. An overview of the opened up product can be seen in figure A.2. This step also reveals the PCB that holds the circuitry on solely the top side. The two major chips that can be seen are a bluetooth low energy (BLE) module (left) and a 24 bit analog to digital converter (bottom right). The piezoelectric sensor (see section 2.1.5) that is attached to the top cover of the SE 80 SleepExpert provides the system with a precice analog signal that is then converted into digital values. These values seem to not be prepeared on the PCB, but sent to the mobile application for

[22] Functions using the interal power supply.
[23] Performs measurements based on a piezoelectric sensor (see section 2.1.5)
[24] Strip shaped sensor system.
[25] Disc shaped sensor system.
[26] Can measure up to two different subjects simultaneously.

further processing.

EightSleep

The EightSleep sleep tracking module is a bed-sheet-like product that is placed between the mattress and the actual bedsheet. For an image of the product take a look at figure 2.11.

To analyse this product it has to be taken apart by cutting open the threads that hold the top and bottom piece of cloth together. This reveals the controller box that is hidden inside a fixed compartment made from fabric that is closed tightly by a strip of velcro fastener. Unscrewing four screws that hold the top of the box onto the body opens it. Inside the PCB can be found (figure A.3). The board has multiple outgoing connections from left to right (each twice for both sides of the bed):

- Piezoelectric sensor (see section 2.1.5)
- Thermistors (for temeperature observations)
- Heat wires (heat actuators)
- Power supply

Taking a closer look at the piezoelectric sensors reveals that there are two of them, one for each side of the bed. It is sewn into the cloth and held in place by velcro fastener. By opening the velcro the strip can be sperated from the sheet. This give a better insight as to how the strip is working since the ballistic force absorbing perpendicular strips assist in transferring the blood preassures signal to the piezoelectric sensor inside. Opening the strip reveals the same wiring technology and a piezoelectric strip as already discovered in the AceSleep system in section 2.7.2.

Withings Aura

The Withings Aura consists of three major components. A slightly inflatable rubber section, the box that contains the printed circuit board and a fabric sleeve that encases these components.

After removing the rubber section and the controller box from the fabric sleeve the box can be opened by removing the screws on the bottom side of it. Removing the cover of the product reveals the following components that can also be seen in figure A.4:

- Printed circuit board containing chips for processing as well as a preassure sensor.
- Air pump
- Air valve
- Tubing connecting the PCB, air pump and valve.

Therefor it can be concluded that the system uses air preassure to measure data. The pump inflates the rubber section to a certain degree where then the air pressure sensor on the PCB and the air valve work in combination to gather information about pressure changes. This data is then used to calculate vital data such as heart rate.

Chapter 3

System Concept

This chapter contains information about the planned concept that is to be implemented. The project itself is seperated into three different sections that are also represented by different bachelor thesis [7] and [6] created by the team members. Further details about the entire project can be found in the project documentation [5].

3.1 Concept Description

The idea behind this project is to fill the gap in the available products of sleep trackers: a system that actively assists the subject in achieving more power recovering, relaxing and comfortable sleep. By using sensors that measure the subjects vital information, such as heart- and respiration rate, and processing this information on a server, the system is able to conclude to actions that help the subject to a better sleep. This actions can for example be warming of the mattress during certain sleep periods to deepen the sleep or adapting the firmness of different sections of the mattress to prevent unwanted tensions. The mobile application is used to visualize and present the tracked data to the subject.

Use case descriptions as well as diagrams and the corresponding requirements are located in the project documentation [5].

3.2 System Architecture

A block diagram (figure 3.1) was created to represent the system architecture of the project. The blocks function as described below.

3.2.1 Mobile Application

While there is no direct communication from the hardware to the mobile application [7] in the prototypical implementation it is used for user interaction. This includes presenting measured data that is previously prepared by the backend (section 3.2.3) to provide insight into the users sleep phases. It is also used to send configuration data over the backend to the hardware. Furthermore its purpose is to gather feedback of the user to the tracked sleeps that are then processed by the backend which may result in configuration changes that are sent to the hardware.

The structure of the mobile application is a MVVM (Model View ViewModel) pattern. It therefore distinguishes between the following architectural components:

- View (user interface without any logic)
- ViewModel (utilizes data binding to update data on the View)
- Model (business logic to process and transceive data over a network)

Utilizing this pattern allows clean responsibility seperation between the components which makes it more manageable and adaptive to future updates.

3.2.2 Hardware

The hardware consists of multiple foam sections. Inbetween the foam sections the sensors and the controller are located. The controller communicates through the internet with the backend and receives commands from the application over the backend. Commands that are received from the backend can then be processed to let the actuators perform the mechanical changes. To do so the hardware system is split into the following components:

- Sensors
  - Ballistocardiographic Sensor
  - Temperature Sensor
- Actuators
  - Hardness Regulator
  - Heater
- Communication Module
- Controller
- Storage

The ballistocardiography sensor sends measurement data to the controller component every second which is persisted in the storage module. When the subject gets out of bed the data is processed by removing parts of the mearuement results that are not required for sleep analysis such as time sections in which the user was laying inside the bed but has not gone to sleep yet. It is then compressed by reducing the measurement points from one per second to one every thirty seconds. This is performed to provide lower network traffic as well as storage usage while still being able to extract information about sleep phases. This form of compression also links together with sleep analysis algorithms since these often are set out to use one value per thirty second formats [6]. If networking is available the system sends the gathered information to the backend by handing the data over to the communication module. Else the system sends the data as soon as the communication module is reconnected to the network. For reference take a look at the sequence diagram in figure 3.2

The communication module also receives commands from the backend that were sent by the user using the mobile application. These commands are then forwarded to the controller that persists the received commands in storage so that they can be recalled if the hardware system is restarted or not connected to the internet. After persisting the incoming commands the controller sends out control signals to the hardness- and heat actuators to adapt the environment according to the changes instructed by the received commands.

To achieve a risk- and effort estimation for this concept and its components the most vital functionalities such as a prototype appropriate ballistocardiographic sensor that still emulates the target sensor as much as possible and the controller are implemented in chapter 4. The prototypical system implementation is oriented to enable a transition from the prototypical sensor to the target sensor.

For optimized network traffic usage the compression algorithm is implemented in section 4.3.4. Furthermore the implemented sensor and its measurement results are described and analysed in chapter 5 and sent to the backend (section 3.2.3) thorugh the implemented communication module.

3.2.3 Backend

The three-tier Representational State Transfer (REST) backend [6] links the mobile application (section 3.2.1) with the hardware (section 3.2.2). The features it provides to the system are as follows:

- Authentication
- Data storage
- Data access
- Measurement Analysis

Any data transferred from or to the backend is encrypted and secured through Hypertext Transfer Protocol Secure (HTTPS). Authorization is also provided thorugh the implementation of different roles that restrict the users ability to perform actions on the backend depending on their authorization role. The steps each request has to go thorugh to be authorized and performed is as follows:

- Authentication (login)
- Authorization (role)
- Business Logic (data validation)

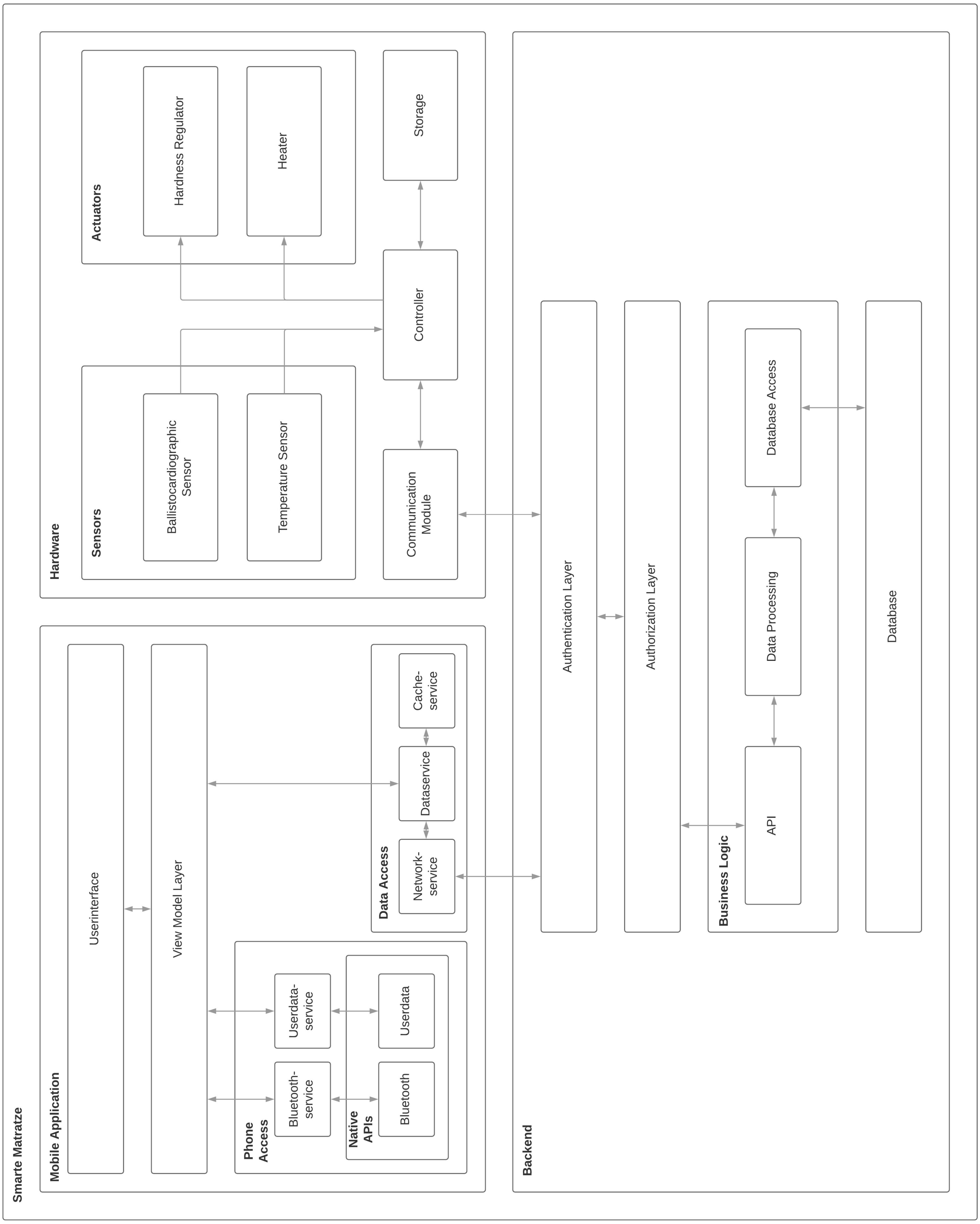

Figure 3.1: Block diagram of the system.

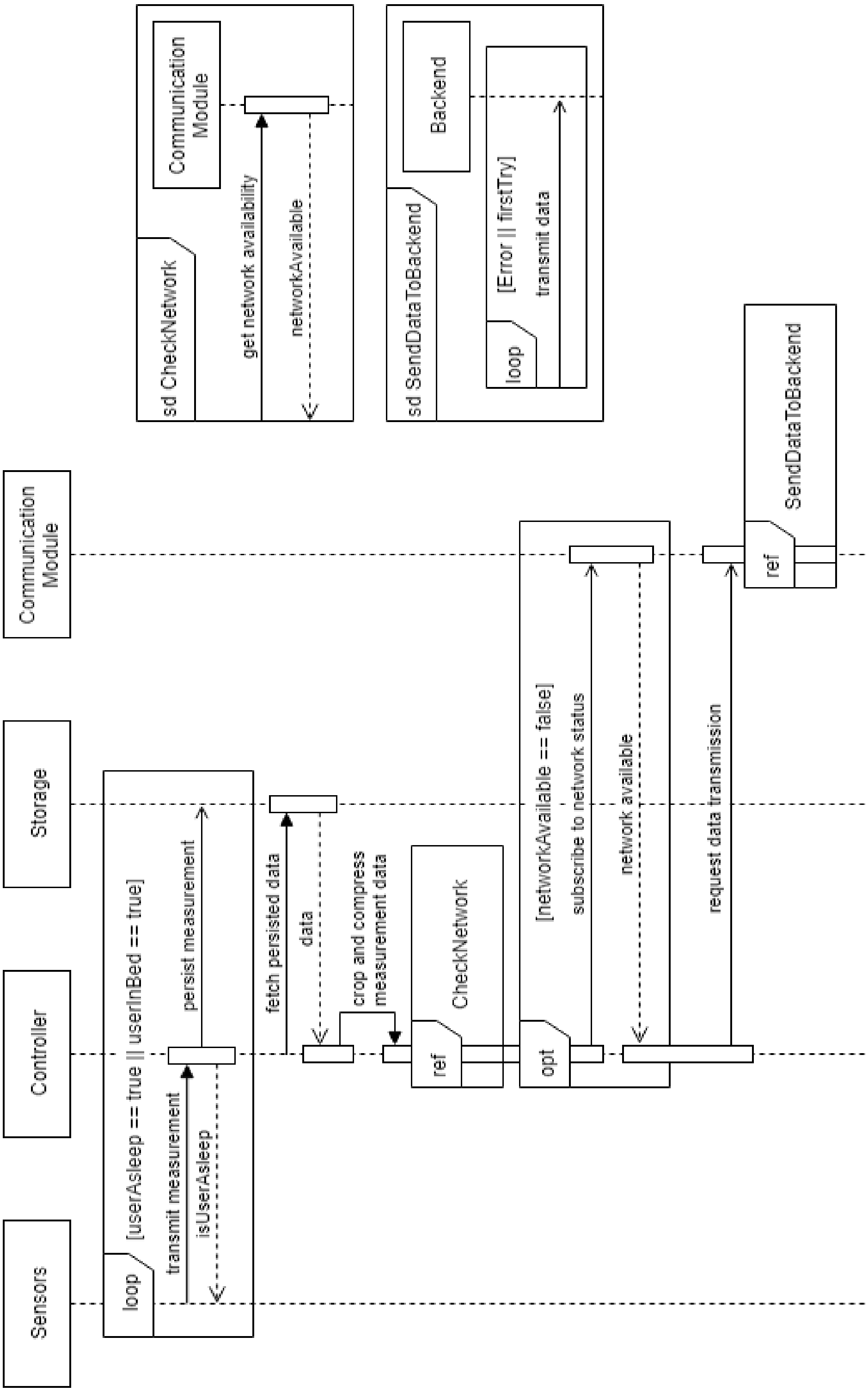

Figure 3.2: UML sequence diagram of the measurement, processing and forwarding of the data.

Chapter 4

Implementation

This chapter contains the prototypes implementation that is mainly targeted on gathering vital data. The purpose of the developed infrastructure is to emulate the target system as well as possible. This is done to face possible problems and enable the thinking process to solving them as soon as possible during development. With this implementation strategy in mind the prototype infrastructure consists of the following components that will be explained in detail further down the line.

4.1 Sensors

Taking into the prevoisly mentioned characteristics of suitable ballistocardiography sensors (section 2.3) into account the most suitable sensor in terms of presicion is the SCA10H. Considering the lifespan of accelerometer based ballistocardiography sensors compared to piezoelectric sensors this choice is enforced (section 2.1.5).

4.1.1 Ballistocardiographic Sensor

The selected target accelerometer based ballistocardiography sensor, SCA10H, is not capable of communication over Wireless Lan and only provides wired interface such as UART (Universal Asynchronous Receiver Transmitter). This sensor would have to be put through a rather complex process, such as reflow soldering, to be able to be tested. Therefore the first implementations and tests were performed using a Wireless Lan enabled accelerometer based ballistocardiography sensor, SCA11H (see section 2.3)), that utilizes the same sensor chip as the SCA10H. Since both modules use the same chip the PDR (Pulse Detection Range) does not differ and the increased current consumption of the SCA11H is due to the Wireless Lan interface. Using the SCA11H 4.1 features can be implemented and prototype applications can be developed with acceptable accessebility since the power consumption can be neglected for this prototypical implementation. For further comparison between the SCA10H and the SCA11H take a look at table 4.1.

Network Setup

To start working with the SCA11H sensor it has to be configured to connect to a Wireless Lan network. The process to do, is to download the android mobile application from

Figure 4.1: The SCA11H sensor used in the prototypical implementation.

	Size (mm)	Current Consumption	Pulse Detection Range	Waterproofing
SCA10H	28 x 26 x 7	8 mA	40 - 120 bpm	none
SCA11H	84 x 41 x 18	60 - 65 mA	40 - 120 bpm	IP55

Table 4.1: Technical data of the SCA10H and SCA11H [16].

the murata homepage[1] that may be used for the first time setup of a SCA11H ballistocardiography sensor [17]. The way the application works is that the SCA11H hosts a Wireless Lan network with the name "BSN-<serial number>". The mobile application knows the passphrase to this WPA secured network and uses the REST interface of the sensor [18] to configure the modules parameters.

After downloading, installing and launching the application the following steps need to be performed in the application to set up the sensors connection to a Wireless Lan network. Each of the following instructions is located on a seperate screen between which can be navigated using the arrow shaped buttons on the bottom left (previous step) and the bottom right (next step) of the screen.

1. Let the application scan for available networks.
2. Select a target wireless network.
3. Enter the passphrase to the selected network.
4. Choose the communication setting "Local" to enable REST functionalities for measurements.
5. Select an SCA11H network node from the provided list. The elements of the list are SCA11H nodes that are not yet connected to a network and whose Wireless Lan is in range of the mobile device.
6. Click "Connect to target network".

[1] https://www.murata.com/products/sensor/accel/sca10h_11h/sca11h

The SCA11H now persists the provided network data (SSID and passphrase) in storage and the device reboots. During the following boot process the device reads the stored network information and attempts to connect to the target network. If the connection is established successfully the process network set up process ends. If the credentials are incorrect or the target network is not available or out of reach the sensor re-opens his own Wireless Lan interface and is ready to be reconfigured through the android mobile application.

A problem that occured during this setup process is that there is no visual distinction between 2,4 GHz and 5,0 GHz Wireless Lan networks. The network that was used for setting up the SCA11H ballistocardiography sensor in the first place was a 5,0 GHz network. It was shown the same way 2,4 GHz networks were shown in the murata android application and therefore could be chosen to connect to. The problem is that the SCA11H does not support 5,0 GHz communication. To solve this problem a new 2,4 GHz network had to be created. After creating a seperate, 2,4 GHz based, network and distinguishing it visually from others by ending the SSID with "_2G4" the sensor module was able to connect to the newly created network.

HTTP REST API Structure

Now that the initial Wireless Lan network setup is completed the next step is to implement the REST functionalities of the device [18]. In front of all following endpoint names the sensor modules local IP address needs to be added to be able to communicate with the device. If no return parameters are defined the body of the response will contain a "errno" field that is 0 on success while otherwise containing an error code. The http REST api endpoints have both POST and GET request functionalities unless stated otherwise and the main components are structured as follows:

- **/sys**: resource system that modifies the state of the system.
  - **/sys/mac**: returns the devices MAC address (GET only).
  - **/sys/scan**: listenes for available Wireless Lan networks and returns a list of the results (GET only).
  - **/sys/netowrk**: SSID and passphrase of hosted or connectable Wireless Lan networks.
  - **/sys/netinfo**: detailed Wireless Lan network data such as DHCP configuration and channel selection.
  - **/sys/rssi**: returns signal strength to the connected wireless network.
- **/bcg**: resource system that modifies the state of the BCG module.
  - **/bcg/sn**: returns the bcg sensors serial number (GET only).
  - **/bcg/mode**: ballistocardiographic running mode.
  - **/bcg/pars**: calibration parameters.
  - **/bcg/dir**: measurement direction.
  - **/bcg/cali**: ballistocardiographic calibration.

Get System Information

To perform the "Hello World" test the "/sys" command was performed. This command returns information about the device such as the universally unique identifier (UUID) and firmware versioning. For all initial REST api tests the software Postman[2] was used. After configuring Postman to send a **GET** request to the endpoint **/sys** the result in listing 1 is returned upon sending it to the sensor.


```
{
 "uuid": "5CF8A15D8714",
 "name": "BSN-5CF8A15D8714",
 "alias": "Bedsensor-1",
 "fs_ver": "1.0.4.0",
 "fw_ver": "2.3.0.0",
 "wlan_ver": "2.0.0.0"
}
```


Listing 1: Example response of the SCA11H /sys command.

The information in listing 1 is read as follows:

- uuid: universally unique identifier of the device.
- name: the name that represents the device in a Wireless Lan network. It consists of BSN-X, the X being the MAC address of the device.
- alias: human readable alias of the device.
- fs_ver: file system version.
- fw_ver: main firmware version.
- wlan_ver: Wireless Lan firmware version.

Reboot and Restore

After confirming that the sensor module is operative and ready to receive further commands the next step is to be aware of the **/sys/cmd** endpoint functionalities. The possible options that can be sent to this **POST** endpoint are javascript object notation (JSON) encoded **reboot** and **restore**. After performing any changes in the sensor module configuration using the http REST api the device needs to be rebooted using the "reboot" command. If the sensors measurements are lower quality because of a wrong calibration or the settings have been modified unintentionally it is possible to rollback the sensor module to factory default settings using the restore command. A JSON encoded body template for both of these functionalities can be seen in listing 2.

BCG Running Mode

Up next is to define the format that the sensor should return the measured ballistocardiographic data. This is done by sending a **POST** request to the running mode endpoint

[2] www.getpostman.com

```
{
 "cmd": <command>
}
```

Listing 2: POST body of the SCA11H /sys/cmd endpoint. In the <command> field either "reboot" or "restore" may be used.

/bcg/mode. The possibilities to choose from are stated by murata as follows [18]:

- BCG: The module measures acceleration with 1kHz interval and runs the result through the algorithm. Processed output data is sent at a 1Hz rate.
- Data Logger: 1-axis, AC. The module measures and sends raw acceleration data with 1kHz.

The data logger mode provides the raw accelerometer data of the sensor module. This running mode is used if the accelerometer data is to be processed into vital information such as heart rate and respiration rate on a seperate device. Because of limited knowledge about such data processing the BCG mode that returns already processed information is chosen and sent to the sensor node as javascript object notation in the POST body of the request. For reference of the body modify the content of the listing 2 to set the **"mode"** parameter to either **0** for ballistocardiographic (BCG) or **1** for data logger running mode.

Calibration

The final step of the setup is the calibration process. This step, while not necessarily needed, enables the ballistocardiographic sensor to measure with higher accuracy which then provides more reliable data. This process is split into two seperate sub processes or phases: empty bed calibration and occupied bed calibration. Both need to be performed to receive optimal quality of measurement data. What is interesting to note is that the calibration data is mainly influenced by its environment, especially the matress it is used in comination with. For production in bigger numbers with similar sensor positioning and mattress material the calibration data only needs to be collected for one of these products. It can then be sent to the sensor modules with a **POST** request to the **/bcg/pars** endpoint [18].

To check the calibration status of the sensor module send a **GET** request to the **/bcg/cali** endpoint. The result is structured as presented by listing 3.

The way to read the response of the calibration GET request is defined by murata as follows [18]:

1. status: calibration status code. The most important status codes are -2 (calibration not performed yet), -1 (calibration in progress), 0 (successfully calibrated) and 8 (calibration failed).
2. phase: calibration phase indicator. Can either be 1 (empty bed callibration) or 2 (occupied bed calibration).
3. step: calibration step counter. The time for calibration, both empty and occupied

```json
{
  "status": -1,
  "phase": 2,
  "step": 0
}
```

Listing 3: GET request response body of the SCA11H /bcg/cali endpoint. If the "status" field has the value -2 (not calibrated yet) neither "phase" nor "step" are contained in the response.

bed, take 60 seconds. In this field the step counter is displayed starting from 0x00 and counting every second to 0x3B (decimal 59). After a calibration phase is finished the step field is set to 0xFF (decimal 255).

After knowing how to check the calibration status the actual calibration process begins. For this the same **/bcg/cali** endpoint is used but this time with a **POST** request. The JSON encoded body of this request contains the field "phase" that may be set to the values 1 for empty bed calibration or 2 for occupied bed calibration. Before sending this request the bed should either be empty or occupied, depending on the calibration phase that is to be started, beforehand. If the occupied calibration phase is performed make sure that the subject lies comfortable in the bed and does not toss, turn or talk during the 60 second calibration process. After having sent the command to start a calibration phase the previously mentioned GET request for calibration data can be performed to get insight into the current status of the calibration. Especially the "step" field needs to be observed and checked regularly to know when the process is finished.

When the "step" field reaches the value 0xFF the calibration phase is finished. Now the not yet performed calibration phase, either occupied or empty calibration, is up next. After finishing the second phase the calibration is finished and the calibration parameters may be read from the device with a **GET** request on the **/bcg/pars** endpoint. As previously mentioned these parameters can be used so skip the setup process in similar sensor environments.

4.2 Raspberry Pi 3 - Controller

For the controller as well as the communication / storage module a Raspberry Pi 3[3] device was chosen. The reason for this is that the device has got very lightweight hard- and software and allows for quick and comfortable prototyping. As previously mentioned at the current state of the system the controller does not have any actuators whose interface can be implemented. Therefore no components can be controlled by this component. The current purpose of this device is to transceive information that is communicated through the communication module that is described in more detail in section 4.3.

[3] www.raspberrypi.org/products/raspberry-pi-3-model-b/

4.2.1 VNC Viewer

To use the Raspberry Pi efficiently and to not having to have a seperate monitor for the modules the Virtual Network Computing (VNC) interface was enabled on both devices. To set up this interfacing option on the device the Pi needs to be connected to a monitor through HDMI. Furthermore a keyboard and mouse are required. After having prepared the hardware a terminal can be opened and the command "raspi-config" can be executed. This command assists in performing system changes such enabling VNC, changing passwords, overclocking and more. From here "Interfacing Options" needs to be selecet. On the following screen select "VNC" and enable it.

Furthermore the resolution of the VNC screen can be defined by navigating back to the main menu. From here select advanced options and set the VNC resolution to something that fits the developers needs but still does not demand too many resources from the Pi. For this implementation the resolution was set to 1920x1080. After rebooting the raspberry pi a VNC client such as RealVNC[4] can connect to it.

4.2.2 Enable UART

The future target sensor, the SCA10H, is not capable of Wireless Lan networking and rather uses the universal asynchronous receiver transmitter (UART) protocol. To emulate this target environment for the system as much as possible the communication of the controller is solely through UART (section 3.2.2). Similarly to the previous VNC setup the UART communication has to be enabled before being able to use it. For this process follow the steps of setting up the VNC Viewer (section 4.2.1) but in the "Interfacing Options" menu select and enable UART communication. This step reconfigures the raspberry pi registries and configuration files to enable the UART pins GPIO14 and GPIO15 to be used as communication pins, namely transmit data (TXD) and receive data (RXD).

4.2.3 Circuitry

The universal asynchronous receiver transmitter protocol requires two connections. Since we enabled UART previously (section 4.2.2) the GPIO pins 14 and 15 now function as UART TXD and RXD. These connections need to be crossed so that data that is transmitted (TXD) by one module is received (RXD) on the other and vice versa. Additionally the GND pins are connected to each other and therefore provide a common reference voltage between the two devices.

4.2.4 Transceive Data

Having established the hardware infrastructure needed to communicate between the two modules using UART the next step is to set up the software connectivity. The following script in listing 4 opens a connection to a serial port line 1. The specific serial port that is being connected is defined by the "/dev/ttyS0" parameter which references to the UART interface. The second parameter defines the speed of communication on the data channel also called baudrate. It is important that the sender and receiver define this

[4] www.realvnc.com

parameter with the same value. The third and last parameter defines that the connection will not time out even when the interface is inactive. The second line attempts to create a file in the Pi home directory that contains a timestamp in its name and accesses it with writing permission. If this step succeeds the script listens in a loop for incoming data transmissions on the previously opened port. When data is received it is stored in the created file in cache and afterwards flushed for persistence. If any exceptions are thrown they are caught in line 8 and printed onto the console in line 9.

```
1 port = serial.Serial("/dev/ttyS0", baudrate=9600, timeout=None)
2 with open('/home/pi/eaf_' +
  ↪ str(datetime.datetime.now().strftime('%Y-%m-%d_%H-%M-%S')),
  ↪ 'w') as f:
3   while 1:
4     try:
5       data_chunk = port.readline()[:-2]
6       f.write(data_chunk.decode('utf-8')+'\n')
7       f.flush()
8     except Exception as e:
9       print(str(e))
```

Listing 4: Transmission of data via UART on a Raspberry Pi.

4.3 Raspberry Pi 3 - Communication Module / Storage

The communication module and storage are combined into one Raspberry Pi 3 module for the time being since it provides more flexibility in terms of adapting to requirement changes and testing the developed code. This module is in charge of the following functionalities:

- Host Wireless Lan network for the SCA11H to connect to.
- Receive measurement data from the SCA11H sensor and route it to the controller.
- Persists received measurement data.
- Acts as interface to the backend of the system.

When implemneting the SCA10H sensor module the measurement data will be communicated directly to the controller module through the UART system that is already implemented (section 4.2.2).

4.3.1 VNC Viewer

A VNC setup was also performed on this raspberry Pi to ease the development process. The steps of the setup can be copied from the previous VNC setup in section 4.2.1.

4.3.2 Enable UART

Since this component has to communicate with the controller the same UART enabling process has to be performed. These steps can also be copied from the previous UART setup in section 4.2.2. The code snippet in listing 5 is responsible for routing measurement data to the controller over UART.

```
1  print('UART setup in progress...')
2  serialUart = serial.Serial('/dev/ttyS0', 9600, timeout=None)
3  filename = 'logged_data_' +
   ↪  str(datetime.datetime.now().strftime('%Y-%m-%d_%H-%M-%S')) +
   ↪  '.txt'
4  fid = open(filename, 'w')
5  print('Starting to read data. Press \"ctrl+c\" to quit.')
6  while True:
7      try:
8          s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
9          s.settimeout(10)
10         s.connect((IP, PORT))
11         while True:
12             data = readLine(s)
13             print(data, )
14             serialUart.write(bytes(data, 'UTF-8'))
15             fid.write(data)
16             fid.flush()
17     except (KeyboardInterrupt, SystemExit):
18         print('Exiting program.')
19         fid.close()
20         break
21     except (socket.timeout):
22         print('Timed out, reconnecting.')
23     except socket.error as msg:
24         print(msg)
25         print('Trying to reconnect.')
26     finally:
27         s.close();
```

Listing 5: Routing script for the received measurement data.

The code looks similar to the controllers receiver code fom section 4.2.4 since the data is still received in a loop from the sensor module. The UART setup and file creation (line 2, 3 and 4) are of similar functionality as in section 4.2.4. The script then enters a loop in which data is received from the SCA11H sensor module in line 12 after establishing the connection in lines 8 and 10. Line 9 sets a timeout to the connection so that in case the connection can not be established the process is exited. Immediatly after receiving data in line 12 the data is printed onto the console in line 13 and is written to the created file that acts as storage for the specific measurement and can later be recalled. The lines 17 to 20 handle keyboard interrupts such as "ctrl+c", lines 21 and 22 handle timeout exceptions. Lines 23 to 25 handle socket errors while lines 26 and 27 are responsable for closing the socket connection if any of the exceptions occur.

4.3.3 RaspAp WebGui

The RaspAp WebGui[5] is an open source software that allows for the creation and modificaiton of a raspberry pi hotspot through a web user interface rather than ssh commands. Or in the words of its creator:

> A simple, responsive web interface to control wifi, hostapd and related services on the Raspberry Pi [27].

Setup

To install the software the following command in listing 6 needs to be executed in a shell session on the communication and storage module device. This can be done either through a secure shell, the previously set up VNC service or by working directly on the raspberry pi hardware.

```
pi@localhost:~$ wget -q git.io/voEUQ -O /tmp/raspap && bash
↪  /tmp/raspap
```

Listing 6: Shell command for installing the RaspAp application.

After this process is finished the device needs to be restarted in order to create a Wireless Lan network.

Configuration

Now that the installation is complete, connect to the newly created Wireless Lan network with the default credentials which are:

- SSID: **raspi-webgui**
- Password: **ChangeMe**

When working directly on the device this step can be skipped. After connecting to the network enter the gateway IP address which can be acquired with the command **ifconfig** on Linux or **ipconfig** on Windows. When working directly on the device use the loopback IP address **127.0.0.1**. On the web gui you will be prompted for administration credentials which are by default:

- User: **admin**
- Password: **secret**

[5] www.github.com/billz/raspap-webgui

After the authentication is finished the hotspot is reconfigured to have the SSID **smarte-matratze-host** and the password **smartematratze**. Further changes such as DHCP configuration can also be performed on the user interface.

Internet Protocol Address Lease Time

Even though the IP address of the ballistocardiography sensor is searched for with the simple service discovery protocol (SSDP) this process may take a minute or longer. To bypass this time the SSDP process is started only on the initial start. The IP address is then stored and can be recalled for instantaneous connection to the sensor. The discovery script utilizes parameters and request responses that are predefined and therefore semi unique to the ballistocardiographic sensor module [20].

This time conservation comes with a cost: If the lease time of the IP address runs out the stored IP address may no longer be corresponding to the sensor module. To fix this problem the lease time of the IP addresses in the hotspot are set to 0 and last therefore indefinate.

4.3.4 Tornado Webserver

The creation of algorithms that detect specific events such as a person going to sleep or waking up a Tornado[6] web server was implemented to emulate such events. These event are triggered through the press of a button on the web interface of the developed web server. To start the service the following command in listing 7 is executed.

```
pi@localhost:~$ python webserver.py
```

Listing 7: Shell command for starting the web server.

After having started the python script the service opens a connection on port 8888. Connecting to this service through the IP address, loopback if localhost, and said port reveals a basic html page with a button. To emulate a person finishing a sleep session press the button. This in turn triggers a jquery hook to run a python function for getting authentication of the mattress on the backend. The code for fetching the authentication token can be seen in lsiting 8.

The script additionally makes sure that the mattress is assigned to a user that the measured data will be associated with. The mattress serial number (line 3) and secret (line 4) are set during the production process by the manufacturer and can not be changed by the user.

After confirming that the mattress is assigned to a user the measured data is compressed to consume less traffic while still being able to extract sleep phase information. This compression is done by combining every 30 one second measurements to a single measurement point through the median function. The data is then written to a dictionary for direct JSON export capabilites. During this step the timestamps are also

[6] www.tornadoweb.org

```python
def __getToken(self):
    # Result in dictionary format
    data = {"serialNumber": self.__serialnumber,
            "secret": self.__secret}
    url = "{}/api/mattress/token".format(self.__host)
    print("{}\n".format(url))
    # The actual backend request, verify=False since the backends certificate is not officially signed
    response = requests.post(url, json=data, verify=False)
    if(response.ok):
        # Bearer token
        self.__token = response.headers["Authorization"]
        # Mattress identifier
        self.__mattress_id = response.json()["id"]
        # User identifier
        self.__user_id = response.json()["userId"]
        # Debug prints to console
        print(self.__token)
        print(self.__mattress_id)
    else:
        response.raise_for_status()  # exception: Http-Status != 200
```

Listing 8: Script for fetching authentication token.

corrected after deviating of the compression. The script that performs these actions can be seen in listing 9.

```python
result = {
    # Values of the arrays (RRRes, HRRes,...) are formatted to dictionary (JSON)
    # and timestamps are corrected by index multiplication with 30
    "respiratoryRate": [{"timestamp": self.__get_datetime_string(startTime + datetime.timedelta(seconds=(i*30))), "value": RRRes[i]} for i in range(0, len(RRRes))]
    # ...
}
```

Listing 9: Script for measurement data compression.

One problem that occured during the development process was that the Tornado framework upgraded to a python version that was not yet available through the raspberry pi apt-get mirrors. To work around this problem the source code of the new python version had to be downloaded manually and be compiled locally on the device itself using the following commands that can be seen in listing 10.

```
$ sudo apt-get update
$ sudo apt-get install build-essential tk-dev libncurses5-dev
$ sudo apt-get install libncursesw5-dev libreadline6-dev libdb5.3-dev
$ sudo apt-get install libgdbm-dev libsqlite3-dev libssl-dev libbz2-dev
$ sudo apt-get install libexpat1-dev liblzma-dev zlib1g-dev
```

Listing 10: Manual download of the required packages for building python locally.

These lines set up the build environment that is required for the compilation process. After having installed the above packages the python (in this case version 3.6.0) setup can commence with the following lines of code in listing 11.

```
$ wget https://www.python.org/ftp/python/3.6.0/Python-3.6.0.tar.xz
$ tar xf Python-3.6.0.tar.xz
$ cd Python-3.6.0
$ ./configure
$ make
$ sudo make altinstall
```

Listing 11: Download and build process for python.

Chapter 5

Results

This chapter is focused around the evaluation of the measured sensor data and a comparison of two example results. These measurement results are compared to each other and differences and outcomes of certain values are described and discussed.

5.1 Data Analysis

Figures A.5 and A.6 are both measurement results that were gathered by the project teams members. All the different data that is sent by the sensor can be seen in the images. The timestamp value, that starts at zero when the measurement process is started by the sensor, is incremented every second and acts as the x-axis in the graphs seen in the images. Both data sets have a similar length of 25000 data entries. Since these are, as mentioned before, recorded every second these sleep measurements both have a duration of approximately seven hours. The measured vital functionalities are:

- Heart rate (HR)
- Respiration rate (RR)
- Relative stroke volume (RSV)
- Simplified heart rate variability (HRV)

Signal strength (SS) and status values are solely used for weighting results according to their propability to be authentic. These parameters may be processed in the backend developed by [6] to perform accurate sleep phase analysis. Both the signal strength, as well as the the status signal values, are referring to the signal that is received from the subjects vital functionalities. The status value provides the values zero, one or two with the corresponding meanings low-, ok- or high signal [19].

The three beat-to-beat time (B2B) parameters are non-zero if one/two/three beats have been detected during one second [19]. This data is used by the sensor to calculate the vital functionalities mentioned above.

5.2 Measurement Comparison

When comparing figure A.5 and A.6, henceforth referred to as data sets A and B, some indications for data analytics can be taken before going into algorithm processing in the backend. The two data sets were recorded by two different team members that are using different types of beds and therefore provided a contrasting environment.

5.2.1 Measurement Interruptions

When taking a look at the A and B data sets multiple measurement interruptions, where the measured value appears to become zero, can be seen. This behaviour is observed to occur when the subject is still awake and is not lying as motionless as he would be if the subject was asleep. Little motions such as tosses and turns which may naturally occur during the sleep also cause such behavior in the measurement result. Note that the majority of these interruptions occur at the start and end of the sleep since the subject may not be sleeping deep enough or might be interrupted by his environment, such as noise, more often. Data set A provides an example where a lot of tossing and turning is present especially at the start of the measurement, while data set B shows that the subject showed a lot of motion approaching the end.

5.2.2 Data Authenticity

Another difference between the data sets A and B can be seen at the values of the status graph. Data set A provides more sophisticated vital functionality data since the status value is mostly at two (high signal) and one (ok signal) while the status value of data set B toggles mostly between zero (low signal) and one (ok signal). The observation of measurement interruptions (section 5.2.1) is also reflected at the start of the status values of data set A which is zero (low signal) since the subject was not deep asleep yet and probably performed a lot of motions. The reason for the overall difference in the status is that the sensor was closer to the subject when measuring data set A compared to when measuring data set B.

5.2.3 Sleep Phase Analysis

A reference point for the quality measurement is also the comparison to the systems tested in section 2.7.1. The tested SleepExpert product 2.7.1 is taken as point of reference since it is the only tested system that is able to measure the rapid eye movement (REM) sleep phase. To perform such a comparison the SleepExpert had to measure the same sleep as the developed system. The measured data is then sent to the backend where it is then analyzed [6]. The result (figure A.7) shows comparable values of sleep phases but still requires further development in the analysis algorithm. The line labeled as "project result" represents the sleep analysis of the developed system while the other, filled curve represents the result of the SleepExpert for the same sleep. The color codes for "awake", "REM", "light sleep", "deep sleep" and "not in bed" change according the the height area in which the curve is at the time.

Chapter 6

Summary and Outlook

The contemplated system concepts implementation was accomplished and provided the connectivity to the backend as well as the systems prototypical measuremt functionality described in chapter 3. The implemetations perform their corresponding task without errors and provide the expected results. The measurement results provide enough accuracy as well as authenticity to be used in the further implementations of the system.

6.1 Existing Measurement Methods

Multiple measurement methods were analyzed for suitability of usage in a sleep system environment. Each of them were evaluated and categorized according to their characteristics such as contactless functionality and accuracy in section 2.1. Of all the tested methods for measuring human vital functionalities the ballistocardiographic approach is selected to be implemented in the prototype. Measurement of unusual breathing breathing behavior, such as snoring, may be performed using a microphone. The implementation of the microphone was however not relevant for the prototypical implementation.

6.1.1 Sleep Phases

An introduction into the topic of sleep phase analysis was given which provided insight into the different types of phases, such as REM, light sleep and deep sleep, and their impact on energy restoration (section 2.2).

6.1.2 Environment

Padding and positioning are crucial in gathering accurate vital functionality data in a sleep system. This is due to the cushioning mattress which may seperate the sensor from the subject and have negative impact on the quality of the measurements performed. The benefits and drawbacks of the different positioning possibilities are described, discussed and evaluated in section 2.4.

6.2 Existing Actuator Systems

Existing actuator systems for hardness- as well as temperature regulation are described and evaluated for their suitability in the system in section 2.5. While temperature regulation may be performed thorugh conductive yarns or wires, the hardness regulation would require either viscoelastic foam or preassure distribution systems.

6.3 Existing Products

Three existing products that perform tasks comparable to the project were tested for usability in section 2.7. These three and one other system was then disassembled and their hardware was reverse-engineered to get insight into the methods the systems use for sensors as well as actuators.

6.4 System Concept

Based on the gathered knowledge about exisitng and tested systems as well as the researched methods of measurement a system concept is developed in section 3. This system concept includes the work of two other team members (mobile application [7] and backend [6]) and the implementation plan for a prototype of the system.

6.5 Hardware Infrastructure

The infrastructure of the hardware is implemented using the architecture that consists of ballistocardiographic sensor, communication module, controller and storage as described in section 4. While the communication- and storage modules are ready for further implementation the controller still needs to be further developed. This is due the actuator hardware not being available for testing which is required to develop the controllers interfaces to these components. Another future step is to exchange the prototypical ballistocardiographic sensor for the target sensor which is more suitable for mass production. This switch to the target sensor was considered during the development of the prototype.

6.6 Results

The data measured by the prototype system implementation is described and discussed using two example measurements performed by two different subjects and abberations of expected results are given reasons for. Using the backends sleep phase analysis [6] a comparison between the systems results and an existing products results is performed.

Appendix A

Images

Figure A.1: Removing the foam material reveals two wires inside the SleepAce.

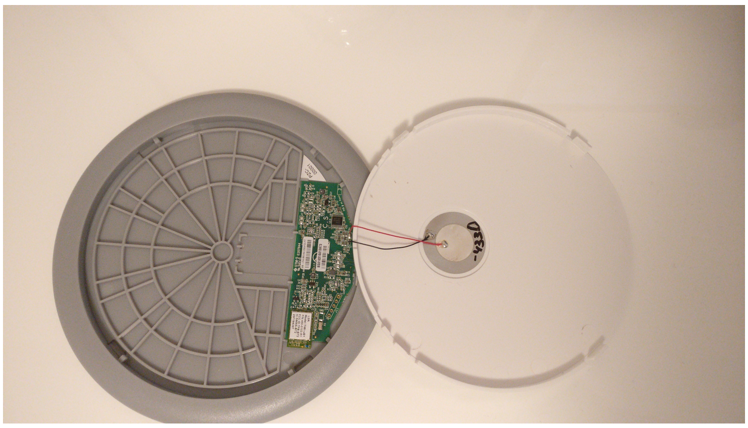

Figure A.2: Overview of the opened SE 80 Sleep Expert.

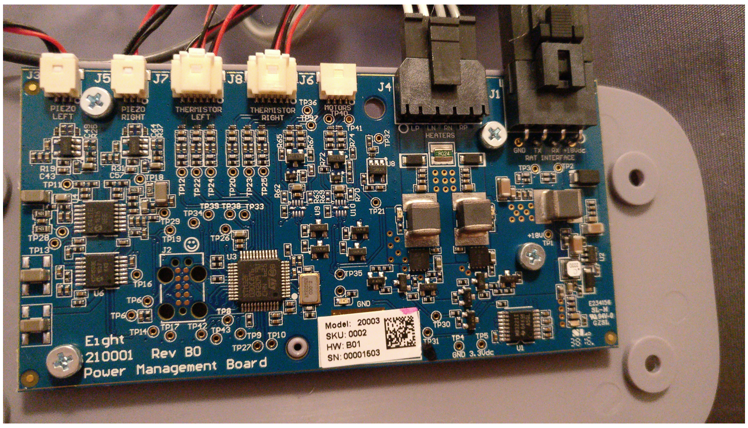

Figure A.3: A closer look at the EightSleep PCB inside the controller box.

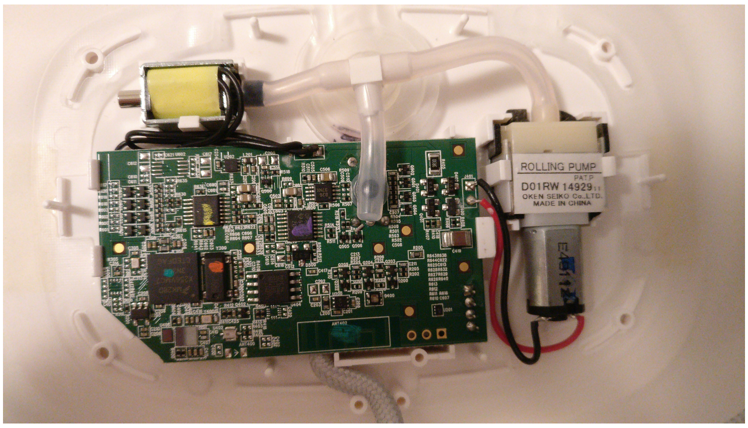

Figure A.4: Withings Aura sensor module box opened up reveals PCB.

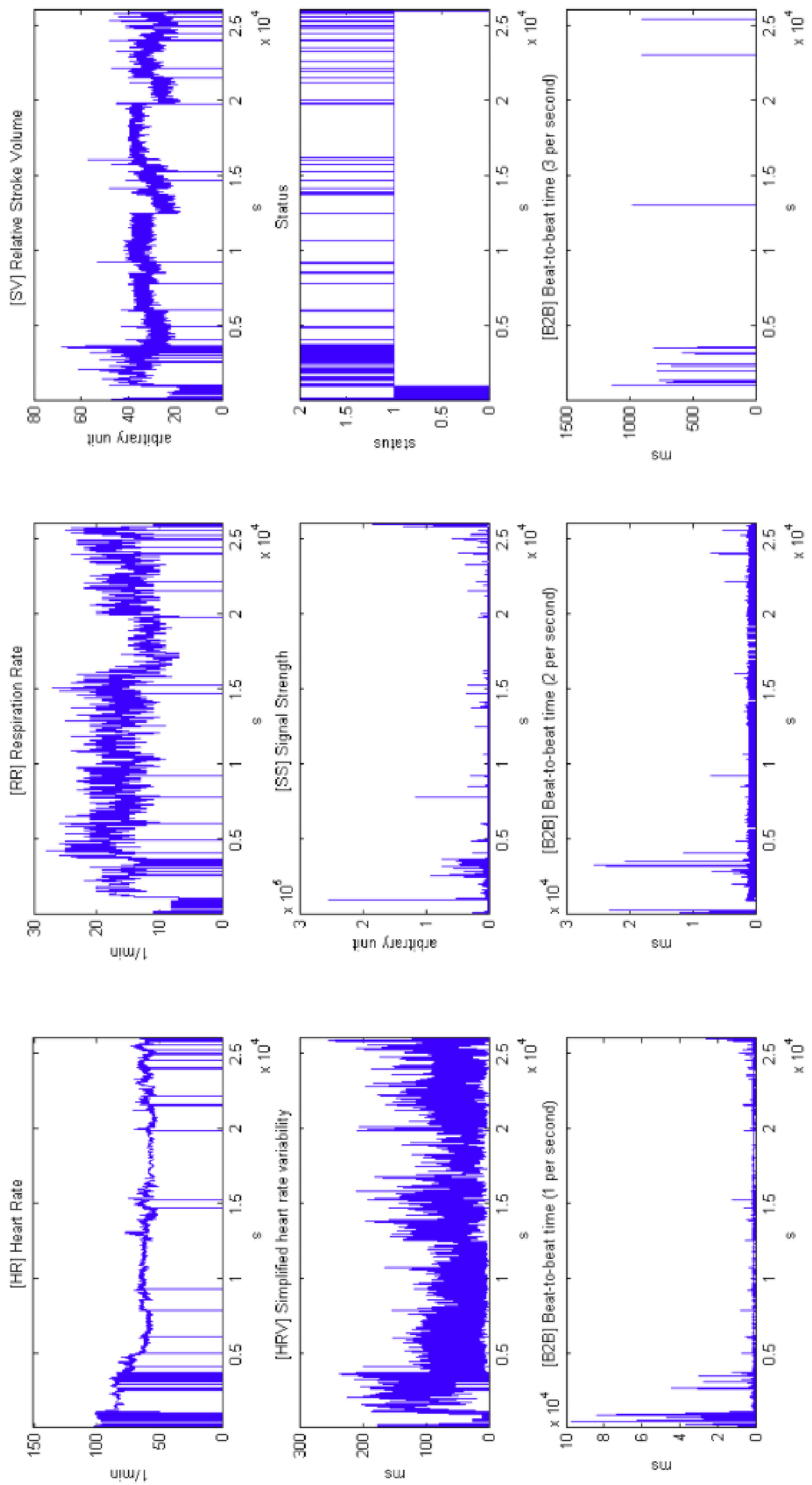

Figure A.5: Visualization of a raw measurement data.

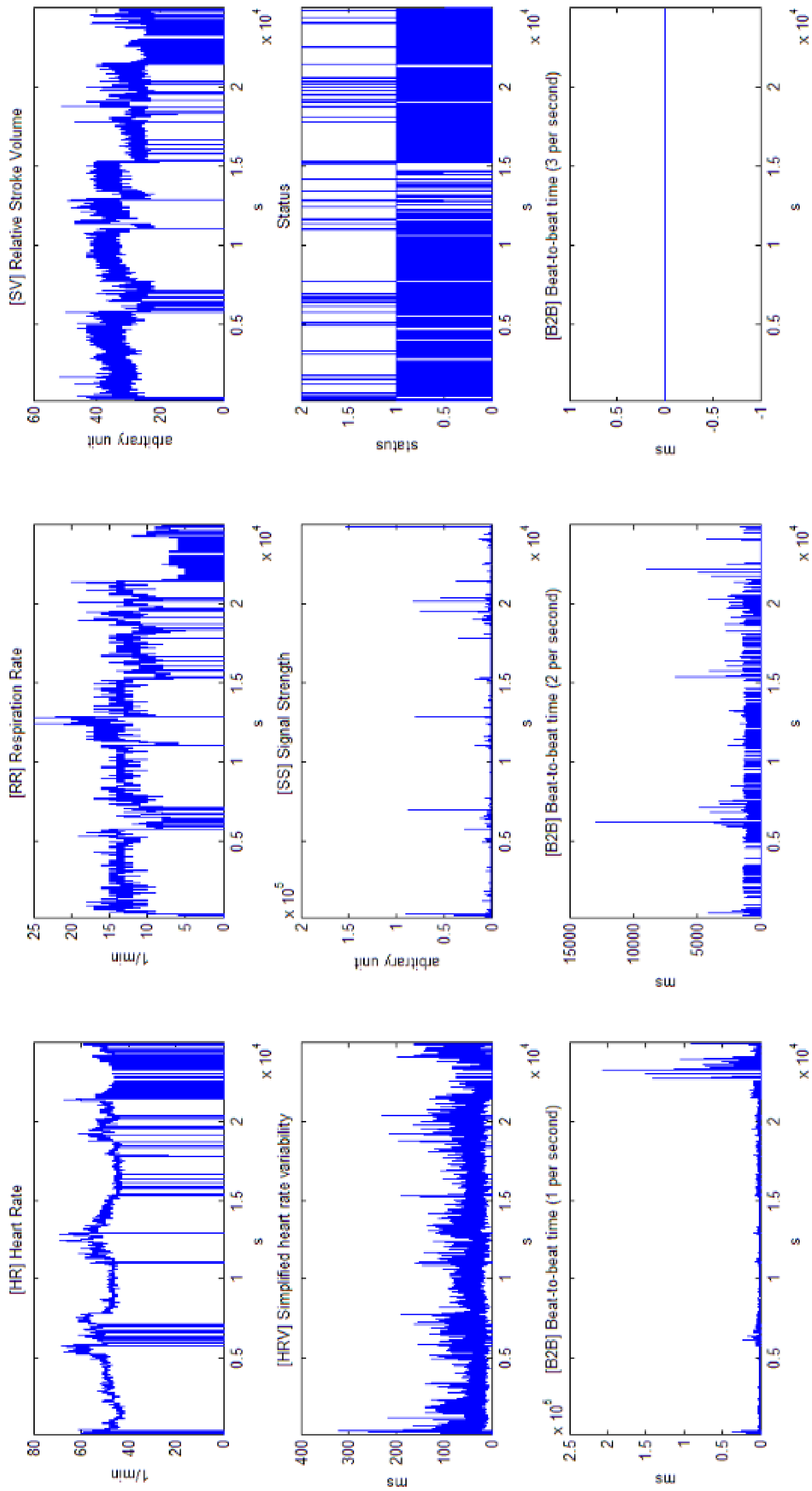

Figure A.6: Visualization of another raw measurement data.

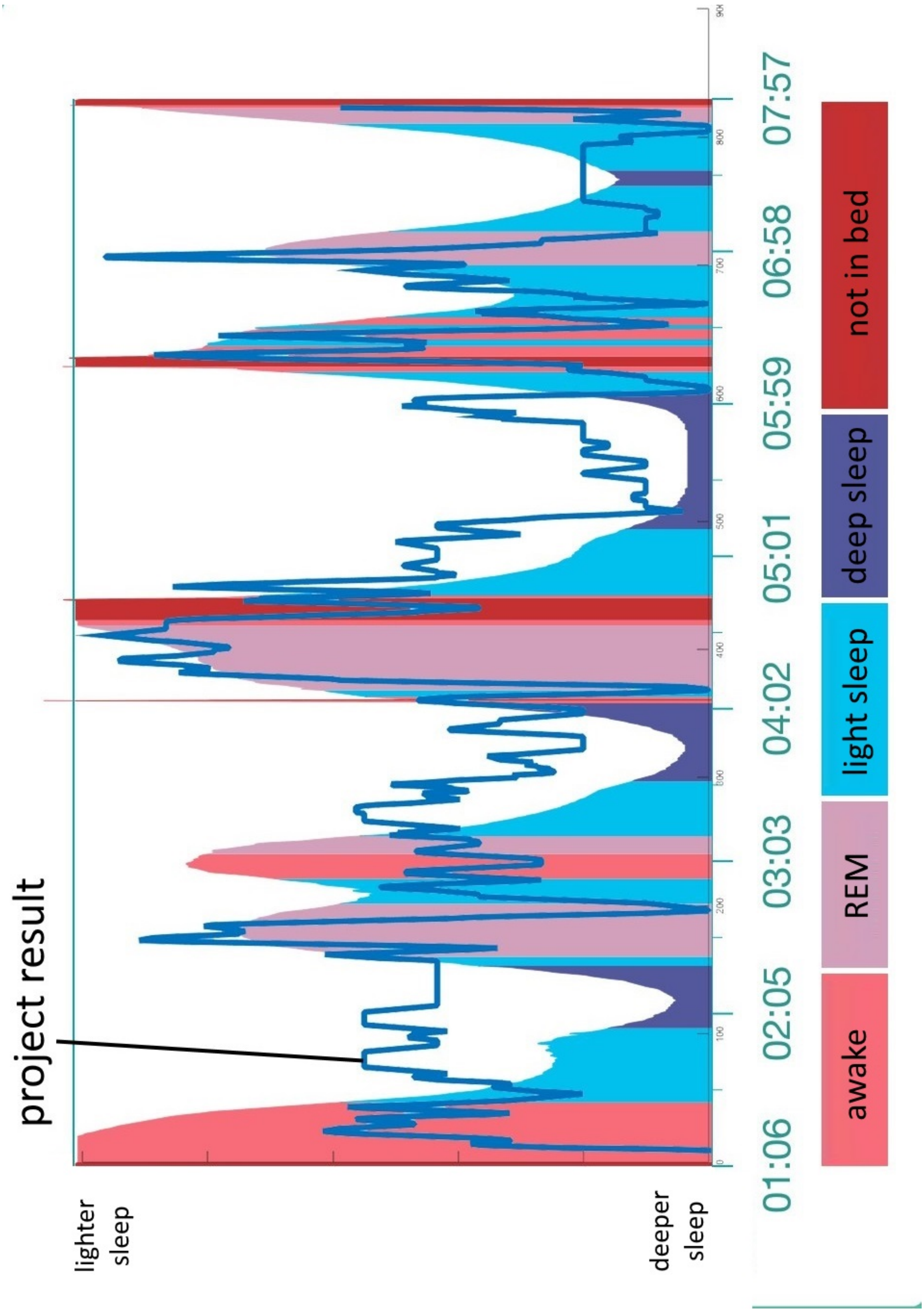

Figure A.7: Comparison between the existing SleepExpert system and a self performed sleep phase analysis using our measurements based on [6].

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