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Recovery and Stress Meter

Requirement Specifications

Hardware project

School of ICT

Metropolia University of Applied Sciences

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Version history

Ver	Description	Date	Author(s)
0.1	First draft. Translated from Finnish template.	23.9.2022	SL
0.2	Working principle added to the introduction. Description of the current situation added.	24.11.2022	SL
0.3	Description of the target state added.	25.11.2022	SL
0.4	Continuing description of the targe state.	28.11.2022	SL
0.5	Added heart rate detection and heart rate variability to Ch 3. Edited Ch 4. Added key features, use and users, and platforms of application.	2.12.2022	SL
0.6	Added first draft of functional and non-functional requirements, users and use cases	3.12.2022	SL
0.7	Updated non-functional requirements. Minor changes and proof reading.	11.12.2022	SL
0.8	Some language corrections up to 3.3. May need further correcting.	13.12.2022	SH, SL
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1.0	Added Table 3. Components	23.1.2023	SL
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Commented [SH1]: Tarkastin tekstin vielä loppuun ja tein jonkin verran muutoksia + lisäsin muutaman kommentin. En saanut lisättyä tähän taulukkoon uutta riviä, mutta sinä varmasti saat :-)

Table of contents

1 Introduction

This document is part of a hardware project for the first year ICT engineering students studying at Metropolia University of Applied Sciences. The aim of this document is to give the requirement specifications for a new health technology device for measuring recovery and stress index using optically detected heart rate and its variability.

The state of the autonomous nervous system (ANS) can be estimated from the heart rate variation. Nowadays most of the wearable activity tracking devices and sports watches detect the heart rate and its variability either electrically (e.g. detecting the electrocardiogram or some parts of its signal) or optically (e.g. optical heart rate detector or oxygen saturation detectors). [1]

Heart rate variability (HRV) is an accurate method to assess the autonomic nervous system (ANS) function. HRV is widely used by health and wellbeing professionals to objectively measure the physiological and mental stress and recovery. In addition, HRV is a commonly used tool in the research of different cardiovascular and metabolic diseases and their risk factors. [2]

The aim for the project is to build an objective and easy to use device for measuring HRV and estimate the current stress or recovery status. The device is intended to be used in home or office environments either by the end users themselves or together with health and wellbeing professionals such as physiotherapists, nurses or medical doctors.

The device detects the heart rate and its variability using a photoplethysmography (PPG). It measures optically blood volume changes in the microvascular bed of tissue. The change in volume is detected by measuring the light emitted by the light emitting diodes (LEDs), absorbed by the tissues and detected with photodiodes. The heart rate can be measured from the peaks of the alternating signal presenting the volumetric blood changes in the tissue. [3]

2 Concepts and definitions

α	Slope of the linear interpolation of the spectrum in a log-log scale
ANS	Autonomous nervous system
BPM	Beat per minute
ECG	Electrocardiogram
IBI	Inter-beat-interval, measured from PPG signal, given in milliseconds (ms)
HF	High frequency
HR	Heart rate, typically given in units of beat per minute (BPM)
HRV	Heart rate variability, measures how much there is variability in the heart rate from beat to beat over longer time period, can be characterized by several parameters
LAN	Local area network
LED	Light emitting diode
LF	Low frequency
LF/HF	Ratio of LF/HF
NN interval	Time difference between two peaks either in ECG or PPG signal, either PPI and RRI
NN50 count	Number of pairs of adjacent NN intervals differing more than 50 ms
OLED	Organic light emitting diode
pNN50	NN50 count divided by the total number of all NN intervals
PPI	peak-to-peak interval, time difference between two pulse peaks in photoplethysmography signal
PPG	Photoplethysmography, optically detected heart pulse typically detected from peripheral blood circulation, like from finger, wrist, toe, or ear lobe
PNS	Parasympathetic nervous system, part of autonomic nervous system
PTSD	Post-traumatic stress disorder
RMSSD	The square root of sum of squares of differences (ms)
RRI	RR-interval, time difference between two R-peaks in ECG signal
SD1	Poincaré plot index
SD2	Poincaré plot index
SDANN	Standard deviation of the average of NN intervals (ms)
SDNN	Standard deviation of all NN intervals (ms)
SI	Baevsky's stress index
SDSD	Standard deviation of differences between adjacent NN intervals (ms)
SNS	Sympathetic nervous system, part of autonomic nervous system
ULF	Ultra-low frequency
USB	Universal serial port
WiFi	Wireless fidelity
VLF	Very flow frequency

3 Description of the current situation

3.1 Stress

Stress is defined as “a physical, mental, or emotional factor that causes bodily or mental tension” [4]. According to the American Institute of Stress [5] [6]:

- 77 % of people experience stress that affects their physical health
- 73 % of people have stress that impacts their mental health
- 48 % of people have trouble sleeping because of stress
- 33 % of people report feeling extreme stress

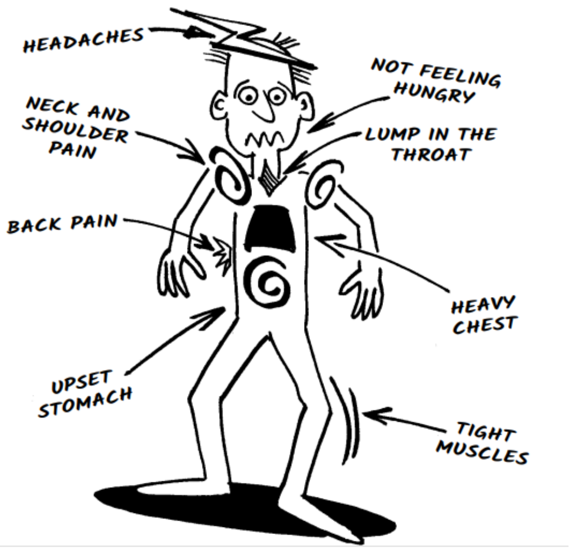

Figure 1. Very high stress often affects the body. Many people get unpleasant feelings. Original from [7].

Physiological or mental imbalance can induce stress. Our autonomic nervous system (ANS) quickly responds with physiological changes through our sympathetic (SNS) and parasympathetic (PNS) nervous systems. During the stress response our body’s endocrine system releases hormones, and several changes in our physiological state occur. For example, heart rate (HR) can even double or triple and causes changes to HRV. [8]

3.2 Detecting heart rate

The heart rate or pulse rate measures how often the heart beats and is given units of beats per minute (BPM). Usually, the heart rate varies on the body’s physical need, but is also affected by physical fitness, stress of psychological status, diet, drugs, hormones, environment and diseases and illnesses. The normal resting adult heart rate is 60-100 BPM. During sleep, a heart rate of 40-50 BPM is common and considered normal. [9]

Heart rate variability (HRV) is the variation of the time intervals between heartbeats and it is measured in units of seconds, or more commonly, in milliseconds (ms). Other terms used include RR interval (RRI) variability, where R corresponds to the peak of QRS-complex of electrocardiography (ECG), and Peak-to-Peak interval, if the HRV is measured optically. Figure 2 visualizes heart HRV with R-R interval changes. [10]

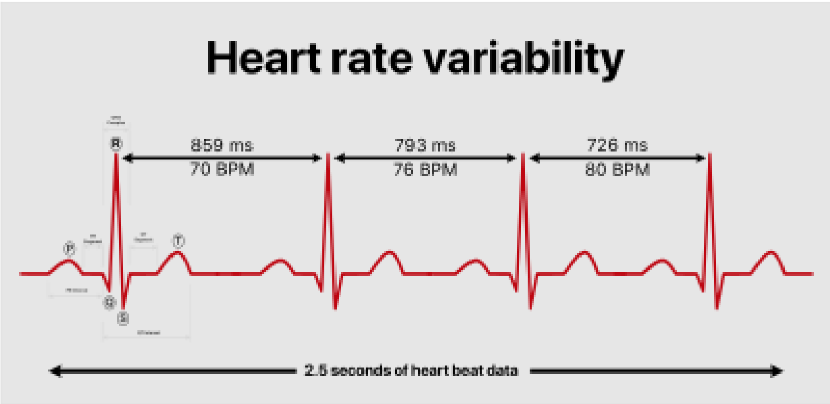

Figure 2. Heart rate variability (HRV) calculated from the R-R intervals (RRI) [10].

Heart rate variability can be detected with various methods. ECG is considered the golden standard for HRV measurement [10]. Other methods are photoplethysmography (PPG), which detects the heart rate variability optically, usually measured from fingers, wrists, forehead or earlobes, blood pressure or ballistocardiography, which measures small changes in body's weight when the blood flows from the heart to the aorta.

Figure 3 shows a typical fitness and wellness watch having an optical heart rate sensor [11]. The light emitting diodes (LEDs) and optical detectors are seen on the back of the watch.

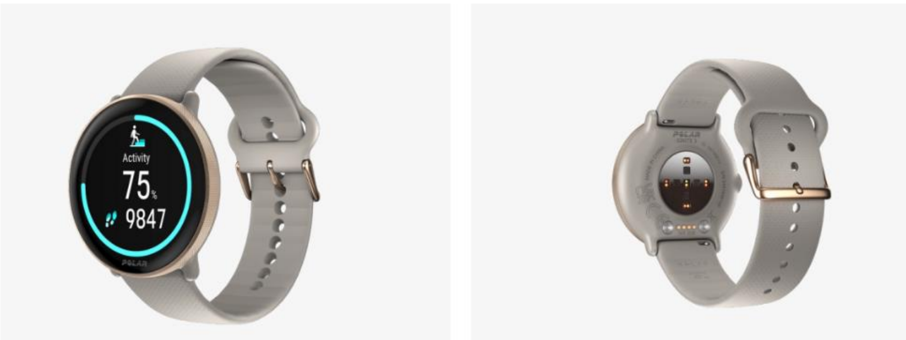

Figure 3. An example of fitness and wellness watch having an optical heart rate sensor. [11]

Figure 4 shows an example of photoplethysmography signal recorded with wrist worn pulse oximetry [12]. The device is shown on the left. The sensor is attached to the thumb. The PPG signal is shown on the right. The inter-beat-interval (IBI) is calculated from the negative peaks (the bottoms) of the PPG signal. It could be calculated also from the positive peaks (the maximum) or from the rising edges of the signal.


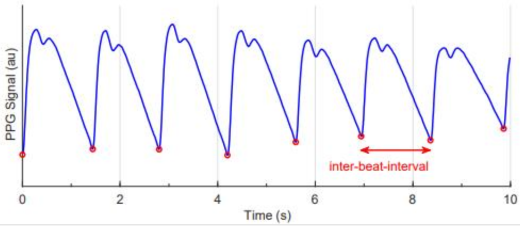

Figure 4. An example of photoplethysmographic signal recorded with pulse oximetry used on the thumb. [12]

3.3 Heart rate variability

At present there is no accepted standard for stress evaluation. However, several HRV variables change in response to stress. Usually, stress induces low parasympathetic nervous system activity, which is associated with variation of some HRV variables such as high-frequency band and an increase in the low-frequency band. [8]

European Society of Cardiology together with the North American Society of Pacing and Electrophysiology have defined and established the standards for the measurement, physiological interpretation, and clinical use of HRV [13]. Most used selected time-domain and frequency-domain measures of HRV are summarized in Table 1 and Table 2.

Table 1. Selected time-domain measures of HRV [13].

Variable	Units	Description
		Statistical measures
SDNN	ms	Standard deviation of all NN intervals
SDANN	ms	Standard deviation of the averages of NN intervals in all 5-minute segments of the entire recording
RMSSD	ms	The square root of the mean of the sum of the squares of differences between adjacent NN intervals
SDNN index	ms	Mean of the standard deviations of all NN intervals for all 5-minute segments of the entire recording
SDSD	ms	Standard deviation of differences between adjacent NN intervals
NN50 count		Number of pairs of adjacent NN intervals differing by more than 50 ms in the entire recording; three variants are possible counting all such NN intervals pairs or only pairs in which the first or the second interval is longer
pNN50	%	NN50 count divided by the total number of all NN intervals
		Geometric measures
HRV triangular index		Total number of all NN intervals divided by the height of the histogram of all NN intervals measured on a discrete scale with bins of 7.8125 ms (1/128 seconds)
TINN	ms	Baseline width of the minimum square difference triangular interpolation of the highest peak of the histogram of all NN intervals
Differential index	ms	Difference between the widths of the histogram of differences between adjacent NN intervals measured at selected heights (e.g., at the levels of 1,000 and 10,000 samples)
Logarithmic index		Coefficient φ of the negative exponential curve $k \cdot e^{-\varphi t}$, which is the best approximation of the histogram of absolute differences between adjacent NN intervals

Table 2. Selected frequency-domain measures of HRV [13].

Variable	Units	Description	Frequency range
		Analysis of short-term recordings (5 min)	
5-min total power	ms^2	The variance of NN intervals over the temporal segment	≈≤0.4 Hz
VLF	ms^2	Power in VLF range	≤0.04 Hz
LF	ms^2	Power in LF range	0.04–0.15 Hz
LF norm	n.u.	LF power in normalized units LF/(total power-VLF)×100	
HF	ms^2	Power in HF range	0.15–0.4 Hz
HF norm	n.u.	HF power in normalized units HF/(total power-VLF)×100	
LF/HF		Ratio LF/HF	
		Analysis of entire 24 hours	
Total power	ms^2	Variance of all NN intervals	≈≤0.4 Hz
ULF	ms^2	Power in the ULF range	≤0.003 Hz
LF	ms^2	Power in the VLF range	0.003–0.04 Hz
VLF	ms^2	Power in the LF range	0.04–0.15 Hz
HF	ms^2	Power in the HF range	0.15–0.4 Hz
α		Slope of the linear interpolation of the spectrum in a log-log scale	

ULF = Ultra low frequency, VLF = Very low frequency, LF = Low frequency, HF = High frequency.

Time-domain analysis measures variation in the intervals between successive cardiac cycles whereas frequency-domain analysis provides information how power is distributed as function of frequency. [8]

3.4 Recovery and stress indexes

Based on the common measures of HRV, special indexes representing the parasympathetic and sympathetic cardiac activity have been developed. For example, Kubios HRV software is based on the following parameters to calculate PNS and SNS indexes [14]:

- Mean RR interval
- Root mean square of successive RR interval differences (RMSSD)
- Poincaré plot index SD1 and SD2 in normalized units
- Baevsky's stress index (SI)

Each parameter is compared to their normal population values and the values are then scaled with standard deviations (SD) of normal population and finally a proprietary weighting is applied to obtain the index values. These are illustrated in Figure 5 and Figure 6.

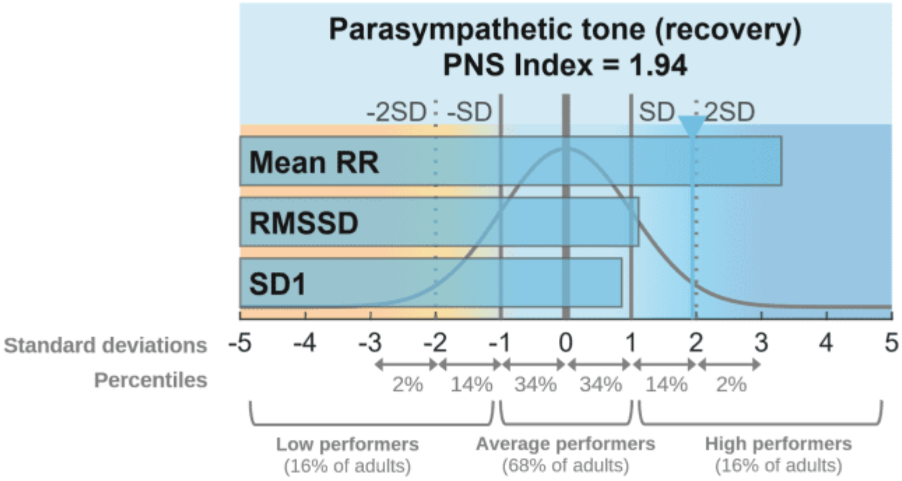

Figure 5. Parasympathetic nervous system (PNS) index. High positive values are interpreted as a good recovery of the test subject. Source: [14]

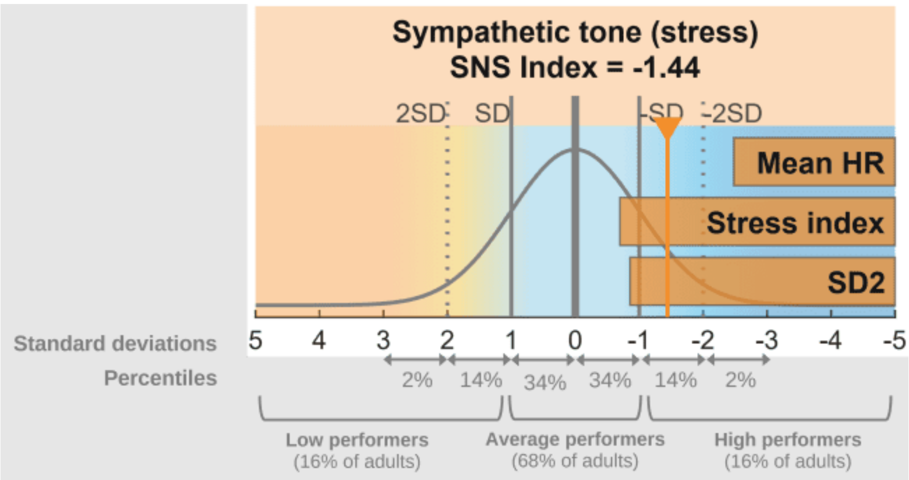

Figure 6. Sympathetic nervous system (SNS) index. High negative values are interpreted as a low stress of the test subject. Source: [14]

Positive index values tell how many SDs above the normal population average values are, whereas a negative value tells the value is below normal values [14]. PNS index describes the parasympathetic tone and can be interpreted as the ability to recover from stress, as SNS index describes the sympathetic cardiac activity and can be interpreted as the current stress situation. An article “HRV analysis methods” gives a more detailed description of the analysis methods [11].

4 Description of the target state

4.1 The purpose

The aim is to develop a working proof-of-concept of the recovery and stress meter. A suitable microcontroller board and additional components are used. The Raspberry Pi Pico was selected for that purpose, as the Raspberry Pi products are extensively supported by the manufacturers and by the user community.

Metropolia University of Applied Sciences' teaching personnel together with senior students have evaluated and selected the hardware components for the project. In addition, a special board for development of IoT devices with Raspberry Pi Pico is designed and tested by one of the senior lecturers. The background development and research results are openly available and readable in Theseus [16] [17] [18].

4.2 Application concept

The core of the proof-of-concept is Raspberry Pi Pico, a small and versatile microcontroller board designed for IoT devices. The device is adaptable to a wide range of applications in home, hobby, education, and industry. It is programmable both in C and MicroPython, of which MicroPython is used for this project. The device has a rich set of peripherals, including SPI, I2C, and programmable I/O state machines for custom peripheral support. It has also a wireless version having a fully certified wireless LAN module. [19]

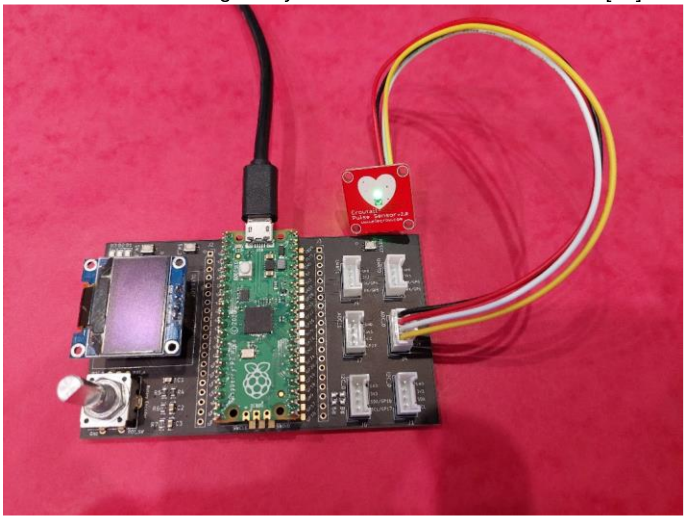

Figure 7. Photograph of the development board with connected Raspberry Pi Pico board, OLED display and optical heart rate sensor.

The development board is shown in Figure 7. On the bottom left the rotary switch and knob is shown. Above it is a 128x64 wide OLED display. At the upper left corner 3 LEDs and two of the three micro buttons are shown, which can be used for interacting with the development board. In the middle, the Raspberry Pi Pico board with soldered pins is shown.

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The Pico board is connected to the laptop or desktop through a USB-cable (black cable at the top of the figure). On the right, 4-pin Grove-connectors for connecting serial communication devices, like I2C sensors or analog input sensors, are shown. The optical heart rate sensor is connected to an ADC_0 pin and is shown above the development board. The components used in the proof-of-concept product are listed in Table 3.

Table 3. Component used in the proof-of-concept product.

Component	Description	More info
Raspberry Pi Pico	Dual-core ARM processor microcontroller having 246 kB SRAM and 2 MB on-board Flash. It also includes 2.4 GHz wireless LAN and 26 mulifunction GPIO pins.	Raspberry Pi Pico series – Raspberry Pi
Crowtail Pulse Sensor v2.0	Optical heart rate sensor having LED, photodiode, analog amplifier, and analog signal output. Operating voltage 3-5 V	Crowtail- Pulse Sensor 2.0 (elecrow.com)
OLED display	SSD1306 compatible 128x64 monochrome organic LED-display. Communicates with I2C or UART-protocol.	Sensors Modules SSD1306 Oled Display | Sensors Modules Using a SSD1306 OLED display — MicroPython latest documentation
Protoboard	Passive protoboard specially designed for this project to help to connect the other components to the Raspberry Pi Pico.	Joseph Hotchkiss, Senior Lecturer, Metropolia UAS
Rotary knob	Digital rotary knob with push button.	Keijo and Joseph knows

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4.3 Operating principle

The heart rate is detected using the optical heart rate sensor (Pulse Sensor v2.0, Crowtail) [20]. The analog signal is converted into digital using Raspberry Pi Pico's AD-converters. The heart rate is calculated using peak-detection algorithms for photoplethysmography (PPG) signals using Pico's central processing unit (CPU). The operation can be controlled using the rotary switch and knob. Results and feedback to the user are shown on the OLED display. In addition, the extra LEDs can be used to indicate, for example, the quality of the signal or the data collection operations to the user.

The data is preprocessed with Pico. Pico's wireless connection can be used to send the data to a cloud server and return the analysis results to the development board and show them to the user. Figure 88 illustrates the cloud and web-server architecture of the system.

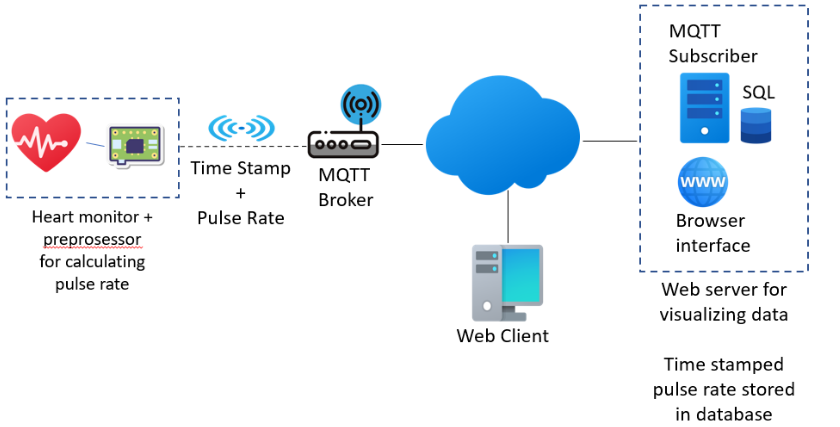

Figure 8. Illustration of the web-server architecture of the whole system.

The development board acquires and records the optical heart pulse data and preprocesses the data as seen in Figure 8. All heart rate calculations can be also processed in the development board. The time stamped preprocessed pulse data is sent wirelessly to the base station which sends the data to the Web server. The data is stored in the webserver's database where more analysis and reporting can be done. The health care professional interacts with the webserver through Web clients.

4.4 Key features

The following Table 4. recaps the key features of the system.

Table 4.4 Key features of the system.

Key Feature	Description
HRV detection	PPG signal is detected using the optical pulse sensor and the heart rate variability is measured using the development board's MCU.
Display	The system has an OLED display capable of showing both text and graphics.
Controls	The system has a rotary switch control knob with push button. The control knob can be used for controlling the operation of the system.
MCU	The system contains an MCU with Flash and RAM memory and several peripheral connections enabling to process the detected PPG signal and calculate the inter-peak-interval variations. The raw HRV data (PPI) can be further analysed using the system or sent wirelessly to a Cloud Server for further calculations.
Wireless connection	The system contains a wireless WiFi transmitter. That gives the opportunity to send and receive data to WLAN and Cloud Servers.
USB connection	The system contains a USB connection. The USB can be used to control, code, and download the executable files. In addition, it can be used to debug the code and download and upload data files

	between the development board and laptop. The USB-port can also be used to power the system, if necessary.

4.5 Use and users

The final system is intended to be used for measuring the recovery and stress index based on HRV analysis detected optically from the finger, wrist, hand palm, arm, upper arm, chest, cheek, forehead, or earlobe.

The system is intended to be used by a person, patient, customer, or healthcare professional aiming to measure the subject's recovery and stress index. The information can be used to help understand the study subject's current situation. The system is used in a normal dry home or office environment.

4.6 Applications

The system can be used to analyze the psychophysiological state. HRV is related to emotional arousal, conditions of acute time pressure and emotional strain, and elevated anxiety state. HRV has also been shown to be reduced in individuals reporting to worry more. In individuals with post-traumatic stress disorder (PTSD), HRV is reduced. [10]

5 Functional requirements

The functionality of the device will be based on functional requirements, i.e. what the system will contain and what it will not contain. This chapter presents the essential functional requirements related to the system.

The original table is maintained in Excel and is attached to the document, making it easier to structure the data. A snapshot of the table is shown here.

Table X1. Functional requirements

ID	Category	Description	Justification and source	Depends on	Importance	Implemented
FR01		User records HRV			1	
FR02		User reviews previous HRV analysis		FR01	1	
FR03						
FR04						
FR05						

6 Non-functional requirements

Non-functional requirements define the limitations and boundary conditions for functional requirements. Non-functional requirements may relate to, for example, security and privacy, scale, performance and response time, operating languages and localization, execution environment, implementation techniques and languages, as well as compliance with standards, usability, responsiveness, documentation, rights to implementation, and customizability and accessibility of the implementation.

This chapter presents the essential non-functional requirements related to the system.
The original table is maintained in Excel and is attached to the document, making it easier to structure the data. A snapshot of the table is shown here.

The minimal sampling rate of the PPG for accurate pulse rate variability parameters in healthy volunteers is 50 Hz. For monitoring the average heart rate, 5 Hz sampling frequency can be sufficient. Correct HRV analysis requires higher sampling rates. Interpolation can improve HRV accuracy from lower temporal resolution PPGs. [21]

Table X2. Non-functional (quality) requirements

ID	Category	Description	Justification and source	Depends on	Importance	Implemented
Q01		Sampling rate	The sampling rate for the PPG data should be at least 250 Hz. Preferrable sampling rate is 1 kHz.		2	
Q02		IBI calculation accuracy	The IBI (inter-beat-intervals) for the HRV analysis should be calculated within 1 ms accuracy.		1	
Q03		Wireless link	The data should be send to the web-server through Wifi-connection using standard WLAN frequencies and protocols.		2	
Q04						

7 Use cases

7.1 User roles

Table X3 summarizes the different user roles.

Table X3. User roles

User	Abbreviation	Description
User	U1	A person using the device
Medical professional	U2	A medical doctor, nurse or other medical professional interpreting the results
System administrator	U3	A technical person responsible for the system administration
Other role	Un	

7.2 Use cases and use case diagram

Table X4 presents the application use cases and ties them to the previously presented user roles. Table X4 also prioritizes (1=mandatory, 2=important, 3=useful) the use cases, explains the interfaces to functional and non-functional requirements, and presents dependencies on other use cases. For a more detailed description of the use cases, see Section 7.3.

Table X4. Use cases

ID	Name	User role(s)	Importance	Links to requirements	Links to use cases
UC01	Recording new HRV analysis	U1: User	1	FR01	
UC02	Reading previous HRV analysis	U1: User	1	FR02	UC01
UC03					

7.3 Detailed description of the use cases

This chapter introduces the system-related use cases using the format in Table X5 given in the Requirements Specifications Excel document.

Table X5. Use Cases.

Use case ID	**UC01**
Name	**Recording new HRV analysis**
Author and date	Sakari Lukkarinen, 2.12.2022
User roles	U1: User
Importance	1
Links and sources	FR01
Prerequisites	The system is on and ready to record.
Description	1. User selects new recording from the system.
	2. User attaches the sensor on the skin.
	3. User starts the recording. The system records the signal.
	4. Recording period is over and the signal is analysed.
	5. The results are shown on the display.
Exceptions	1. The signal is low quality or the sensor is not properly on the skin. The user is warned about the situation and asked to restart recording.
	2. After the recording the signal is too low quality. The user is warned about the situation and the results are not stored.
Final result	The HRV analysis is ready and shown to the user.
Other requirements	

Use case ID	**UC02**
Name	**Reading previous HRV analysis**
Author and date	Sakari Lukkarinen, 2.12.2022
User roles	U1: User
Importance	1
Links and sources	FR02
Prerequisites	The system is on and ready to go.
Description	1. User selects reading previous HRV analysis from the system.
	2. List of previous recordings and their dates/times are shown to the user.
	3. User selects one of the previous recordings.
	4. The results of the previous HRV analysis are displayed to the user.
Exceptions	1. There are no previous HRV analysis results. The user is warned about that.
Final result	The previous HRV analysis results are shown to the user.
Other requirements	

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