

Bachelor Project



**Czech
Technical
University
in Prague**

F3

**Faculty of Electrical Engineering
Department of Control Engineering**

Long-term postulometric data analysis

David Laušman

**Supervisor: doc. Ing. Tomáš Haniš, Ph.D.
Field of study: Cybernetics and Robotics
May 2023**

Acknowledgements

I would like to thank my supervisor doc. Ing. Tomáš Haniš, Ph.D., for his advice and support while working on my bachelor project.

I would especially like to thank my colleagues Mr. Josef Vágner and Mr. Adam Šťastný for their teamwork during the development of this posturometric platform. I also thank my high school, SPŠ na Proseku, for the space, equipment, technical machinery, and moral support provided for the development of this bachelor project.

Most of all, I'd like to thank my family and girlfriend for their moral support throughout my studies and for helping me through difficult times.

Finally, I would like to thank the developers of the Altium Designer and Autodesk Inventor Professional software I use in this thesis, which helped me with my development.

Declaration

I declare that the presented work was developed independently and that I have listed all sources of information used within it in accordance with the methodical instructions for observing the ethical principles in the preparation of university theses.

In Prague, May 2023

.....

Authors's signature

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

V Praze, Květen 2023

.....

Podpis autora práce

Abstract

This thesis focuses on the design of a visualization device for a posturometric platform positioned in a traditional treadmill. This platform aims to analyze the stability of a patient while walking or running using posturographic methods. The thesis described a selection of appropriate components for display and data processing, including the creation of a 3D model of the device and cooling system. In addition, the proposal of a PCB for the power supply of the device and a communication link between the control unit and the posturographic platform.

The thesis also discusses the design of a suitable database for storing the measured data and the development of applications to process long-term data analysis.

Keywords: treadmill, posturography, visualization device, single-board computer, display, 3D design, CAN, SPI, data analysis

Supervisor: doc. Ing. Tomáš Haniš,
Ph.D.
Katedra řídicí techniky,
Ressova 9
Praha

Abstrakt

Tato práce se zaměřuje na návrh vizualizačního zařízení pro posturometrickou platformu umístěnou v běžném běhacím pásu. Cílem této platformy je analyzovat stabilitu pacienta při chůzi nebo běhu pomocí posturografických metod. V práci je popsán výběr vhodných komponent pro zobrazení a zpracování dat, včetně vytvoření 3D modelu zařízení a chladicího systému. Dále je navržena deska plošných spojů pro napájení zařízení a komunikační spojení mezi řídicí jednotkou a posturometrickou platformou.

Práce se rovněž zabývá návrhem vhodné databáze pro ukládání naměřených dat a vytvořením aplikací, které slouží k zpracování a analýze dlouhodobých dat.

Klíčová slova: běhací pás, posturografie, vizualizační zařízení, jedno-deskový počítač, displej, 3D modelování, CAN, SPI, analýza dat

Překlad názvu: Zpracování dlouhodobého měření posturometrických dat

Contents

List of Notation	3	3.3.1 SQL Database	20
1 Introduction	5	3.3.2 NoSQL Database	20
1.1 Motivation	5	3.3.3 Database selection	21
1.2 General Use	5	4 CCU Development	23
1.3 Thesis goal	6	4.1 Platform selection	23
2 Posturometric Analysis	7	4.1.1 Raspberry Pi 4	24
2.1 Posturography	7	4.1.2 Banana Pi M6	24
2.1.1 Static posturography	7	4.1.3 AML-S905X-CC (Le Potato)	25
2.1.2 Dynamic posturography	8	4.1.4 Compute Module 4	26
2.2 Posturographic platforms	8	4.1.5 Platform for CCU	26
2.2.1 Static platforms	8	4.2 Display	27
2.2.2 Dynamic platforms	9	4.3 3D model prototyping	28
2.3 Treadmills	10	4.3.1 Front cover	29
2.3.1 Classic and rehabilitation treadmills	10	4.3.2 Back cover	29
2.3.2 Posturographic treadmills	10	4.3.3 VESA standard	31
2.3.3 Underwater treadmills	11	4.4 Thermal management	31
3 System Architecture	13	5 Hardware Development	35
3.1 Sensors for posturometric platforms	14	5.1 Power-Supply management	35
3.1.1 Resistive platforms	14	5.1.1 Microprocessor (MCU) selection	36
3.1.2 Capacitive platforms	15	5.1.2 Step-down converter	36
3.1.3 Strain gauges	17	5.2 Communication converter	38
3.1.4 Sensor for our treadmill	18	5.3 Connectors	38
3.2 Communication between platform and CCU	18	5.4 Schematic	39
3.2.1 CAN bus	19	5.4.1 ATtiny414	39
3.3 Database	20	5.4.2 RPI	40
		5.4.3 Step-Down and connectors	41
		5.4.4 Differential CAN \mapsto CAN	41

5.4.5 CAN \leftrightarrow SPI	42	Bibliography	63
5.5 Printed circuit board	43	A Sensor platform drawing	69
5.5.1 PCB main parameters	43	B Tablet 3D model	71
5.5.2 Traces parameters and design rules	44	C PCB 3D model	73
5.5.3 Communication design rules .	45		
5.5.4 Circuits position and EMI elimination	45		
5.5.5 PCB assembly and testing . .	46		
5.6 Power-Supply program	47		
6 Long-term Data Analysis	49		
6.1 Database implementation	49		
6.2 Data analysis	50		
6.2.1 Static data analysis	51		
6.2.2 Dynamic data analysis	52		
7 Validation	55		
7.1 Hardware tests	55		
7.1.1 RPI cooling	55		
7.1.2 PCB Step-Down regulator . .	56		
7.2 Long-term analysis evaluation . .	57		
7.2.1 Static analysis	57		
7.2.2 Dynamic analysis	59		
8 Conclusion and future work	61		
8.1 Conclusion	61		
8.2 Future work	62		

Figures

2.1 Stabilogram and Statokinesiogram [3]	8	5.3 ATtiny414 schematic	40
2.2 Nintendo Wii Balance Board [4]	9	5.4 RPI schematic	40
2.3 Smart Balance Master [5]	9	5.5 Step-Down and connectors schematic	41
2.4 Rehabilitation treadmill [6]	10	5.6 Differential CAN \mapsto CAN schematic	42
2.5 Alexero Gain&Balance posturographic treadmill [7]	11	5.7 CAN \mapsto SPI schematic	42
2.6 Underwater treadmill [9]	11	5.8 20H design rule [58]	46
3.1 System architecture	13	5.9 PCB - front (Power-Supply)	46
3.2 Resistive plane [13]	15	5.10 PCB - rear (Power-Supply)	46
3.3 Surface capacitive platforms [13]	16	5.11 State diagram of Power-Supply program	47
3.4 Projected capacitive platforms [13]	17	6.1 CCU database - Users, Static and Dynamic	50
3.5 Strain gauge [14]	17	6.2 Butterfly pattern	53
3.6 Direction of strain [14]	18	7.1 CPU temperature measurement	55
4.1 Raspberry Pi 4 SBC [25]	24	7.2 Statokinesiogram - first data	57
4.2 Banana Pi M6 SBC [28]	25	7.3 Statokinesiogram - second data	57
4.3 AML-S905X-CC SBC [30]	25	7.4 Stabilogram - first data	58
4.4 Compute Module 4 SBC [32]	26	7.5 Stabilogram - second data	59
4.5 LCD display for CCU [34]	28	7.6 Dynamic analysis	60
4.6 Front cover - front view	29	A.1 Sensor platform drawing [mm]	69
4.7 Pure back cover	30	B.1 Tablet 3D model - front view	71
4.8 Dual cooling fan [37]	32	B.2 Tablet 3D model - rear view	71
4.9 Back cover - front view	32	C.1 PCB 3D model - front view	73
4.10 Back cover - rear view	33	C.2 PCB 3D model - rear view	73
5.1 Pololu step-down regulator [39]	37	C.3 PCB 3D model	73
5.2 Pololu powerful step-down regulator [40]	38		

Tables

3.1 Comparison of sensors [10]–[12], [14], [15]	18
3.2 CAN bus parameters [16], [17] ..	19
4.1 Comparison of platforms [24], [27], [30], [31]	26
5.1 CCU current calculating	37
7.1 CCU actual current	56

I. Personal and study details

Student's name: **Laušman David** Personal ID number: **503257**
Faculty / Institute: **Faculty of Electrical Engineering**
Department / Institute: **Department of Control Engineering**
Study program: **Cybernetics and Robotics**

II. Bachelor's thesis details

Bachelor's thesis title in English:

Long-term postulometric data analysis

Bachelor's thesis title in Czech:

Zpracování dlouhodobého měření posturometrických dat

Guidelines:

The injuries of the musculoskeletal system and especially of the lower limbs is critical issue in society, with high impact on life quality and productivity. Early indication and physiotherapy process monitoring dramatically reduce recovery time. The primary objective of this thesis is to prepare technical equipment for posturometric analysis.

1. Get familiar with posturometric platforms data acquisition and long-term data management and analysis.
2. Develop hardware and software for posturometric platform data management.
3. Long-term data analysis and visualization.
4. Tests execution and evaluation

Bibliography / sources:

- [1] Helštyňová, Barbara, Analysis of Posturometric Data, Ostrava, 2012. VSB – Technical University of Ostrava.
- [2] Bruštková Jolana, Use of Tenzometric Platform in Ambulatory Therapy, CTU in Prague, Faculty of biomedical engineering, 2016
- [3] Tichý, Lukáš, The effect of a six-week physiotherapeutic intervention in child patients with clubfoot evaluated with a change in ROM of ankle dorsiflexion and the quality of gait measured by 2D analysis, Prague, 2021, Charles University, Faculty of Physical Education and Sport

Name and workplace of bachelor's thesis supervisor:

doc. Ing. Tomáš Haniš, Ph.D. Department of Control Engineering FEE

Name and workplace of second bachelor's thesis supervisor or consultant:

Date of bachelor's thesis assignment: **31.01.2023** Deadline for bachelor thesis submission: **26.05.2023**

Assignment valid until:

by the end of summer semester 2023/2024

doc. Ing. Tomáš Haniš, Ph.D.
Supervisor's signature

prof. Ing. Michael Šebek, DrSc.
Head of department's signature

prof. Mgr. Petr Páta, Ph.D.
Dean's signature

III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt

Student's signature



List of Notation

Symbol	Meaning
CoP	Center of pressure
CCU	Central control unit
SBC	Single-board computer
RPI	Raspberry Pi
RPI4	Raspberry Pi 4
CM4	Compute Module 4
MCU	Microprocessor
AT	ATtiny414
CAN	Controller area network
PCB	Printed circuit board
EMI	Electromagnetic interference
GUI	Graphical user interface

Chapter 1

Introduction

1.1 Motivation

In the first years of our lives, our parents teach us basic skills, which is very important to us. One of these is walking. From the early age, they teach us how to hold the body, to walk and run correctly. If we don't follow these skills correctly, it can cause lifelong consequences, which may occur later in our lives. Then it is more challenging to eliminate these problems and in some cases, we need professional medical help.

However, even people who learned this knowledge correctly may have problems. For example, if I have had an injured leg and I didn't do professional therapy, later during my walk my body will instinctively try to spare the injured leg and put more strength on the other leg. This problem may result in the wrong body posture and subsequently health problems caused by bad walking.

If we have some walking problems or after a long-term injury it is important to do correct rehabilitation therapy, during which we slowly learn how to hold the body and walk correctly. These days, for this therapy, we use a unique medical technique called posturography.

1.2 General Use

Our aim is to create a sensor platform to measure the positions of the patient's feet and weight distribution, from which we will calculate the Center of Pressure (CoP), number of steps, stride length, speed, and more. These data will be shown on a visualization device (CCU), including real-time walking or running data, and simultaneously they will be used for a long-time data analysis.

We want to make the overall architecture simple, easy to manufacture and compatible with any treadmill available to the user.

This thesis is only one-third of the overall project. The remaining parts of this project were developed by Mr. Adam Štastný, who designed the hardware and software of the sensor platform and Mr. Josef Vágner, who created the software application, computational algorithms and graphs for the CCU.

■ 1.3 Thesis goal

The goal of this thesis has two parts. The first is to propose a 3D model prototype of a CCU and printed circuit board, which must have two functions: the power supply for CCU components and connect communication between the sensor platform and CCU controller. For this purpose, make the circuits and choose the suitable components.

The second part is to create application windows and database to process data from individual exercises and make long-term analysis for patients and specialists.

Chapter 2

Posturometric Analysis

2.1 Posturography

Posturography is a method that uses a variety of techniques to measure, quantify and assess a person's postural stability in an upright position under static (standing balance) or dynamic (moving platform) conditions. [1], [2] Posturography is widely used in clinical practice to analyze and assess reaction forces under the feet while standing or walking. [1]

This method measures reaction forces distributed in three mutually perpendicular planes acting on a force or pressure platform. The measurements are made using planar platforms fitted with suitably positioned sensors that measure the force or pressure load.

The force platforms measure the force vector applied to the pad CoG (center of gravity), and the pressure platforms measure the pressure load on each sensor from which they calculate the center of pressure (CoP), the same as CoG after approximation. [1]

2.1.1 Static posturography

Static posturography is based on measuring the patient's CoP while standing on a fixed platform to assess the patient's state of balance. Graphing these values can easily detect various disorders that lead to poor balance. [2]

To compare the measurement results statokinesiogram or stabilogram is most often used. The statokinesiogram (Fig. 2.1 right) shows the motion of the CoP in a coordinate system where the x-axis is represented by right and left movement, and the y-axis is represented by forward and backward movement. The stabilogram (Fig. 2.1 left) then shows the motion of the CoP as a function of time, where each direction of motion (right/left and forward/backward) can be displayed separately.[1], [2]

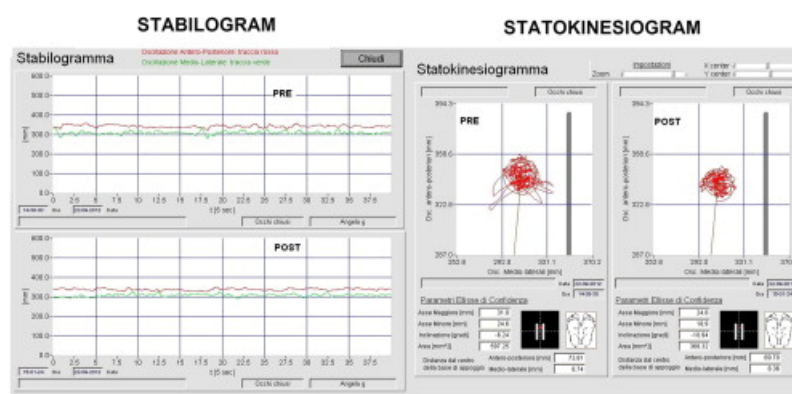


Figure 2.1: Stabilogram and Statokinesiogram [3]

2.1.2 Dynamic posturography

Dynamic posturography differs from static posturography in the use of a motorized platform. Thus, the patient's CoP is monitored in real time, and the physician observes the patient's balance responses to random external stimuli, which are translational or rotational movements of the platform or changes in the visual scene in front of the patient. [1], [2]

Measurements may include various test protocols focusing on a sensory organization test, a motorized or adaptation test, and a spontaneous test that measures the patient's reactions to unexpected abrupt movements of the platform. [2]

2.2 Posturographic platforms

These days, many types of platforms are used in hospitals, neurological clinics or even for home use to study stability or balance disorders.

The use of posturographic platforms is a suitable complement to classical methods with more precise targeting for the correct treatment of the patient's disorder. [1]

2.2.1 Static platforms

Static platforms are less demanding in terms of space, manufacturability and price. They allow users to use them in the home without needing professional supervision.

One of these platforms is the **Nintendo Wii Balance Board** (Fig. 2.2). This platform was developed for the Nintendo Wii Fit game console as a game controller, allowing players to control the game by tilting their bodies in different directions.

It later became apparent that the platform could also have applications in posturography for measuring CoP, and the company developed its own Wii posturography software for home diagnosis of stability disorders. [1]



Figure 2.2: Nintendo Wii Balance Board [4]

2.2.2 Dynamic platforms

Dynamic platforms are primarily used in the medical field under the supervision of a specialist who evaluates the measured data to determine a more accurate diagnosis of a stability disorder.

One such platform is the **Smart Balance Master** (Fig. 2.3). This platform was initially developed for NASA to study the effects of flight on the vestibular function of astronauts. [1]

The platform contains two sensor boards (one for each leg) and allows translational and rotational movements with environmental changes on a screen in front of the patient. [1]



Figure 2.3: Smart Balance Master [5]

2.3 Treadmills

Treadmills can generally be divided into four categories - classic, rehabilitation, posturographic and underwater treadmills. Each type of treadmill has different use specifications and provides different feedback to the user.

2.3.1 Classic and rehabilitation treadmills

Classic treadmills are usually used in the gyms or at home to simulate walking or running. The user can set the speed or the inclination of the platform (hill simulation) and usually receives the run distance, burned calories, heart rate and more as feedback.

Rehabilitation treadmills (Fig. 2.4) are used in the rehabilitation process of patients who have problems with walking (severe injury or surgery) when they are slowly learning how to walk or control their body again. These treadmills are equipped with a unique construction that serves as a support point to help patients maintain stability. Then they can focus more on walking without fear of falling.



Figure 2.4: Rehabilitation treadmill [6]

2.3.2 Posturographic treadmills

These treadmills have the same properties as rehabilitation treadmills. But they have a built-in sensor platform (under the belt) that can measure the patient's CoP, step length and width, number of steps, and more. The measured data are shown on a monitor so the doctor can study the patient's walk in real-time and easily find stability or any disorders.

An example of such a treadmill is the Alexero Gain&Balance (Fig. 2.5).



Figure 2.5: Alexero Gain&Balance posturographic treadmill [7]

■ 2.3.3 Underwater treadmills

Underwater treadmills (Fig. 2.6) can be used in many areas (e.g. post-operative, orthopedic and neurological conditions). The advantage of using them in water is that the water creates buoyancy that floats the patient. This buoyancy provides an undemanding but very effective way to exercise, reducing joint stress, and the effect of water is to slow down all movements. This allows the patient to focus better on walking and improving movement skills. The resistance of the water also helps increase cardiovascular fitness. [8]

A significant disadvantage of these treadmills is that they do not usually include a sensor platform for measuring the patient's CoP and other data.

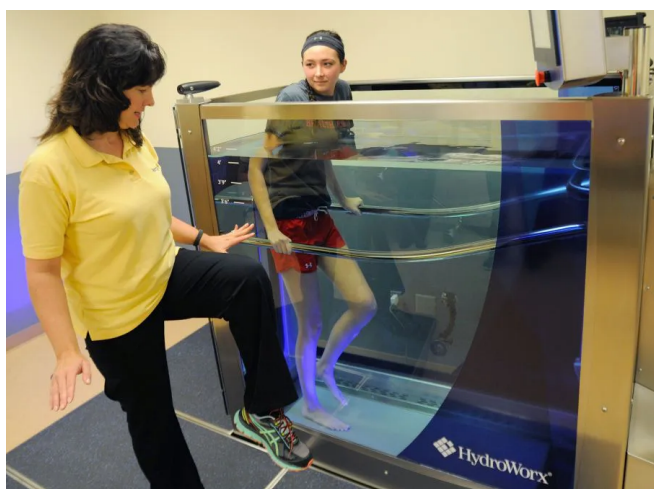


Figure 2.6: Underwater treadmill [9]

Chapter 3

System Architecture

Figure 3.1 illustrates the basic structure of the system architecture. It includes a classical treadmill that will be equipped with our sensor platform. The measured data (CoP) will be transmitted to the CCU, which includes a control unit and a display. In this CCU, the data will undergo real-time processing using algorithms and will be presented visually. Upon completing the exercise, all the data will be stored in a database, which allows future utilization in a long-term analysis.

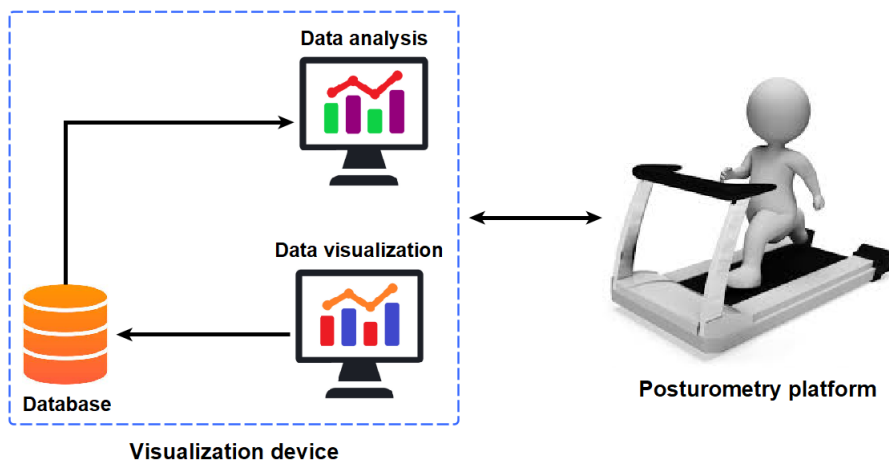


Figure 3.1: System architecture

Initially, it was essential to select the fundamental components of the architecture that would be the building block for all parts.

We had to determine the most suitable method for collecting data from the treadmill board, which will be necessary for Mr. Šťastný to develop the overall sensor platform, for Mr. Vágner to implement the algorithms from the measured data and for me to create a long-term data analysis.

We also had to choose the appropriate communication method for transferring data from the sensor platform to the CCU. This was necessary for Adam and Josef to establish the transmission of data frames, error messages, and calibration values, while I am be responsible for establishing the connection between the sensor platform and the CCU controller. Finally, I had to select a suitable database for storing different data that would be subsequently used to analyze long-term data.

■ 3.1 Sensors for posturometric platforms

To calculate CoP and other data, we need to measure the position of the feet on the board and weight distribution. We can use several technologies to do this, but the technology must meet our requirements.

Technology requirements:

- Usable for large platforms
- Multi-touch support
- Any object detection
- Easy to manufacture
- Easy implementation
- High durability

■ 3.1.1 Resistive platforms

Touch platforms based on this method are called pressure-sensitive film touch platforms. We can control the measuring plate by everything (for example, finger, pen, or other objects) because the resistive platforms detect the position using changes in pressure. [10]–[12]

Resistive platforms use a rigid bottom layer (glass or plastic) and a top layer of foil, separated by insulating points, each with a transparent electrode foil attached. When the measuring plate is pressed (Fig 3.2), the electrodes in the foil come into contact to form the exact resistance we are measuring. The resulting point of contact is determined by measuring the change in voltage. [10]–[12]

Main advantages:

- not affected by external elements (water, dust)
- relatively easy to manufacture
- any object detection

Main disadvantages:

- scrolling can be difficult due to non-smooth surface
- can be damaged by sharp objects
- do not support multi-touch

Resistive Film

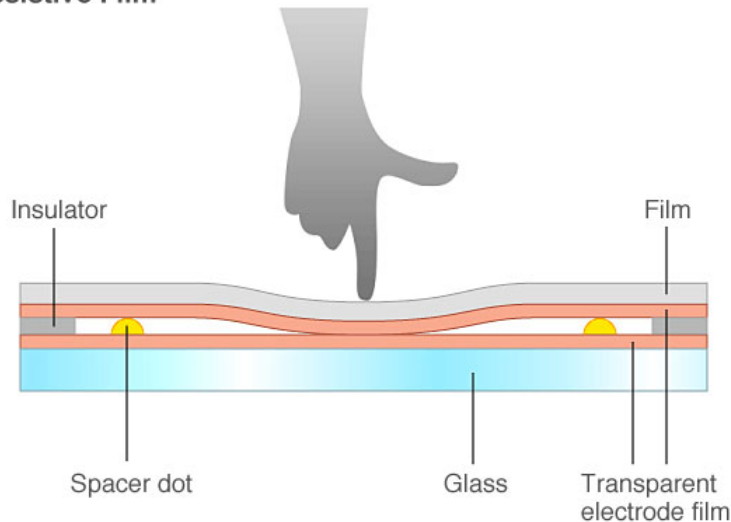


Figure 3.2: Resistive plane [13]

■ 3.1.2 Capacitive platforms

Capacitive platforms are the second most used position sensors. The touch point is identified by two methods.

The first measures the tiny changes in the electric current and the second measures the changes in the electrostatic field when it is touched by a finger. [10]–[12]

■ Surface capacitive platforms

This technology uses a transparent electrode film placed on a glass or plastic screen and covered with a protective layer. A small voltage is applied to the film to create a uniform electrostatic field. A capacitor is dynamically formed when a conductor (finger) touches the surface (Fig. 3.3) and the touch point is located by the change in the capacitance, which is measured by the four sensors located at the corners. [10]–[12]

Main advantages:

- not affected by external elements (water, dust)
- scratch and impact resistant
- usable for large platforms

Main disadvantages:

- do not support multi-touch
- relatively difficult to manufacture
- only finger detection

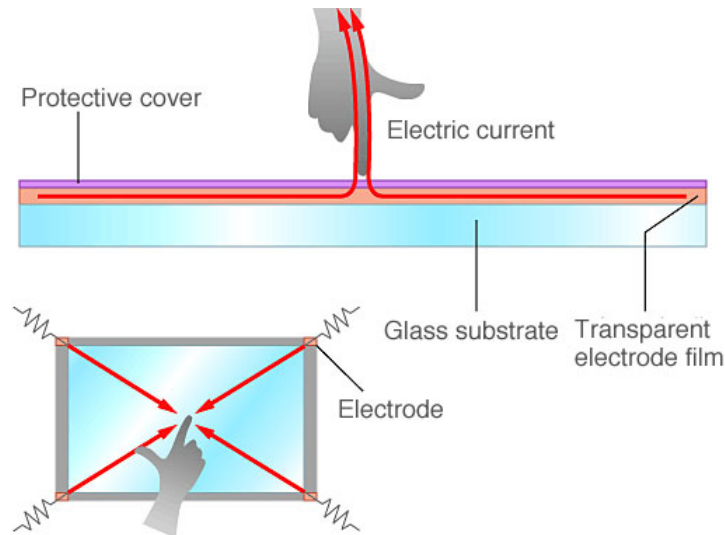


Figure 3.3: Surface capacitive platforms [13]

■ Projected capacitive platforms

This technology uses a pattern of electrode layers (called the matrix) with an IC chip for processing computations, which is atop the glass or plastic screen, with the protective layer. [10]–[12]

When a finger touches the screen (Fig 3.4), the electrostatic capacity among multiple electrodes changes at the same time where the position can be identified by measuring the ratios between these electrical currents. [10]–[12]

Main advantages:

- not affected by external elements (water, dust)
- more scratch and impact resistant
- multi-touch capability

The main disadvantages:

- the size of screen limits the accuracy of the sensitivity
- relatively difficult to manufacture
- only finger detection

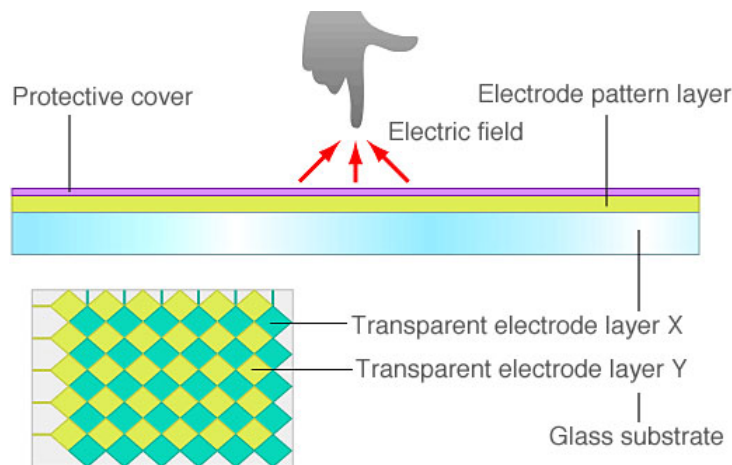


Figure 3.4: Projected capacitive platforms [13]

3.1.3 Strain gauges

Strain gauges are used for measuring the electrical resistance that varies with changes in strain (deformation). The sensors use a resistive foil (Fig. 3.5) glued on the measured object. Strain is the deformation of material that results from applied pressure. [14], [15]

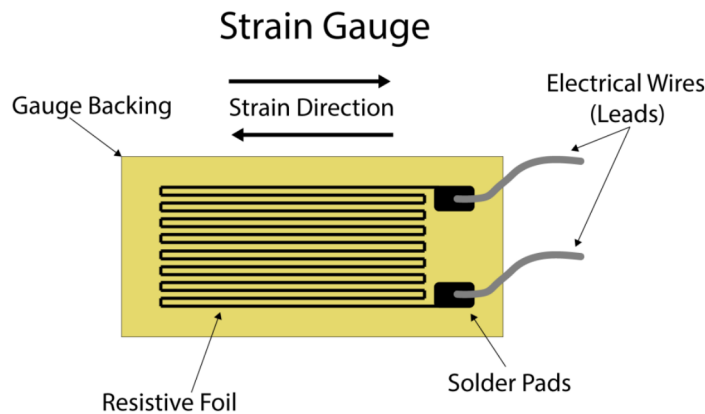


Figure 3.5: Strain gauge [14]

The electrical resistance value changes with the direction of strain. If the resistive foil is bended, the electrical resistance is lower, and if it is stretched the electrical resistance is higher (Fig 3.6). The change in resistance is proportional to the change in the length of the object's surface. The strain gauges can measure different angles of strain but for our treadmill we need to measure a strain force only in a vertical direction.

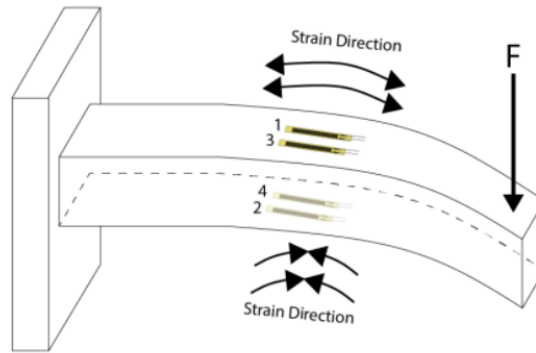


Figure 3.6: Direction of strain [14]

3.1.4 Sensor for our treadmill

For our sensor platform, we choose strain gauges. In Table 3.1 you can see the reasons for this choice, where I compare the main requirements. The most important requirements for us were object detection because we must detect any object, multi-touch support and weight measurement.

Technology	Resistive	Surface cap.	Projected cap.	Strain gauges
Multi-touch	no	no	yes	yes
Durability	low	medium	medium	high
Object detection	any	special	special	any
Manufacturability	medium	difficult	difficult	easy
Implementation	medium	difficult	difficult	easy
Weight measurement	no	no	no	yes

Table 3.1: Comparison of sensors [10]–[12], [14], [15]

On the other hand, the strain gauges have the lowest accuracy of all of them, but in the appearance of the size of the sensor platform in our treadmill, this accuracy will be considered sufficient.

3.2 Communication between platform and CCU

The controller, which will perform all the mathematical algorithms, will be located in the CCU. For this purpose, it is necessary to select a suitable communication, which will send the measured data from the sensor platform to the CCU.

Before we get to the choice, we must choose between wireless or wired communication.

Initially, we considered using wireless communication, which would be more user-friendly. However, this decision turned out to be wrong later on. In the future, we would like to improve this project for underwater treadmills. If the wireless communication would not work entirely well, the complete architecture would have to be redesigned.

We decided to use wired communication. If the sensor platform will be powered through a cable from the CCU, so there will be no problem adding communication wires to the power wires.

My colleagues and I agreed to place six strain gauges (App. A.1) on the sensor platform to measure the patient’s CoP. Due to the size of the treadmill board, using only four strain gauges (one in each corner) would not achieve a sufficiently accurate measurement.

We also determined the minimum data speed for selecting the appropriate communication. To ensure that the real-time graph in the application is smooth, we set the minimum update frequency to 100Hz. Considering this and the size of the data to be transferred, we set the minimum communication speed to 500kb/s to have enough data available.

Finally, we decided to employ CAN bus communication, which aligns with our requirements and offers favorable properties and structure, including addresses, priority messages and data control. Additionally, CAN bus communication utilizes differential twisted pair wires. Thus, we would effectively eliminate the impact of electromagnetic interference emitting from the motor. The specific parameters for CAN bus communication can be observed in Table 3.2.

3.2.1 CAN bus

Controller Area Network is half-duplex communication that uses a pair of differential wires: CAN-H (high) and CAN-L (low), making it more noise resistant. CAN is not Master/Slave communication. It means every device sends a message frame in a pre-defined period and with a unique ID, which determines the message’s priority (logic 0 is dominant priority and logic 1 is recessive priority). A typical CAN message frame is created from ID identifier, control, data and CRC. [16], [17]

Comm.	Type	Devices	Speed [Mbps]	Noise resis.	Distance [m]
CAN	half-duplex	127	1	high	100

Table 3.2: CAN bus parameters [16], [17]

■ 3.3 Database

A database is an organized file to access, manage and update data easily. Nowadays, they are used a lot on web servers (e-shop, cloud, etc.), in companies that need to collect large amounts of data (customers, orders, production costs and processes) and also in games that contain all data and information related to user management and game data. [18], [19]

Most data in databases today is structured and modeled in rows and columns in a series of tables, which may be linked together. This structure allows operators to access and manage data quickly and efficiently. However, there are many other database structures, their use depend entirely on the organization's requirements and how they intend to manage and use the data. [18], [19]

■ 3.3.1 SQL Database

SQL is a programming language primarily using relational databases (series of tables) to quickly and efficiently access, manage and update data. [19]

Relational databases are used for structured and predefined data placed in defined categories. Users assume that their database structure will stay mostly the same in the future and can only suffice with the ability to add, edit and remove tables or their rows or columns (e.g., e-shops). [18]

For fast access and organization of data, relational databases use primary keys, which can be used to quickly and efficiently retrieve the data needed.

■ 3.3.2 NoSQL Database

NoSQL or non-relational databases are used for unstructured and undefined data. Users have a basic idea of what data they want and how they want to store it. Still, as time goes on, the entire database structure may need to be redefined. It is easier in the case of NoSQL databases than, for example, in relation databases, where the structure is strictly defined. [18], [19]

The advantage of these databases is that they can handle large amounts of data at once, and as the data grows, the database scales it to handle it efficiently. [20]

However, a significant disadvantage is that data management is too complex in comparison to other databases, the installation is complicated and day-to-day access is more difficult. [20]

■ 3.3.3 Database selection

Concerning my thesis, I will need to store basic information about users such as first name, last name, age, height, weight, etc. and data from individual exercises, divided according to the type of exercise (static or dynamic).

In a static exercise, we are able to determine the precise amount of data we can retrieve from the sensor platform, which includes the position of the center of gravity (x, y) in time, exercise time and date of exercise.

In a dynamic exercise, we are able to obtain additional data beyond the static exercise. Specifically, we can retrieve the center of gravity position (x, y) in time, exercise time, date of exercise, step count, step length, step width, average speed and distance. However, the number of data we can retrieve in a dynamic exercise was also predetermined.

Since I have already known the data that I will be storing, and I expect that the data structure will not change significantly. It is more efficient for me to use a relational SQL database with tables. With a relational database, each type of data would have its position in the table. If I needed to add or remove different data in the future, it would not be necessary to change the entire database structure.

Using a relational SQL database would eliminate the need for a complex implementation, and data management would be simple and efficient for later data analysis from individual exercises.

Chapter 4

CCU Development

In this chapter, I will discuss the development of CCU to display data from the treadmill sensor platform. I will describe the selection of the platform and display, followed by the design and prototyping of the 3D model, and finally, I will design the cooling system.

4.1 Platform selection

When choosing a platform for the CCU, I focused on single-board computers (SBC). These can offer everything that I need on one small board without having to add more expandable peripherals.

These days, SBC are widespread and available with many peripherals. Some of the best known include Raspberry Pi, Banana Pi, Arduino and many others that vary in size, processor, power, memory size, etc. [21], [22] So before selecting the platform itself, it was necessary to set the minimum parameters that the board should have.

Platform requirements:

- Powerful enough for computational algorithms
- HDMI or any display connection
- Touch screen connectivity
- SSD connection option
- Two USB ports for connecting a keyboard, mouse and flash drive
- Low purchase price

4.1.1 Raspberry Pi 4

Raspberry Pi is a low-cost, credit card-sized computer, which was developed by the British company Raspberry Pi Foundation and are one of the best-known and most widely used platforms around the world, mainly due to the large number of expandable accessories and modules manufactured specifically for them. They are available in many variants, from the smallest RPI Pico to the large RPI Pi 4. [23]

The Raspberry Pi 4 - RPI4 (Fig. 4.1) is the latest board and it is one of the new generation that supports significantly higher performance CPU, GPU and I/O tags as well as more RAM, which is available in multiple variants. [24]

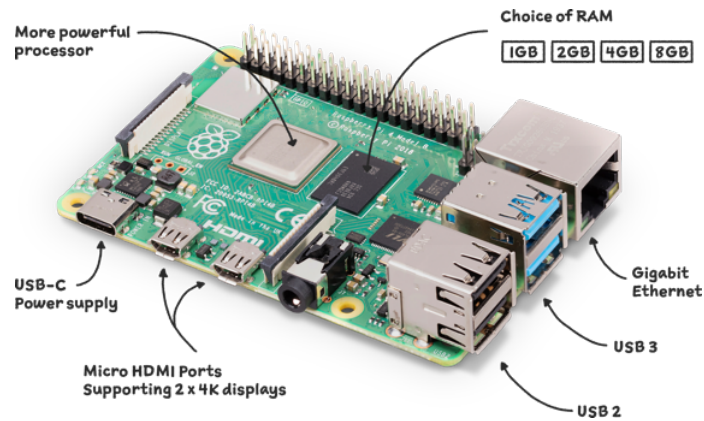


Figure 4.1: Raspberry Pi 4 SBC [25]

4.1.2 Banana Pi M6

Banana Pi is an open-source hardware community developed by Guangdong Bipai Technology and supported by Taiwan Hon Hai Technology (Foxconn). It is widely used by developers around the world as all the development documents, software, hardware and schematic diagrams of any computer are publicly available. [26]

"Banana Pi (Fig. 4.2) BPI-M6 is the next generation single-board computer from Banana Pi in 2022. It is powered by Synaptics VS680 quad-core Cortex-A73 and One Cortex-M3 processor, Imagination GE9920 GPU and NPU Up to 6.75Tops." [27]



Figure 4.2: Banana Pi M6 SBC [28]

■ 4.1.3 AML-S905X-CC (Le Potato)

Libre Computer is dedicated to carefully designing SBC to provide standards compliant platforms using open-source software. Their expertise lies in selecting reliable hardware, developing long-build products that can be extended to support purpose-specific features, and it providing long-term software support. [29]

The AML-S905X-CC (Fig. 4.3) is a flagship SBC supporting the latest operating systems (Android 9, upstream Linux, Kodi, etc.). It is a suitable platform for projects requiring CPU power for demanding computing operations. Simultaneously it offers secure or non-secure 4K data delivery. [30]

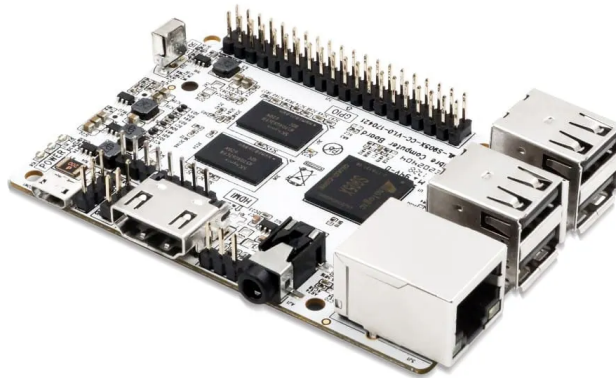


Figure 4.3: AML-S905X-CC SBC [30]

4.1.4 Compute Module 4

The Compute Module - CM4 (Fig. 4.4) is a SBC from Raspberry Pi. It's a module that contains a processor, memory, eMMC flash and supporting power circuits. The module's electrical interface consists of two high-density 100-pin connectors that can allow designers to use all the hardware and software of the Raspberry Pi. In addition, they also provide extra I/O interfaces over and above classic 40-pin GPIO (Fig. 4.1), allowing designers many more options. [31]

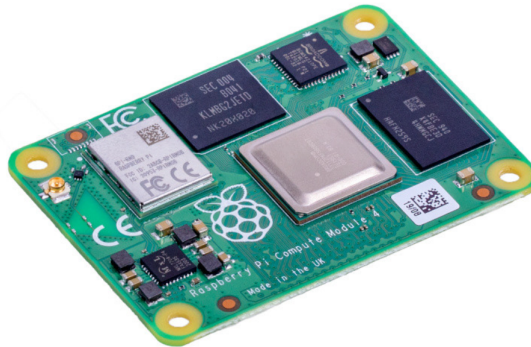


Figure 4.4: Compute Module 4 SBC [32]

4.1.5 Platform for CCU

According to Table 4.1, the best SBC would be the Banana Pi M6 due to its performance and available peripherals. However, it has the disadvantage that all connectors have fixed positions on the board and the 3D design will have to be adapted to these positions, which can be very limiting.

Platform	Raspberry Pi 4	Banana Pi M6	Le Potato	Com. Module 4
Processor	Cortex-A72 4 core 1.5GHz	Cortex-A73 4 core 2.1GHz	Cortex-A53 4 core 1.5GHz	Cortex-A72 4 core 1.5GHz
RAM	1-8 GB LPDDR4	4 GB LPDDR4	2 GB DDR3	1-8 GB LPDDR4
Display	2x micro-HDMI 4Kp60	1x micro-HDMI 4Kp60	1x HDMI 4Kp60	2x HDMI 4Kp60
Touch conn.	yes	yes	yes	yes
SSD conn.	only USB	M.2 PCIe	only USB	PCIe (5Gbps)
USB ports	2x 2.0, 2x 3.0	4x 3.0	4x 2.0	2x 2.0
Size [mm]	85x56	92x60	85x56	55x40
Price [\$]	51 – 116	120	30 – 35	50 – 140

Table 4.1: Comparison of platforms [24], [27], [30], [31]

For a better 3D design, it will be more beneficial to choose Compute Module 4. It has a weaker performance, but its advantage is that it contains only two 100-pin connectors and I as a designer can place all the required connectors (USB, HDMI, power, etc.) on the PCB as I need. This feature can significantly reduce the CCU's overall size despite the disadvantage of weaker performance.

Unfortunately, when I was developing this project, this platform was unavailable anywhere due to the chip shortages. So the second choice was the Banana Pi M6 board. However, only an older version of this was available, the Banana Pi M5. It has the exact specifications as the Raspberry Pi 4 board but is slightly more expensive. Therefore, I decided to use the third variant, the Raspberry Pi 4, for this prototype and I would use the compute module 4 to develop the following prototypes.

■ 4.2 Display

So that the patient and doctor can see real-time data from the actual exercise or analyze long-term data from multiple exercises. The CCU needs to include a large enough display with touch functionality to allow users to control it more comfortably without using a keyboard and mouse.

Touch displays are divided into several categories according to the touch processing technology. [11]

- Resistive technology
- Surface capacitive technology
- Projected capacitive technology

I already described all these technologies in Chapter 3.1, so it is not important to explain them again here.

Since I chosen a Raspberry Pi 4 as the platform, selecting a display that is directly compatible with this SBC would be advisable. Company Waveshare manufactures LCD/OLED displays that are recommended by Raspberry Pi boards and compatible with them.

My display requirements were not decisive for the final choice, but the display had to meet at least the following requirements.

- Touch screen display
- Size ≥ 10 "
- Multi-touch support
- Handles for mounting

Many displays met these requirements, but as with most SBC, availability was an issue for many. When making the final choice, I mainly looked at availability, price and which display would be the most suitable for prototyping the 3D model. So as a final display, I chose the *Waveshare 10.1" HDMI LCD (E)* [33] (Fig. 4.5).



Figure 4.5: LCD display for CCU [34]

Despite the limiting selection conditions, several alternatives to this display have a better resolution or include a special DSI connector, which is also available on the Raspberry Pi 4. However, I chose this display because it is the only one with suitable mounting holes placement and it is the thinnest.

4.3 3D model prototyping

The entire 3D model was created in Autodesk Inventor Professional 2023 and it consists of two main parts. The first is the front cover, which houses the display, and the second is the back cover, which houses all the electronics, including the Raspberry Pi 4 and the power and communication PCB.

The 3D model should meet a few basic design parameters. It should be as thin as possible and simultaneously ergonomic so that the user can hold it in his hand or stand it on the table (as a monitor) without need for an external holder.

4.3.1 Front cover

The front cover (Fig 4.6) forms a protective frame around the display. At the start, I specified that the front and back cover would be held together by M3 screws mounted from the back, and the thread would thus be formed in the front cover.

The thread for the screw could be created already in the plastic, but this way, it could wear out over time and the screw would stop holding. For this reason, I decided to use so-called threaded inserts for plastic, which are fused into the plastic by the effect of heat and inside them, there is a metric thread for the screw.

Therefore, the thickness of the frame must be sufficient so that the threaded insert can be sealed into it and simultaneously, there is enough material around it to prevent it from loosening in case of impact or high pressure from the screw. The resulting thickness of the frame was set at 9.5 mm.

The design of the display is such that the mounting grips are located on the back. To save space, I decided to make the depth of the frame the same as the depth of the display without the mounting grips. The display will then be attached to the front cover using tabs with a hole where the mounting grips are. The screws will be inserted into it. These tabs will then hide into the back cover.

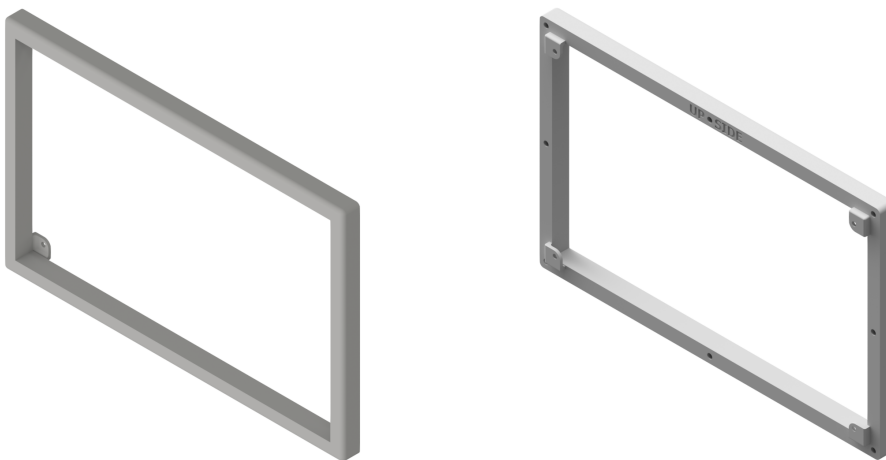


Figure 4.6: Front cover - front view

4.3.2 Back cover

The back cover will be used as a protective cover for all electronics. It must have enough space to accommodate the Raspberry Pi 4, power and communication PCB, On/Off button, power connector and the connector for communication with the sensor platform.

Firstly, I created the whole cover (Fig. 4.7). In the bottom part, I made something as a box that will store the electronics and will have an ergonomic stand/hold function.

I made this prototype, in a smaller version, on a 3D printer to inspect its ergonomics and whether the stand/holder function works properly.

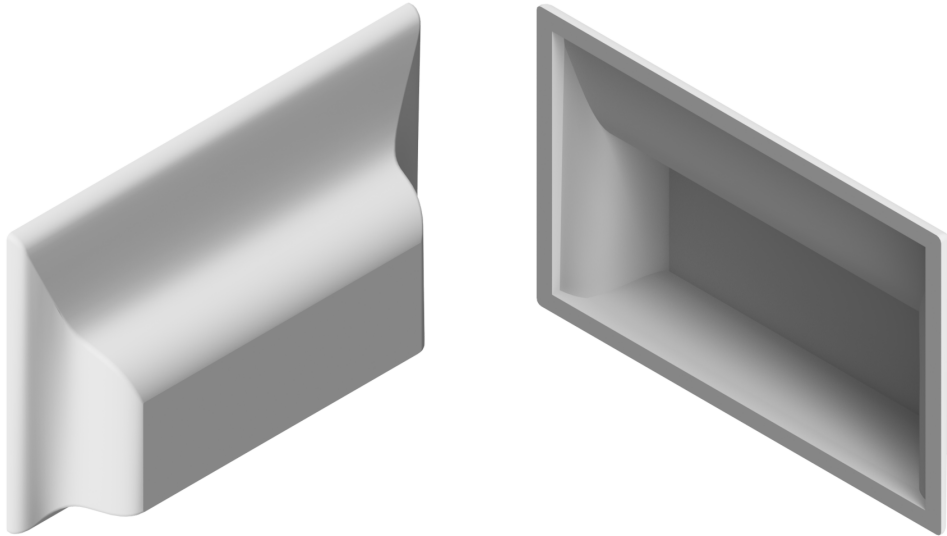


Figure 4.7: Pure back cover

After inspecting the ergonomics, I started with placing the individual parts of the electronics. First, I had to place the Raspberry Pi 4.

To connect it to the other parts of the CCU, I needed 1x micro HDMI and 1x USB port to join the display, a GPIO header to attach the power and communication, and 1x USB port to connect an SSD card if needed. It is also crucial that the user has access to two USB ports, for connecting a keyboard and a mouse or a flash drive for data storage and access to an Ethernet port for connecting the CCU to the network.

So I placed the RPI4 in the left part of the box (Fig. 4.9) on the support spacers with holes for threaded inserts. I made a protective frame for the USB and Ethernet ports and formed an opening to access the connectors from the outside.

The power and communication PCB I placed in the right part next to the RPI4 and it will be connected to it via a 40-pin GPIO header. For communication with the sensor platform, there will be a connector on the PCB that will be placed on the right side of the CCU. In the sketch, I outlined the PCB, using which I formed the spacers for the threaded inserts. After that, I calculated the exact position of the communication connector for which I created a slot (Fig. 4.9).

In the last stage, it was necessary to provide the CCU with a slot for the power connector and the On/Off button (Fig. 4.9).

The power connector was placed under the communication connector into one slot to prevent the power cable from hindering the CCU when standing or holding it.

The On/Off button was placed on the backplate in the upper right corner to be as close to the PCB as possible, so there was no need for unnecessarily long cables to connect it.

4.3.3 VESA standard

During development, I considered that some users might use the CCU as a monitor and want to place it on a mount. To make this feature user-friendly and allow the user to use any holder (e.g., for a monitor or TV), it must provide the same mounting standard.

Mounts for holding flat screens today use the VESA standard, which defines different dimensions (length \times width) for placing the four screws. [35] If I use one of the VESA dimensions to mount my CCU, the user will have many mounts to choose from. The smallest VESA dimension is 75×75 mm, but this dimension is still too large to place on a CCU. So I decided to set the bolt size to 50×50 mm (Fig. 4.10) and to create a reducer already with the VESA standard size (e.g. 100×100).

4.4 Thermal management

To prevent the Raspberry Pi from overheating, due to mathematical algorithms and user application, it must be adequately cooled. If the CPU temperature approaches 85°C , Raspberry will limit its performance (CPU speed) so that the temperature never exceeds the maximum limit. [24]

Maximum CPU performance is essential for our application, so I must design a suitable cooling system to avoid overheating.

The RPI can be cooled in two ways, passive, which uses only the heat sink, or active, using a separate fan or in combination with the heat sink. A comparison of the effectiveness of these two methods is described in the article [36], which analyzes the effect of cooling under a very high CPU load and shows that passive cooling is insufficient for very heavily loaded RPI and CPU power must be limited to avoid overheating.

The article [36] also mentions that active cooling implemented only by a fan is effective, but the temperature rises faster. For this reason, I will use a fan with a heat sink in the CCU to ensure that the CPU limitation does not cause slower rendering of real-time graphs, thus invalidating the data.

Finally, I chose "Dual cooling fan 5V for Raspberry Pi 4" [37] (Fig. 4.8) as the active heatsink because its design is large enough to cover the main chips on the RPI, contains two fans so that the heatsink will be sufficiently cooled, and its small size allows it to be used without interfering with the 3D model.

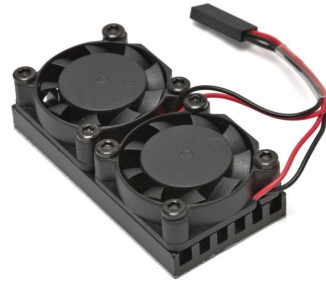


Figure 4.8: Dual cooling fan [37]

The cooling designed in this way would not be very efficient. While active cooling would work properly, it is also important that the fans placed on the heatsink have something to cool them. Since the RPI will be placed in a box, any heat released from the heatsink will accumulate inside, raising the temperature and making the cooling less efficient. So it is essential that the air inside the CCU is circulating and the warm air released from the heatsink is exhausted outside.

In the 3D design, I created a slot just below the RPI to place a 30×30 mm fan that will exhaust air, and diagonally at the top, I made vents for a fresh air intake (Fig. 4.10). By placing the vents in this way, I achieved that the air would flow through the whole CCU and all the warm air would be extracted outside.

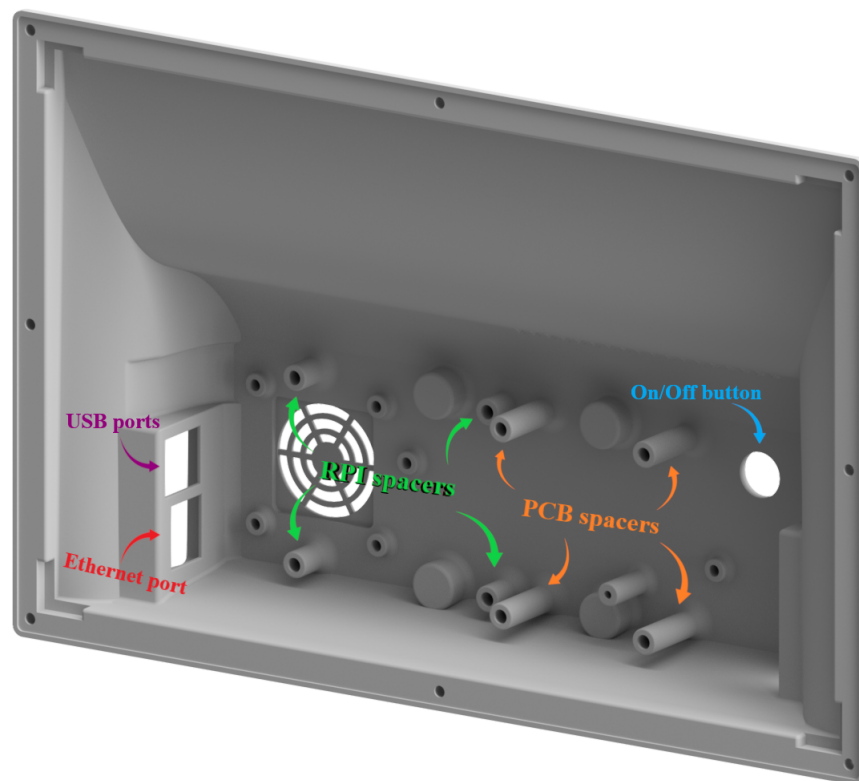


Figure 4.9: Back cover - front view

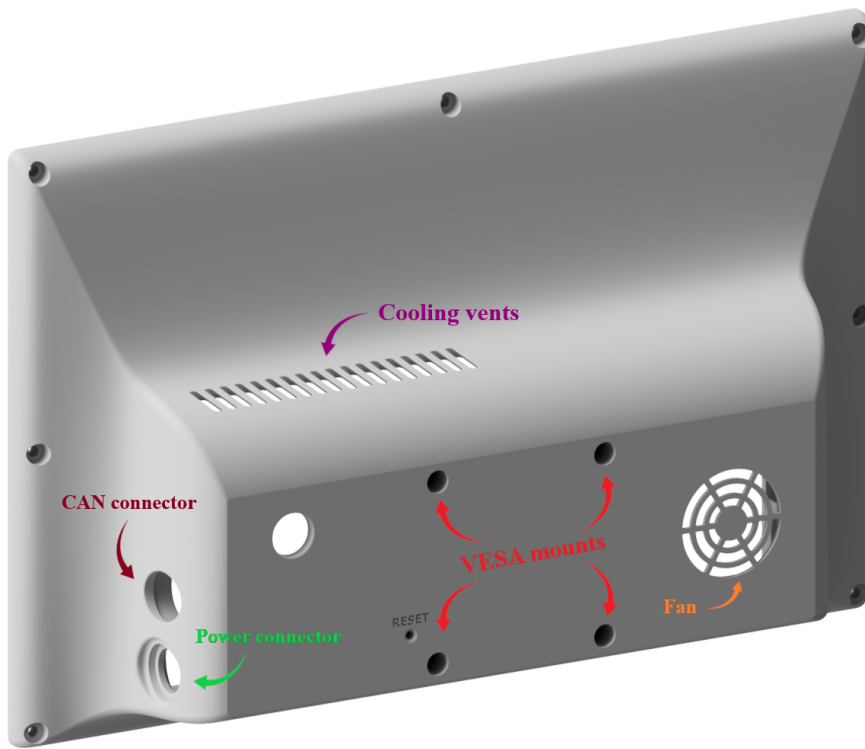


Figure 4.10: Back cover - rear view

Chapter 5

Hardware Development

In this chapter, I will discuss the design and implementation of two important circuits for the proper operation of the CCU. The first circuit will take care of the power supply for all the electronics and the second will take care of the communication link between the sensor platform and the Raspberry Pi 4. Then, I will describe the design and manufacturing of the PCB.

5.1 Power-Supply management

The Raspberry Pi is a development board that lacks a physical On/Off button for powering it on or off. Instead, when the power is supplied to the board, it automatically boots up. To shut it down, the user must execute a command within the operating system or use a button on the main desktop. However, to power it on again, the user must unplug and plug in the power supply. This startup process can be inconvenient for users and requires a more user-friendly solution. One possible solution is to introduce a single On/Off button, allowing users to easily power the Raspberry Pi on or off at any time.

The Raspberry Pi operating system is loaded onto an SD card, which frequently reads and writes data. Due to this, it is not advisable to disconnect the CCU from the power while it is still running. To properly shut down the CCU, a command must first be issued to initiate the power-down sequence. Once a visual signal is given, the CCU can be safely disconnected from the power.

To achieve this goal, I need to design a circuit that utilizes the On/Off button to power up all the CCU components, including the Raspberry Pi, the display, the cooling fans, and the sensor platform on the treadmill. Additionally, the circuit must ensure that when the CCU is turned off, the Raspberry Pi initiates its shutdown process before cutting power to all the components.

■ 5.1.1 Microprocessor (MCU) selection

There are two methods for constructing the power supply circuit - the first method involves using electrical components such as resistors, capacitors, semiconductors and integrated circuits. The second method uses a MCU with a control program to replace the entire circuit. After careful consideration, I decided to use the MCU for two main reasons.

Firstly, since there will be a communication circuit on the PCB that connects the Raspberry Pi and the sensor platform, it is important that the power supply circuit generates minimal EMI. However, with the first method, there could be numerous voltage loops that may cause interference. Secondly, during the design of the analog circuit, it became apparent that it contained many components. Therefore, for future PCB designs, it would be more practical to choose a small MCU instead.

MCU requirements:

- Operating voltage - 5V
- Program memory \geq 4kB
- GPIO's pins - 7
- Interrupt pins - 2
- Current for pin \geq 20mA

Several MCUs, that meet my requirements for the power supply circuit, are available. Although they may vary in parameters such as size, case type, and speed, these differences are not significant for future use, and it is difficult to determine which one is the most ideal.

After careful consideration, I decided to utilize the ATtiny414 MCU [38] as it aligns with my requirements and it is a MCU I am already familiar with. It is straightforward to program and no complex processes are required to load the program.

■ 5.1.2 Step-down converter

To use a single power supply for the entire project, the sensor platform will be powered through the CCU. The platform will be equipped with 6 PCBs, with a theoretical current (according to datasheets) consumption of 150mA per board and a total consumption of 900mA.

After consulting with Adam Stastny, I determined that the prototype PCB had a current consumption of 400mA, which would result in a platform current consumption of 2.5A. This current consumption seemed to me relatively high and as a result, I calculated with current consumption in a range of 1 – 2.5A.

Device	Current [A]
RPI 4	2.5
Display	0.9
Fan	0.1
RPI fan	0.1
Sensor platform	$\approx 1 - 2.5$
PCB	0.15
Total	$\approx 5 - 6.5$

Table 5.1: CCU current calculating

According to Table 5.1, the entire CCU, including the sensor platform, will require a minimum of a 5V/5A power supply with a performance of 25W. Such power supplies are rare and are typically made as internal module power supplies.

To achieve similar performance, I can use a more commonly available power supply, such as 12V/2A. For this purpose, I must choose a suitable step-down regulator to transform the input voltage to the desired output voltage of 5V.

Step-down regulator requirements:

- As small as possible
- Output voltage 5V/5A

Out of the available options that meet my requirements, I chosen the "*Step-Down Regulator D24V50F5*" [39] (Fig. 5.1). This particular step-down regulator is ideal for use on a PCB due to its compact size of 18×20 mm.

**Figure 5.1:** Pololu step-down regulator [39]

However, I can only use this step-down regulator if the total current consumption of the platform will not exceed 1A. But since the current consumption can be up to 2.5A, I decided to add another, more powerful step-down controller ("*Step-Down Regulator D24V90F5*") [40] (Fig. 5.2) to the selected one.

Later, in a future PCB design, I will make a position for both of them and in the test phase (according to the real current draw), I will decide which one I will use.

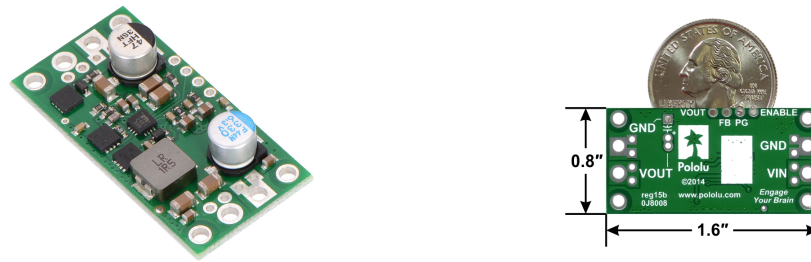


Figure 5.2: Pololu powerful step-down regulator [40]

5.2 Communication converter

During the architecture design phase, we decided to use CAN communication for transmitting data between the sensor platform and the CCU. We upgraded this to differential CAN to minimize the impact of interference on the transmission cable. However, Raspberry Pi 4 does not support differential CAN communication. For this reason, I needed to design a circuit that can receive differential CAN data, convert it to CAN, and then convert it to the SPI communication protocol that the Raspberry Pi 4 supports.

To convert the data from differential CAN to SPI I used an existing converter [41], which I modified for our communication structure. The converter employs two chips. The first chip (TJA1050) transforms the differential CAN data to CAN and sends the data to the second chip (MCP2515), which transforms it from CAN to SPI data.

For our communication, we agreed on a bus voltage of 3.3V since the RPI only supports a maximum of 3.3V. As a result, I needed to replace the TJA1050 chip, which requires a 5 V supply voltage [42], with the SN65HVD230 chip. The SN65HVD230 chip has the same size and pin-out as the TJA1050 and performs the same function, but its supply voltage is 3.3V [43].

5.3 Connectors

When selecting connectors for connecting components to the PCB, I focused on making them simple, universal and large enough. Most importantly, they should have a click function to prevent them from loosening due to vibrations caused by the treadmill.

I chose *JST-XH 2.54mm 2-pin* connectors [44], which are often used nowadays and thus allow the user to replace them in case of failure easily.

As a connector for programming ATtiny414, I chose *1734598-3* from TE Connectivity [45], which is not universal and does not allow the user to interfere with the program. It is also small enough not to take up much space but it allows easy connection and programming in case of a malfunction.

The essential connector is the one that will connect the sensor platform to the CCU. Initially, I considered using a universal connector (e.g. Ethernet). But this could be a problem because if someone inexperienced handled with the CCU, it could be easily plugged into a classic Ethernet port, thus damaging the communication.

For this reason, I used an atypical industrial connector *T4145015051-001* from TE Connectivity [46]. It is quite specific and contains protective grooves that will not allow any other connector's connection. It also uses a fixed connection through the M12 thread, so when transferring the CCU there will not be loose.

■ 5.4 Schematic

Before designing the PCB, I must create an electrical schematic for all the components. For this, I will use the software Altium Designer, in which I will make a schematic and then the PCB according to it.

■ 5.4.1 ATtiny414

The ATtiny414 (Fig. 5.3) is powered through a 2-pole switch [47], so the user can program only the AT without powering the rest of the circuit. The switch can therefore be used to power the AT from the step-down regulator or the programming port. The Capacitors $C_{4,6,8}$ I use to eliminate the spikes from the supply voltage.

The AT datasheet [38] recommends placing an anti-interference capacitor ($C_{5,7,9,10,11}$) on each I/O pin used.

To switch the voltage to the whole PCB, I must choose a suitable relay that can handle high current while producing minimal EMI and requiring low switching current.

I chose relay (G3VM-61FR1) [48], which switches the voltage using two Mosfet transistors. Therefore, it does not create any EMI, the switching current is 30mA and the rated load current is 5A.

But I choose the appropriate connection, as shown in the datasheet, and the relay can handle a load current of up to 9A because it switches both transistors and the load current are evenly distributed.

The AT can be easily programmed using an external programmer (Arduino) [49] and PCB must include a programming circuit, with one resistor R_1 , that uses this programmer.

In the last part of the circuit, the LED was connected to the AT to indicate the program status and a RESET button to restart the whole CCU in case of a system failure.

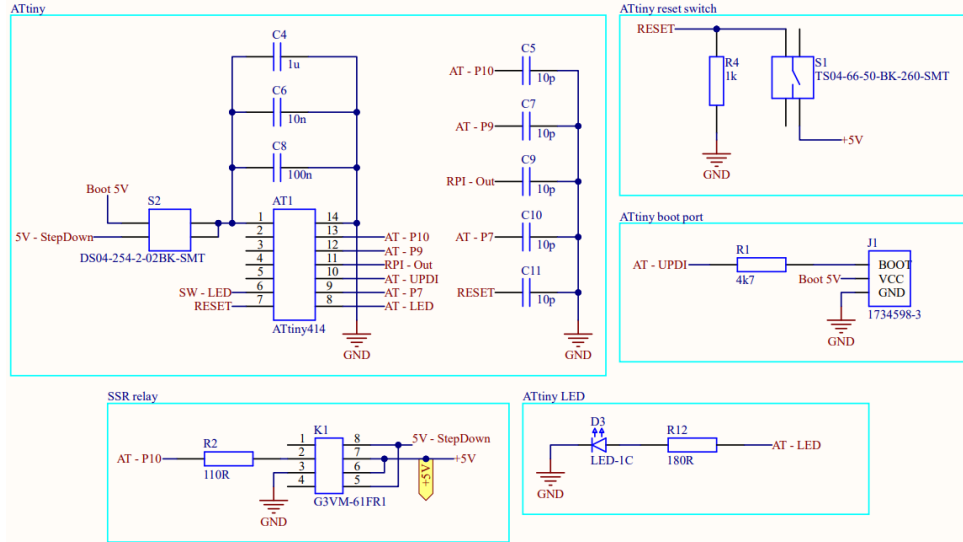


Figure 5.3: ATtiny414 schematic

5.4.2 RPI

On the 40-pin GPIO header (Fig. 5.4), I connected pins for SPI communication, external power supply (pins 1 and 2), and pins that will be used to turn on and off the RPI (*RPI-Out*, *RPI-ShutDown*).

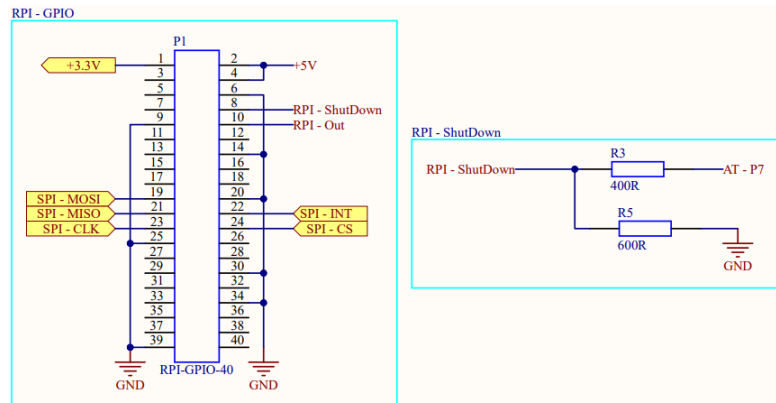


Figure 5.4: RPI schematic

5.4.3 Step-Down and connectors

In the power circuit, it was necessary to create connectors for input power from the power supply, output voltage for the display, both cooling fans, the backlight of the On/Off button, and a connector for the On/Off button (Fig. 5.5).

To protect the circuit in case of a short circuit, these connectors were fitted with fuses.

For this purpose, I chose reversible fuses (non-linear thermistors) [50] with different trip currents and will trip due to heat if this limit is exceeded. After some time, the fuse gradually cools down and switches on again.

Finally, I connected Step-Down regulators to the circuit and an LED to indicate whether they converted voltage.

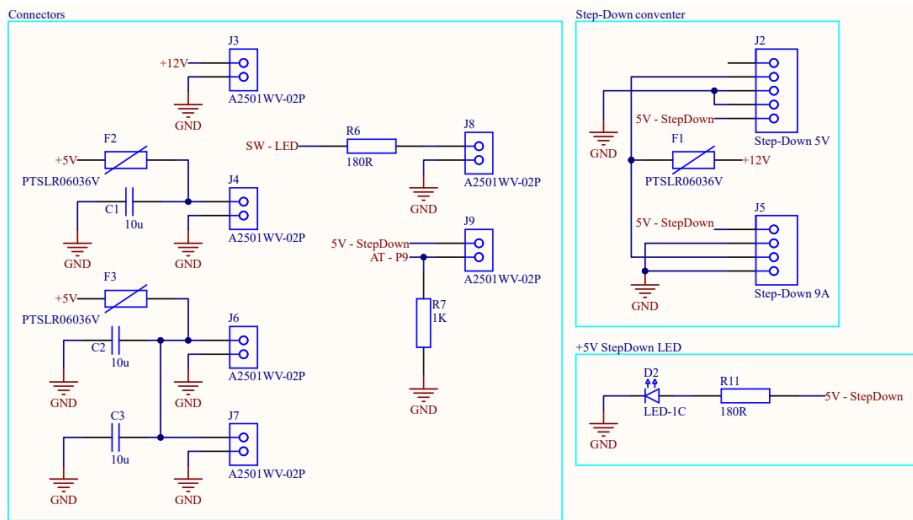


Figure 5.5: Step-Down and connectors schematic

5.4.4 Differential CAN \mapsto CAN

Differential CAN (CAN_P , CAN_N), from sensor platform STM, I transform to CAN (CAN_TX , CAN_RX) signal with SN65HVD230 (Fig. 5.6).

To avoid any spikes that may arise from the CAN communication, I use three capacitors $C_{13,14,15}$ at the 3.3V supply voltage. Additionally, I include resistors $R_{8,9}$ to terminate the end of the CAN bus to reduce crosstalk. These resistors I connect to a capacitor C_{12} and the ESDCAN diode, which protects the circuit from electrostatic discharge. Capacitors $C_{16,17}$ between CAN-P and CAN-N are employed to remove spikes from the CAN bus.

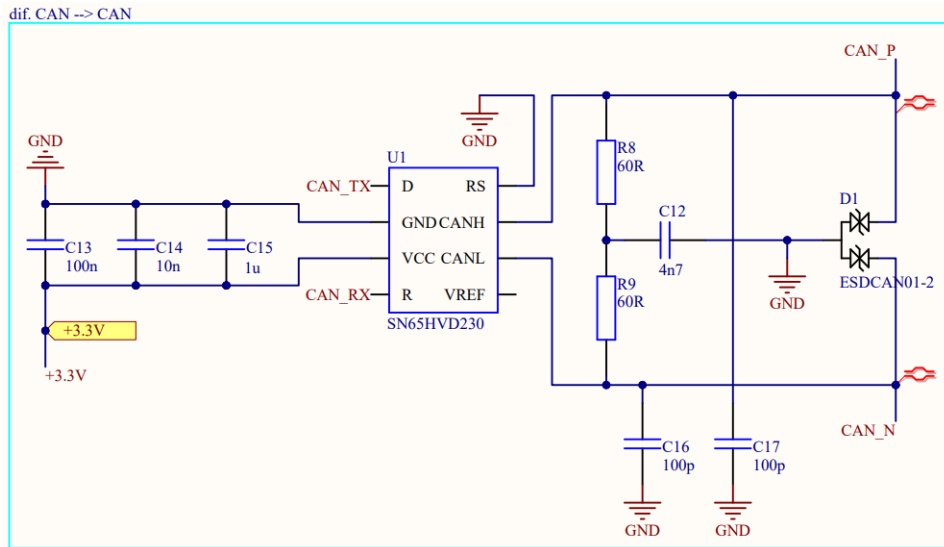


Figure 5.6: Differential CAN ↔ CAN schematic

5.4.5 CAN ↔ SPI

In this schematic (Fig. 5.7), I used an existing converter [41]. To eliminate spikes from the supply voltage, I added capacitors $C_{18,19,20}$. The value of capacitors $C_{21,22}$ is determined, based on the crystal used. I am using an ESC SMD crystal that requires a load capacitance of 10pF [51].

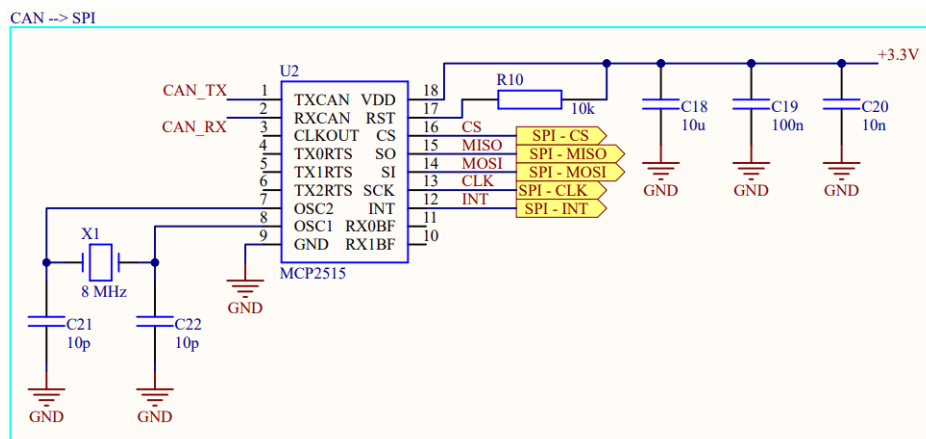


Figure 5.7: CAN ↔ SPI schematic

■ 5.5 Printed circuit board

Before beginning the PCB design process, it is important to establish the key requirements that the PCB must meet.

Both circuits must be able to fit within a predetermined board shape that was established during the 3D modeling phase. Additionally, it is important to ensure that the communication circuit is adequately shielded from any EMI that may be generated by the power supply circuit and that it is designed in accordance with high-speed communication standards.

The second thing that I need to choose is a manufacturing company that will produce my PCB because the design rules according to which I will design the PCB are different for each company and I have to follow them when designing.

■ 5.5.1 PCB main parameters

As a PCB manufacturing company, I chose the JLCPCB because, in the price/quality comparison, it is the best of all available companies, and I also have a good experience with them.

The main parameter of PCB is the number of layers. I chose among 2-layer, 4-layer or 6-layer, where each type has a specific application. 2-layer PCBs are intended only for the design of low-speed applications, 4-layer PCBs are for low-supply impedance, and 6-layer PCBs are for high-supply impedance. [52]

In PCB design, the aim is always to use as few layers as possible, which can be separated into three types. [52]

- outer signal layers (*microstrip*) - have a lower parasitic capacity
- inner signal layers (*stripline*) - higher resistance to interference
- conductive surfaces (*plane*) - for low-impedance power supply

Ideally, the rule of thumb is that each signal layer should be adjacent to a conductive surface (preferably a common ground or power supply).[52]

I have chosen to use a 4-layer PCB for several reasons. Firstly, the many components that will be powered from the PCB could lead to numerous current loops. In the case of a 2-layer PCB, it may cause EMI that could affect the communication circuit.

Secondly, the width of traces is a crucial factor, as wider paths are needed to accommodate higher currents and prevent overheating. Using a 4-layer PCB, I can route the power and ground on the inner layers of the PCB as conductive surfaces, allowing wider copper paths to handle high currents.

Additionally, using internal conductive surfaces helps minimize the occurrence of EMI that could affect the communication circuit.

According to the design rules, the individual layers in the PCB are organized as follows. [52]

- S1 - Signal layer (Power-Supply circuit)
- G - GND (Ground)
- P - Power supply
- S2 - Signal layer (diff. CAN \leftrightarrow SPI circuit)

■ 5.5.2 Traces parameters and design rules

Each company involved in PCB manufacturing has set a minimum of design parameters that they are capable of producing. E.g. drill/hole size, annular ring, clearance, trace width and spacing, solder mask and many others, see [53].

The Altium Designer software allows me to set all these parameters and will not let this minimum parameters be exceeded during PCB design or it will warn me if they are violated.

Another important parameter is the trace width. As I mentioned earlier, the width of the trace depends on the size of the current flowing through it. The required trace width can be calculated according to different standards, where each standard uses different calculation algorithms.

For my PCB design, I chosen to use the IPC-2152 standard and the calculation application [54]. It requires the specification of other parameters that affect the resulting width, such as temperature rise, trace thickness, and board thickness.

For most signal connections between components (microprocessors, resistors, capacitors, etc.), I opted to use universal traces with a width of 0.254mm. However, non-universal traces are required for high-current voltage transfer, and I calculated their widths according to the IPC-2152 standard.

The final important parameter, which depends on the current size, is the number of vias. Since I use a 4-layer PCB with a power layer hidden inside and a relay located in layer S1 to switch it, I need to transfer all the current from this layer to the inner power layer of the PCB.

To determine the number of vias needed to transfer all the current, I needed to know the maximum current that can flow through a single via. To do this, I used a computational application [55]. It calculates the current flow through a via based on the diameter, length, and width of the inner cladding.

■ 5.5.3 Communication design rules

When creating a communication circuit, I must follow special high-speed design rules to avoid data errors, crosstalk or EMI.

The most important design rules [56], [57]:

- As short and straight traces as possible
- Do not use the 90° corners
- All traces are the same length
- Data traces as far apart as possible
- Clock signal as far away from data traces as possible
- Traces with 50 Ω impedance

For the impedance matching of the traces, I use the automatic calculator in the Altium Designer software, which according to the PCB parameters, calculates the necessary width of the traces to have 50 Ω impedance.

To match the lengths of all the traces, I will use the function *Interactively Tune Trace Length*, which uses tuning patterns to extend the length of the traces to match the longest trace.

■ 5.5.4 Circuits position and EMI elimination

As mentioned earlier, I chose to use a 4-layer PCB to ensure that the communication circuit is completely isolated from the power circuit and not affected by EMI resulting from current loops in the power circuit.

I also had to consider a Step-Down regulator in the PCB design. It generates the most EMI and could affect communication the most. To mitigate this, I created the communication circuit on the opposite side of the PCB from where the Step-Down regulator is located.

Despite taking this precaution, EMI could still affect communication speed. To address this issue, I applied specifically design rules to the PCB, which should suppress the effect of EMI completely.

First, to mitigate the effects of EMI through current loops, I created a ground plane in the signal layers (S1 and S2). This plane was connected to the inner ground (GND) layer at multiple points using vias.

Secondly, to prevent the generation of EMI from the edges of the PCB to other layers, I needed to address the issue with electromagnetic fields created when the power layer is too close to the edge. To counteract this effect, the 20H rule is typically used. It states that at the edges of the PCB, the GND conductive area should extend beyond the power or signal layers by 20 times their mutual distance as shown in Fig. 5.8 [59].

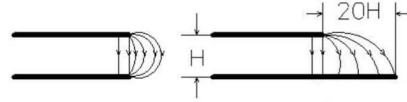


Figure 5.8: 20H design rule [58]

However, I could not use this rule due to the thickness of the PCB, which would require an enormous distance. Instead, I chose an alternative approach and created a ring around the entire PCB using vias connected to the GND layer to form a Faraday cage.

5.5.5 PCB assembly and testing

After sending the order to JLCPCB and receiving the actual PCB, the first step was to solder the components onto it. To do this, I used a specific method where I applied solder paste to the joint locations first. Next, I placed the components onto these locations and finally soldered them using hot air. (Fig. 5.9 and 5.10).

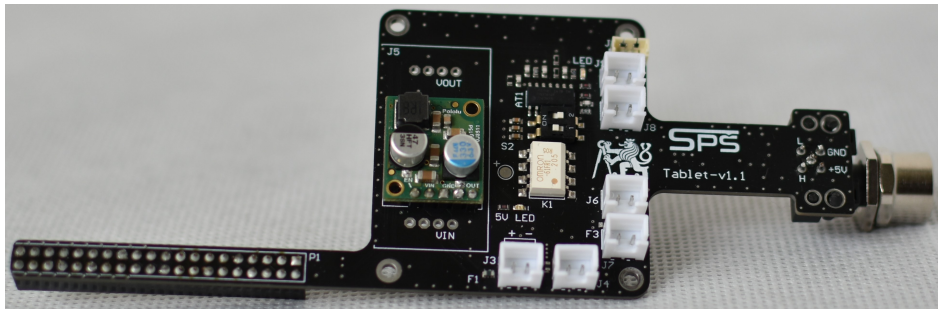


Figure 5.9: PCB - front (Power-Supply)

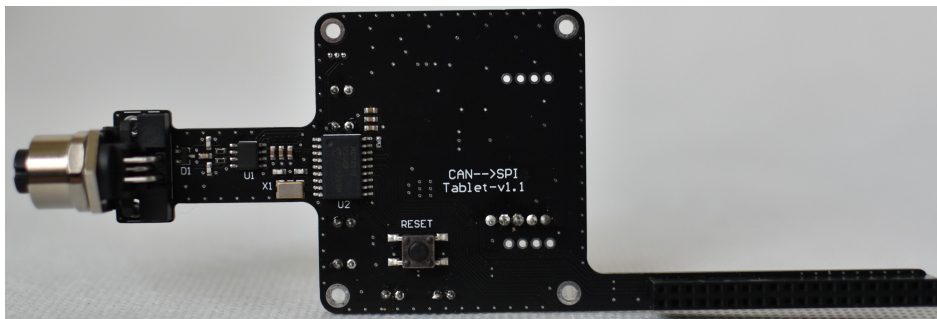


Figure 5.10: PCB - rear (Power-Supply)

5.6 Power-Supply program

For the ATtiny414 microcontroller, I created a simple program in the Arduino IDE software to turn on, turn off and reset the CCU, including all the components (display, cooling fans and sensor platform).

The function of the program is described in the state diagram (Fig. 5.11).

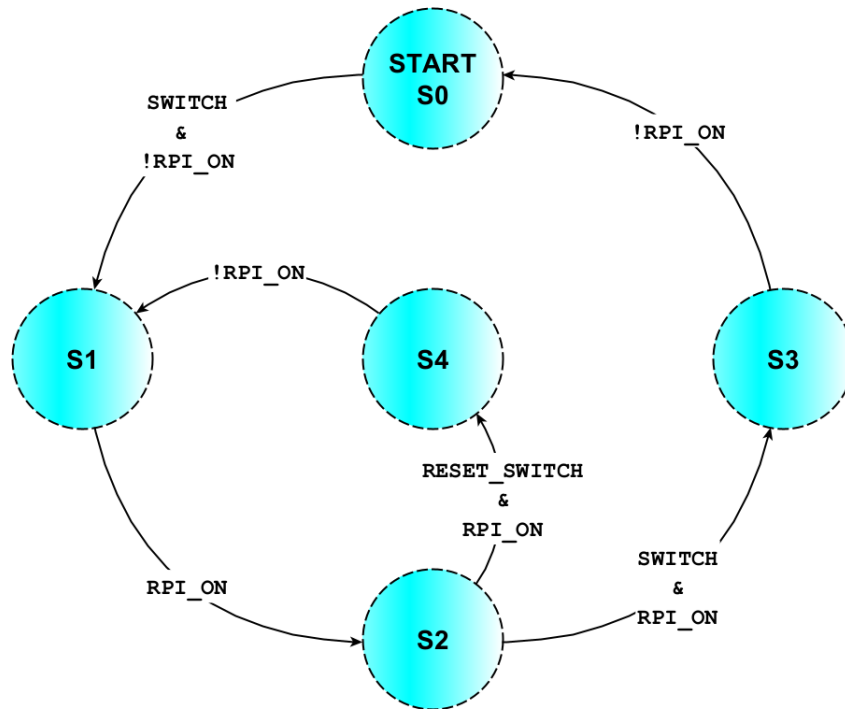


Figure 5.11: State diagram of Power-Supply program

Program states:

- S0 - CCU is off
- S1 - RPI boot process
- S2 - CCU is on
- S3 - RPI shutdown process
- S4 - CCU resetting

Program variables:

- *switch* - state of On/Off button
True ⇒ button pressed
False ⇒ button released
- *rpi_on* - state of RPI pin
True ⇒ RPI run
False ⇒ RPI not run
- *reset_switch* - state of reset button
True ⇒ button pressed
False ⇒ button released

Chapter 6

Long-term Data Analysis

In this chapter, I would like to describe the implementation of a SQL database in which the CCU will store users' information such as age, height, weight, etc. and results from various measurements (static or dynamic). Next, I will discuss the design of the windows for the long-term data analysis, which will be divided into two sections: static measurement analysis and dynamic measurement analysis.

6.1 Database implementation

To create a database, choosing a suitable programming language is crucial. Mr. Vágner, who is responsible for developing the GUI and computational algorithms has selected Python as the programming language for the software development. Therefore, I also decided to use Python to develop the entire database. If I had used a different programming language, it would have been necessary to exchange data between us, which could have been inefficient and slow. To create the database, I will use the SQLite3 library, the most widely worldwide used, which implements the SQL database tool.

Initially, I had to design the database structure appropriately so that it was simple, efficient and the data could be easily stored or retrieved. As mentioned, I will store all users' basic information and data from static and dynamic measurements in the database. However, creating one relational database (table) for all this data would be pointless, as the structure would be very complicated and inefficient in storing or retrieving data. For this reason, I created three relational tables that will be linked together. The first table (Fig. 6.1 **Users**) will store all users' information, each with a specific identifier (*user_id*). The second and third tables (Fig. 6.1) will be used to store data from each exercise (**Static** and **Dynamic**), and each will be linked with a foreign key to the user identifier (*user_id*) to which the exercise belongs.

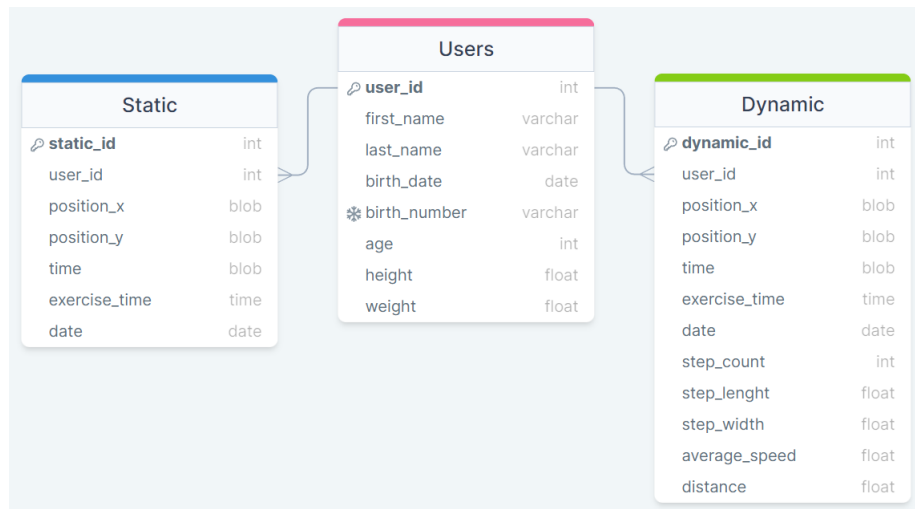


Figure 6.1: CCU database - Users, Static and Dynamic

With a structure designed this way, I can easily add new users and exercises without the need for complex linking for future data reading during analysis. Another advantage of foreign key linkage is the ease of removing users because if I remove a given user, all exercises of that user are automatically deleted from the exercise tables.

6.2 Data analysis

To create individual windows displaying different graphs for static or dynamic data analysis, I choose Python as the programming language using the PyQt5 framework (library).

I decided to use it because Mr. Vágner also uses it to create GUI. We agreed that it would be helpful to have the analysis part as a part of the GUI so that the whole project would have one unified application where the user can find everything he needs.

Nowadays, various methods are available for processing data obtained from the platforms that measure static posturography. The choice of method depends on the technology used for measurement and the data that the platform can measure. Specific platforms can measure the precise distribution of weight on a patient's feet. In such cases, it is beneficial to analyze and display this weight distribution in the resulting analysis.

Our platform uses a method that involves a board for measuring weight distribution, through which we can measure the position of a patient's CoP over some time.

6.2.1 Static data analysis

As mentioned in chapter 2.1.1, many static platforms that use the weight distribution measurement method typically utilize two graphs for analyzing subsequent static data: the statokinesiogram and the stabilogram.

For this reason, I decided to incorporate these two graphs into our application for the static data analysis.

In my first window, I created a classic statokinesiogram that shows the position of a patient's CoP in x and y coordinates. To enhance the visualization of the data and aid physicians in identifying any deviations from the ideal variance of the data, I interleaved these points with a circle.

Next, I will consider the data to have a Normal (Gaussian) distribution and calculate the mean ($\mu_{x,y}$), and standard deviation ($\sigma_{x,y}$) for each direction of CoP movement (x and y-axis).

$$\mu_x = \frac{1}{n} \sum_{i=1}^n CoP_{x_i}, \quad (6.1)$$

$$\mu_y = \frac{1}{n} \sum_{i=1}^n CoP_{y_i}, \quad (6.2)$$

$$\sigma_x = \sqrt{\frac{1}{n} \sum_{i=1}^n (CoP_{x_i} - \mu_x)^2}, \quad (6.3)$$

$$\sigma_y = \sqrt{\frac{1}{n} \sum_{i=1}^n (CoP_{y_i} - \mu_y)^2}. \quad (6.4)$$

To implement these computational algorithms, I will use the already created functions (*mean()* and *stdev()*) from the Statistics Python library. And then I will plot the resulting calculated values in a graph.

By analyzing the measured data on the y-axis, I can also calculate the percentage weight distribution between the feet for each CoP point.

To determine the weight distribution on the right and left leg for each CoP point, I use the calculation

$$m_{RCoP_i} = \frac{d + CoP_{y_i}}{6} [\%], \quad (6.5)$$

$$m_{LCoP_i} = 100 - m_{RCoP_i} [\%], \quad (6.6)$$

where d is the distance between the feet centers and CoP_{y_i} is the y-axis value for the given CoP point. After obtaining these values, I calculate the average percentage distribution for the entire exercise.

For this purpose, I can use the standard algorithm

$$\bar{x}_{m_R} = \frac{1}{n} \sum_{i=1}^n m_{RCoP_i}, \quad (6.7)$$

$$\bar{x}_{m_L} = \frac{1}{n} \sum_{i=1}^n m_{LCoP_i}. \quad (6.8)$$

Instead, I will use the *mean()* function from the Statistics library.

In my second window, I created a Stabilogram that depicts the CoP movement in both the x and y-axis over time. This visualization enables doctors to quickly identify patient data variances for both forward/backward and right/left movement.

To provide a comprehensive analysis, I will again assume that the data will have a Gaussian distribution. As in Statokinesiogram, I calculated the mean ($\mu_{x,y}$) and standard deviation ($\sigma_{x,y}$) from the individual data and plotted them on a graph. Additionally, I created a box plot alongside each graph to illustrate the distribution of the data into quartiles, which includes the minimum, first quartile (Q1), second quartile (median/Q2), third quartile (Q3), and maximum values.

For this purpose, I use the function *boxPlot*, from the Matplotlib library. That computes each quartile from the data set and creates a box plot graph.

6.2.2 Dynamic data analysis

To analyze the data obtained from the dynamic measurement, I created two distinct graphs.

The first graph shows the patient's CoP trajectory across the board during their run. To facilitate the analysis of these data, I will assume that the data will have a Gaussian distribution. I choose this assumption to determine the data's mean (μ) and standard deviation ($\pm\sigma$). I will define these values for each direction of movement (x-axis and y-axis) separately and calculate them using the functions *mean()* and *stdev()*. These values should assist the doctor in determining the variance of the data and retrospectively analyzing the patient's run.

To assess the symmetry of the run, I need to interleave the data with a rectangle. However, to accomplish this, I must first determine the vertices of the rectangle. For this purpose, I must identify all the landing and rebound positions for the patient's right and left foot within the data and then calculate their means.

With the data provided by my colleague Mr. Vágner, I have access to the upper and lower peaks from measured data. The upper peaks correspond approximately to the landing positions of the step. The lower peaks correspond to the rebound positions of the step. To find which peaks correspond to the

right and left foot, I will utilize an algorithm that analyzes the surrounding CoP_y (in the timeline) when a real-time algorithm detects the CoP_x peak.

In an ideal situation, the patient's CoP trajectory, which moves in a particular direction, should resemble a "butterfly" pattern (Fig. 6.2). Analyzing the surrounding CoP_y points, as demonstrated in the Figure, I can determine that peak corresponds to the left foot if the mean of the CoP_y values surrounding the peak is greater than its y-value. Conversely, the peak belongs to the right foot if the mean is lower than its y-value.

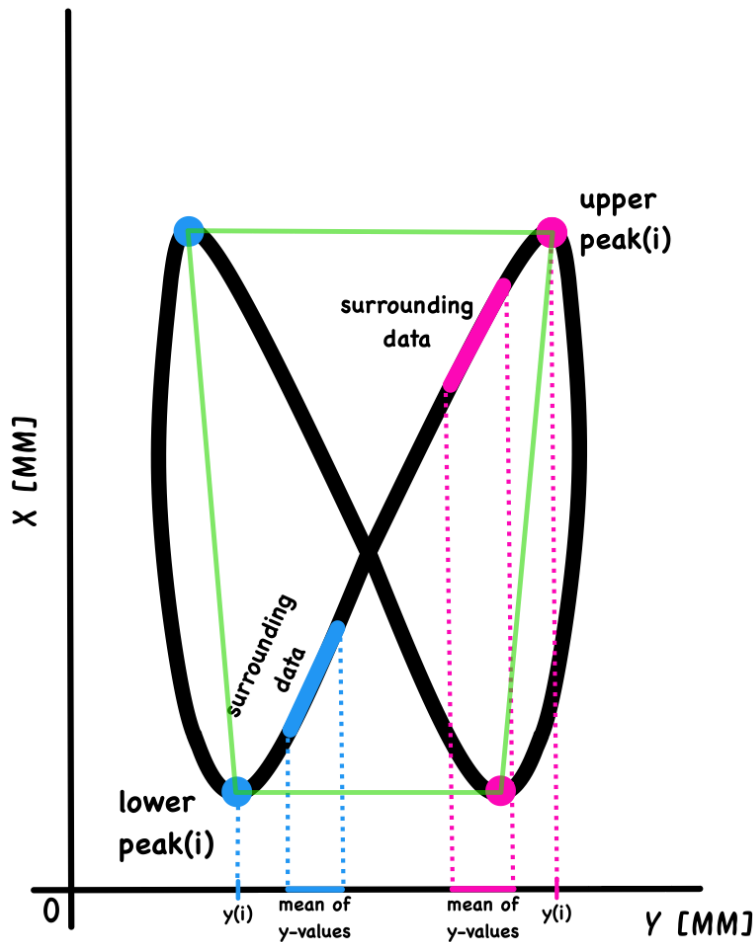


Figure 6.2: Butterfly pattern

After dividing these data, I calculate their mean using the $mean()$ function to determine all four rectangle corners.

Again, to make it easier to determine the variance of these positions of landing or rebound for the right or left leg, I calculate the standard deviations from the data using the $stdev()$ function. I will then use these values to create circles centered in each rectangle corner. This rectangle and each circle should make it easier for the doctor to diagnose the patient's run, symmetry and stability more quickly.

The second graph shows a radar chart that can assist the specialist in analyzing the patient's running ability across various aspects. Based on this data and the pattern shape created by combining all the values, the specialist may more easily diagnose the disorder and suggest appropriate rehabilitation processes.

In the graph, I use the data such as step length, step width, the landing weight of each foot, the standard deviations of CoP_y , CoP_x , and for each set of peaks (landing/rebound of right/left foot).

Chapter 7

Validation

7.1 Hardware tests

7.1.1 RPI cooling

To assess the impact of the proposed active cooling on the CPU of the Raspberry Pi 4, I conducted a test using a simple script to measure the CPU temperature over 20 minutes.

The graph (Fig. 7.1) depicts the temperature levels reached by the CPU when no cooling and active cooling was applied. Specifically, I let the Raspberry Pi 4 remain idle for the first 5 minutes, followed by running a dynamic measurement application that includes several background computational algorithms.

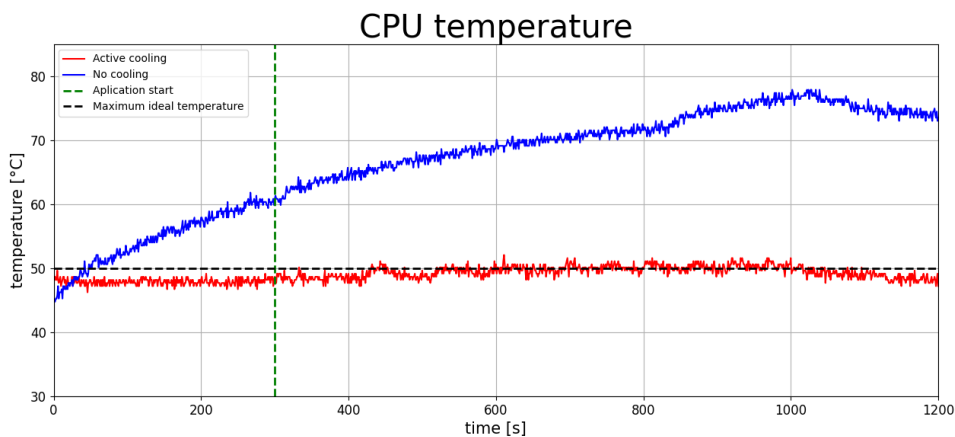


Figure 7.1: CPU temperature measurement

Upon comparing the two graphs, it is evident that active cooling results in the stabilization of the CPU temperature at approximately 50°C, which is notably different from the stabilized CPU temperature in the absence of cooling. The manufacturers state that for an ideal operation, the CPU should operate at a maximum temperature of 50°C. Hence, active cooling proves to be adequate as it can effectively maintain the temperature of the RPI at or below the recommended maximum operating temperature.

7.1.2 PCB Step-Down regulator

To test the real CCU's current consumption, I connected the individual components, including the sensor platform, and measured their actual current consumption. This allowed me to find out the total current consumption and select the appropriate Step-Down regulator. The current consumption of each component is in Table 7.1.

Device	Actual current [mA]
RPI 4	523
Display	327
Fan	33
RPI fan	69
Sensor platform	152
PCB	27
Total	1131

Table 7.1: CCU actual current

Based on the table, the CCU requires a total current of 1.131A at 12V. However, if I convert this value to 5V, the total current consumption is 2.709A. It is worth noting that this current consumption is significantly lower than what I had initially estimated when I designed it in Chapter 5.1.2. During the PCB testing phase, Mr. Šťastný discovered that a small amount of solder paste had remained under several capacitors, which did not heat up sufficiently during the soldering process. As a result, a small connection was created between Vcc and GND, leading to a minor short circuit. Although the PCB still functioned properly, this issue caused a higher-than-expected current consumption.

Based on the actual current consumption, I have chosen to use a 5V/5A Step-Down controller because it can deliver sufficient current even if the user intends to add more sensors to the platform.

7.2 Long-term analysis evaluation

7.2.1 Static analysis

I performed the validation of the proposed algorithms on two test data sets. The generated statokinesiograms can be seen in the Figures 7.2 and 7.3.

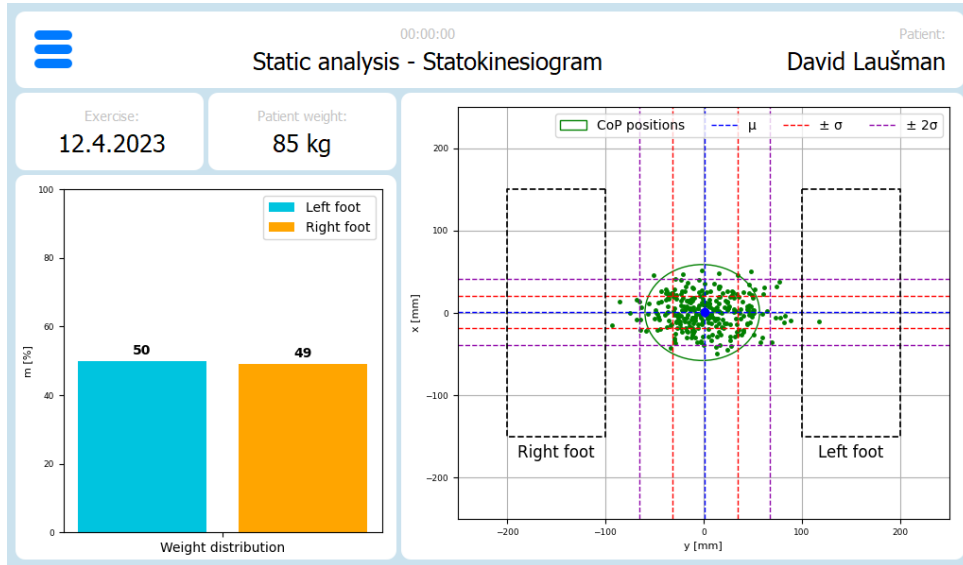


Figure 7.2: Statokinesiogram - first data

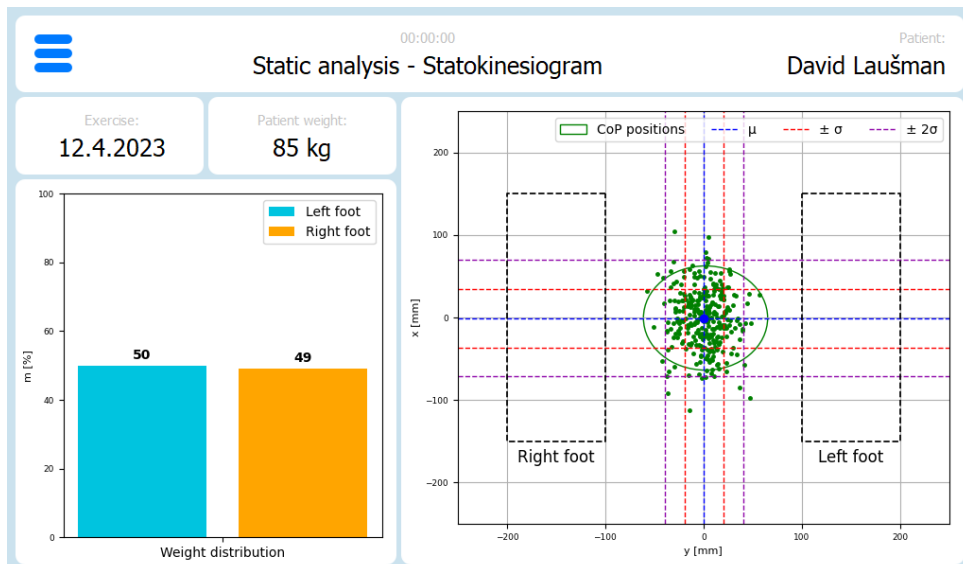


Figure 7.3: Statokinesiogram - second data

These graphs show the CoP points (green) and the circle that intersects 90% of these points. The calculated mean (μ) value for each axis is visible, represented by a blue dot indicating its position. The standard deviation from the mean value is also shown for each axis as $\pm\sigma$ and $\pm 2\sigma$. Moving to the left section, you can observe the calculated average percentage weight distribution between the feet for the entire exercise.

The following pictures (Fig. 7.4 and 7.5) show stabilograms. Similar to the previous figures, the calculated mean (μ) and standard deviation ($\pm\sigma$ and $\pm 2\sigma$) are also plotted here. Looking at the right section of these plots, the presence of BoxPlot plots is worth noting. They show the minimum and maximum values. The center of the red rectangle then indicates the median (Q2), and the bottom and top correspond to the first (Q1) and third (Q3) quartiles.

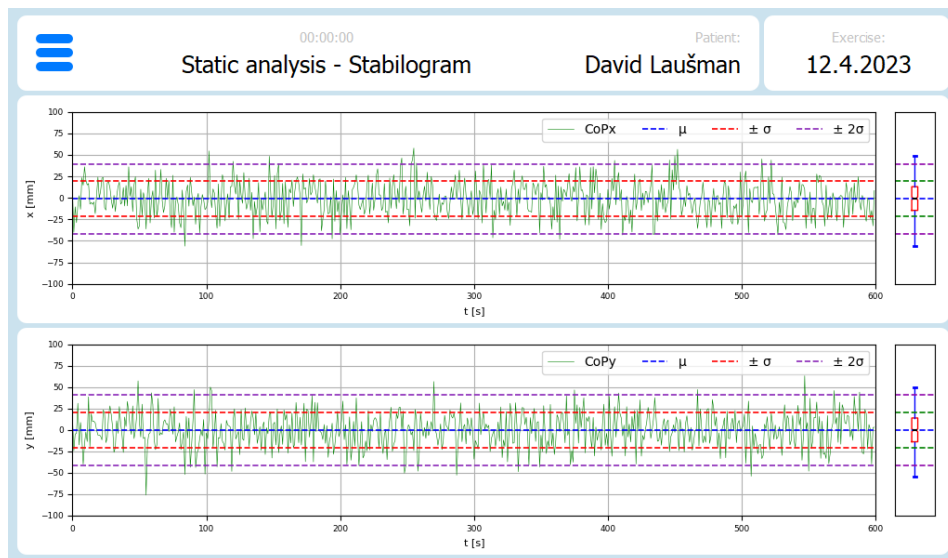


Figure 7.4: Stabilogram - first data

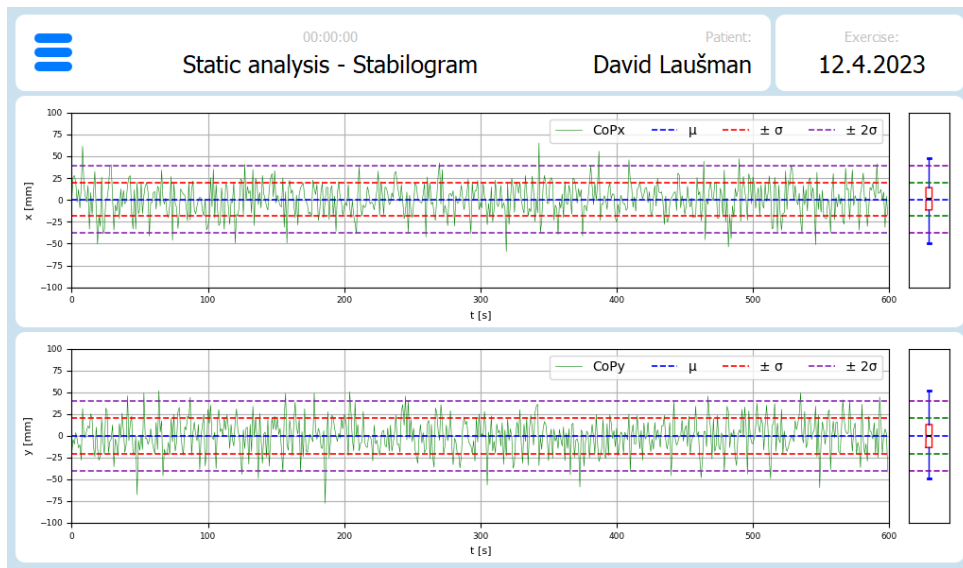


Figure 7.5: Stabilogram - second data

7.2.2 Dynamic analysis

The left part of Figure 7.6 illustrates the trajectory of the CoP point during the patient's running/walking. The graph shows that the algorithm effectively recognizes the individual peaks for both the right and left legs, which are distinguished by different colors.

Subsequently, the mean value for each axis is calculated for each set of peaks, which is represented as a black point on the graph. To demonstrate the symmetry of the patient's running pattern, these four points are connected to form a rectangle. Further, two circles are visible at these four points, indicating the standard deviations ($\pm\sigma$ and $\pm 2\sigma$) of the peaks for each position.

Finally, the plot shows the calculated mean value (μ) and the standard deviation ($\pm\sigma$) for the entire trajectory of the patient's CoP.

Meanwhile, the right side of the figure shows the radar chart. It includes all the parameters mentioned in Chapter 6.2.2.

These values are linked to a unique pattern, which may assist doctors in effectively comparing data from various exercises and diagnosing any disorders.

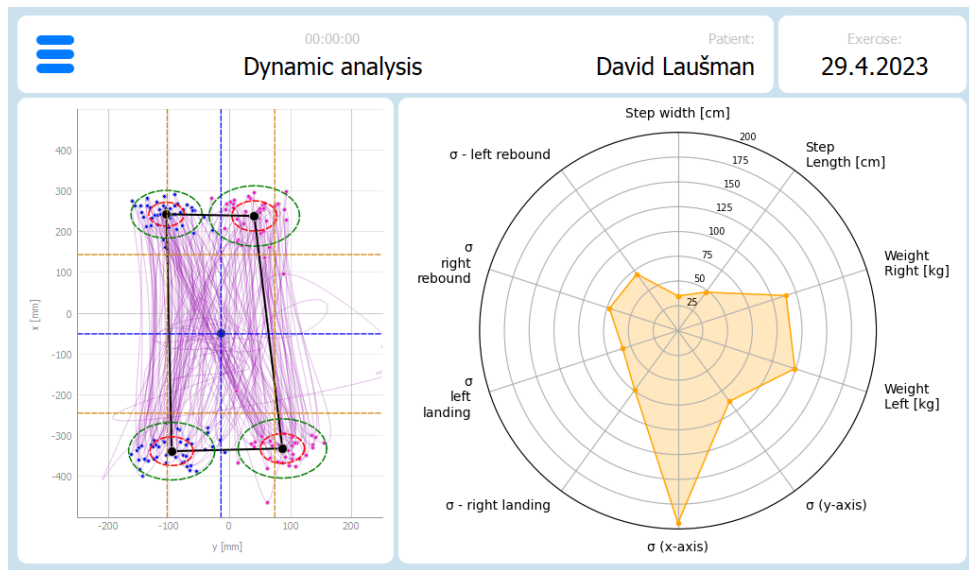


Figure 7.6: Dynamic analysis

Chapter 8

Conclusion and future work

We aimed to develop a sensor platform, including a visualization device (CCU), for use in any treadmill. The platform will be used to measure the position of the patient's Center of Pressure (CoP) while standing or in motion (walking or running). Additionally, it would display measured data in the real-time graph and provide essential information about the patient's walk or run, such as step length, step width, number of steps, current speed, traveled distance and weight.

We would also like to process data for a long-term analysis that would assist the specialist in diagnosing the disorder and in preparing an appropriate rehabilitation procedure.

8.1 Conclusion

The aim of this thesis was to create a visualization device for the posturometric platform. This includes designing a 3D model, selecting suitable components and creating a PCB. That connects all the components and the communication between the CCU and the sensor platform. These goals were achieved.

A prototype 3D model was created to display the user interface (application) to show the obtained data. This included the selection of a suitable controller, display and connector to connect the sensor platform. In the next part, a suitable cooling system was created to keep the control unit at an ideal operating temperature and to avoid performance slowdown due to overheating.

Furthermore, a PCB was designed to connect all the components and allow powering on and off the CCU, including the sensor platform. It is also responsible for linking the CAN communication between the CCU and the sensor platform.

Finally, a database and an application for long-term data analysis were created. Everything was implemented in Python. This includes the design of a suitable database to store users' information and measured data. Three different windows were created for data analysis. Two for static measurements, showing the trajectory of the patient's CoP while standing. And one for the dynamic measurements that show the trajectory of the patient's CoP while walking/running and other important parameters.

The final testing was performed on a real prototype platform using the computational algorithms, a graphical user interface and a sensor platform created by my colleagues Mr. Vágner and Mr. Štastný.

8.2 Future work

Future work includes further development of a visualization device currently used as a prototype to verify functionality and refinement of applications for a long-term data analysis. Future work will aim at creating a PCB connecting all the components, thus achieving a smaller CCU size. Furthermore, based on the testing and patients' or doctors' feedback, also to add the necessary data into the applications and remove the unnecessary data.

Finally, refinement of the algorithms for calculating means, standard deviations, and interleaving values with circles. This process will entail finding the appropriate data distribution to calculate the mean and variance accurately. Interleaving the data with the ellipses will then perfectly match their distribution.



Bibliography

- [1] B. Jolana, “Využití tenzometrické plošiny v ambulanci terapii”, May 20, 2016. [Online]. Available: <https://dspace.cvut.cz/handle/10467/67612> (visited on Apr. 30, 2023).
- [2] B. Helštýnová, “Analýza Posturometrických dat”, *Analysis of Posturometric Data*, 2012. [Online]. Available: <http://dspace.vsb.cz/handle/10084/92986> (visited on Apr. 30, 2023).
- [3] “The stabilogram, statokinesiogram, and spectral composition graphs of...”, ResearchGate. (), [Online]. Available: https://www.researchgate.net/figure/The-stabilogram-statokinesiogram-and-spectral-composition-graphs-of-the-Sway-parameters_fig1_236205524 (visited on Apr. 30, 2023).
- [4] K. a. H. s.r.o. “[Nintendo Wii] Podložka Wii Balance Board (černá, na baterie)”, KONZOLE a HRY, s.r.o. (), [Online]. Available: <https://www.konzoleahry.cz/nintendo-wii-podlozka-wii-balance-board-cerna-na-baterie-p17198/> (visited on May 1, 2023).
- [5] “Balance Master”, www.Cephalon.eu. (), [Online]. Available: <https://www.cephalon.eu/products/balance/balance-master/> (visited on May 1, 2023).
- [6] “GT6800 RF home-use Folding Rehab Treadmill | Body Charger”, Body Charger fitness. (), [Online]. Available: <https://bodychargerfitness.com/portfolio-item/gt6800-rf-rehab-treadmill/> (visited on May 1, 2023).
- [7] “AXELERO Gait&Balance”, Nowoczesna rehabilitacja neurologiczna. (Oct. 19, 2021), [Online]. Available: <https://neurorehabilitacja.com.pl/aktualnosci/axelero-gaitbalance/> (visited on May 1, 2023).
- [8] “Underwater Treadmill for Aquatic Therapy”, EWAC Medical. (), [Online]. Available: <https://www.ewacmedical.com/products/underwater-treadmill/> (visited on May 1, 2023).

- [9] “Mercy Fort Scott Uses the Versatility of the Underwater Treadmill”, HydroWorx. (Oct. 20, 2016), [Online]. Available: <https://www.hydroworx.com/blog/mercy-fort-scott-devonte-wilson/> (visited on May 1, 2023).
- [10] luke. “Resistive or capacitive - what is the right touch panel?”, Riverdi. (Mar. 13, 2019), [Online]. Available: <https://riverdi.com/blog/resistive-or-capacitive-what-is-the-right-touch-panel/> (visited on Apr. 11, 2023).
- [11] Š. Frederik, “Inteligentní zrcadlo s Raspberry Pi pro ovládání chytré domácnosti”, Jun. 13, 2018. [Online]. Available: <https://dspace.cvut.cz/handle/10467/76640> (visited on Apr. 16, 2023).
- [12] M. R. Bhalla and A. V. Bhalla, *Comparative Study of Various Touch-screen Technologies*, 2010. [Online]. Available: <https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=f44e8da5ef07d593cb940c19df30a4028428c47d> (visited on Apr. 16, 2023).
- [13] “How can a screen sense touch? A basic understanding of touch panels | EIZO”. (), [Online]. Available: https://www.eizo.com/library/basics/basic_understanding_of_touch_panel/ (visited on Apr. 16, 2023).
- [14] T. Nachazel. “What is a Strain Gauge and How Does it Work?”, Michigan Scientific Corporation. (Aug. 13, 2020), [Online]. Available: <https://www.michsci.com/what-is-a-strain-gauge/> (visited on Apr. 16, 2023).
- [15] G. Hollings. “Strain Gauges: How they Work, Applications, and Types”. (), [Online]. Available: <https://blog.endaq.com/strain-gauges-how-they-work-applications-and-types> (visited on Apr. 16, 2023).
- [16] “Introduction to CAN (Controller Area Network) - Technical Articles”. (), [Online]. Available: <https://www.allaboutcircuits.com/technical-articles/introduction-to-can-controller-area-network/> (visited on Apr. 16, 2023).
- [17] S. Corrigan, *Introduction to the Controller Area Network (CAN)*, 2016. [Online]. Available: https://www.ti.com/lit/an/sloa101b/sloa101b.pdf?ts=1680577865591&ref_url=https%253A%252F%252Fwww.google.com%252F (visited on Apr. 16, 2023).
- [18] B. Lutkevich. “What is a Database? | Definition from TechTarget”, Data Management. (), [Online]. Available: <https://www.techtarget.com/searchdatamanagement/definition/database> (visited on Apr. 26, 2023).
- [19] “What is a database?” (), [Online]. Available: <https://www.oracle.com/database/what-is-database/> (visited on Apr. 26, 2023).

- [20] “What is a Database? Definition, Types, Examples - javatpoint”, [www.javatpoint.com. \(\)](https://www.javatpoint.com/what-is-database), [Online]. Available: <https://www.javatpoint.com/what-is-database> (visited on Apr. 27, 2023).
- [21] A. KL. “What Are Single Board Computers (SBCs)? And, Why You Should Buy Single Board Computers?”, The Sec Master. (Jun. 2, 2022), [Online]. Available: <https://theseccmaster.com/what-are-single-board-computers-sbcs-and-why-you-should-buy-single-board-computers/> (visited on Apr. 16, 2023).
- [22] M. Ján, “Dotykový ovládací panel pro termovizní smartkameru”, Jan. 28, 2019. [Online]. Available: <https://dspace.cvut.cz/handle/10467/80344> (visited on Apr. 16, 2023).
- [23] “What is a Raspberry Pi?”, Raspberry Pi Foundation. (), [Online]. Available: <https://www.raspberrypi.org/help/what-is-a-raspberry-pi/> (visited on Apr. 16, 2023).
- [24] *Raspberry-pi-4-datasheet*, 2019. [Online]. Available: <https://datasheets.raspberrypi.com/rpi4/raspberry-pi-4-datasheet.pdf> (visited on Apr. 16, 2023).
- [25] R. P. Ltd. “Buy a Raspberry Pi 4 Model B”, Raspberry Pi. (), [Online]. Available: <https://www.raspberrypi.com/products/raspberry-pi-4-model-b/> (visited on Apr. 16, 2023).
- [26] “Banana Pi open source Hardware community-Banana Pi open source hardware community,Single board computer, Router,IoT,STEM education”. (), [Online]. Available: <https://www.banana-pi.org/en/bananapi-profile/> (visited on Apr. 16, 2023).
- [27] “Banana Pi BPI-M6 - Banana Pi Wiki”. (), [Online]. Available: https://wiki.banana-pi.org/Banana_Pi_BPI-M6 (visited on Apr. 16, 2023).
- [28] “File:Banana Pi BPI-M6 1.jpg - Banana Pi Wiki”. (), [Online]. Available: https://wiki.banana-pi.org/File:Banana_Pi_BPI-M6_1.jpg (visited on Apr. 16, 2023).
- [29] “Libre Computer”. (), [Online]. Available: <https://libre.computer/> (visited on Apr. 16, 2023).
- [30] “AML-S905X-CC (Le Potato)”. (), [Online]. Available: <https://libre.computer/products/aml-s905x-cc> (visited on Apr. 16, 2023).
- [31] *Raspberry Pi Compute Module 4*, 2023. [Online]. Available: <https://datasheets.raspberrypi.com/cm4/cm4-datasheet.pdf> (visited on Apr. 16, 2023).
- [32] “Raspberry Pi Compute Module 4”. (), [Online]. Available: <https://rpishop.cz/compute-module-4/3086-raspberry-pi-compute-module-4.html> (visited on Apr. 16, 2023).

- [33] “Waveshare 10,1" HDMI LCD (E) displej, 1024×600, HDMI, IPS LCD, dotykový, kapacitní”. (), [Online]. Available: <https://rpishop.cz/lcd-oled-displeje/4019-waveshare-101-hdmi-lcd-e-displej-1024600-hdmi-ips-lcd-dotykovy-kapacitni.html> (visited on Apr. 16, 2023).
- [34] “10.1inch Capacitive Touch Screen LCD (E), 1024×600, HDMI, IPS, Fully Laminated Screen, Supports Raspberry Pi, Jetson Nano, And PC”. (), [Online]. Available: <https://rarecomponents.com/store/10.1inch-hdmi-lcd-e-waveshare> (visited on Apr. 16, 2023).
- [35] “What is the VESA standard and which one I’ve got?” (), [Online]. Available: <https://www.vesa-standard.com/index.html> (visited on Apr. 13, 2023).
- [36] A. Alasdair. “Do You Need to Use a Fan for Cooling with the New Raspberry Pi 4?”, Hackster.io. (2019), [Online]. Available: <https://www.hackster.io/news/do-you-need-to-use-a-fan-for-cooling-with-the-new-raspberry-pi-4-6d523ca12453> (visited on Apr. 18, 2023).
- [37] “Duální 5V větrák, 50x25x13 mm”. (), [Online]. Available: <https://rpishop.cz/aktivni/2291-dualni-5v-vetrak-50x25x13-mm.html> (visited on Apr. 18, 2023).
- [38] *ATtiny214 / ATtiny414 / ATtiny814 Complete*, 2017. [Online]. Available: <https://ww1.microchip.com/downloads/en/DeviceDoc/40001912A.pdf> (visited on Apr. 16, 2023).
- [39] “Pololu 5V, 5A Step-Down Voltage Regulator D24V50F5”. (), [Online]. Available: <https://www.pololu.com/product/2851> (visited on Apr. 16, 2023).
- [40] “Pololu 5V, 9A Step-Down Voltage Regulator D24V90F5”. (), [Online]. Available: <https://www.pololu.com/product/2866> (visited on Apr. 16, 2023).
- [41] “Buy CAN-bus modul MCP2515 / TJA1050 SPI at the right price @ Electrokit”. (), [Online]. Available: <https://www.electrokit.com/en/product/can-bus-modul-mcp2515-tja1050-spi/> (visited on Apr. 18, 2023).
- [42] *TJA1050 High speed CAN transceiver*, 2003. [Online]. Available: <https://www.electrokit.com/uploads/productfile/41017/TJA1050-Data-Sheet.pdf> (visited on Apr. 19, 2023).
- [43] *SN65HVD23x 3.3-V CAN Bus Transceivers datasheet*, 2018. [Online]. Available: https://www.ti.com/lit/ds/slos346o/slos346o.pdf?ts=1681911304071&ref_url=https%253A%252F%252Fwww.google.com%252F (visited on Apr. 19, 2023).

- [44] “Amazon.com: Daier 20 Sets Jst Xh 2.54 2 Pin Connector Plug Male with 200mm Wire & Female Connector : Electronics”. (Apr. 22, 2023), [Online]. Available: <https://www.amazon.com/Sets-2-5-2-Connector-200mm-Female/dp/B01DUC1NDM> (visited on Apr. 22, 2023).
- [45] “1734598-3 : PCB Headers & Receptacles”, TE Connectivity. (), [Online]. Available: <https://www.te.com/usa-en/product-1734598-3.html> (visited on Apr. 22, 2023).
- [46] “T4145015051-001 : M12 Connector Standard Circular Connectors”, TE Connectivity. (), [Online]. Available: <https://www.te.com/usa-en/product-T4145015051-001.html> (visited on Apr. 22, 2023).
- [47] *DS04-254-SMT Series Datasheet*, 2019. [Online]. Available: https://cz.mouser.com/datasheet/2/670/ds04_254_smt-1777718.pdf (visited on Apr. 19, 2023).
- [48] *En-g3vm_cr_fr*, 2016. [Online]. Available: https://cz.mouser.com/datasheet/2/307/en_g3vm_cr_fr-949213.pdf (visited on Apr. 19, 2023).
- [49] “Getting started with the new ATtiny chips - Programming the Microchip’s 0-series and 1-series ATtiny with the Arduino IDE”, Electronics-Lab.com. (), [Online]. Available: <https://www.electronics-lab.com/project/getting-started-with-the-new-attiny-chips-programming-the-microchips-0-series-and-1-series-attiny-with-the-arduino-ide/> (visited on Apr. 19, 2023).
- [50] *PTSLR0603 PTC fuse data sheet*, 2012. [Online]. Available: https://cz.mouser.com/datasheet/2/87/eaton_ptslr0603_surface_mount_resettable_fuse_data-2492189.pdf (visited on Apr. 20, 2023).
- [51] *ECX-53B SMD CRYSTAL*, 2017. [Online]. Available: https://cz.mouser.com/datasheet/2/122/ecx_53b-3074848.pdf (visited on Apr. 19, 2023).
- [52] J. Šandera, “Elektrické zásady návrhu s ohledem na elektromagnetickou kompatibilitu”, in *Návrh plošných spojů pro povrchovou montáž*, 1st ed., Praha: BEN - technická literatura, 2006, p. 272, ISBN: 80-7300-181-0.
- [53] “PCB Manufacturing & Assembly Capabilities - JLCPCB”. (), [Online]. Available: <https://jlcpcb.com/capabilities/pcb-capabilities> (visited on Apr. 21, 2023).
- [54] “Using an IPC-2152 Calculator: Designing to Standards”, Altium. (Jan. 4, 2019), [Online]. Available: <https://resources.altium.com/p/using-ipc-2152-calculator-designing-standards> (visited on Apr. 21, 2023).
- [55] “The CircuitCalculator.com Blog » PCB Via Calculator”. (2007), [Online]. Available: <http://circuitcalculator.com/wordpress/2006/03/12/pcb-via-calculator/> (visited on Apr. 21, 2023).

- [56] E. Robledo. “10 High-Speed PCB Design Rules to Follow”, Fusion 360 Blog. (Dec. 2, 2022), [Online]. Available: <https://www.autodesk.com/products/fusion-360/blog/10-high-speed-pcb-design-rules/> (visited on Apr. 22, 2023).
- [57] “High Speed Printed Circuit Board (PCB) Design Guidelines”. (), [Online]. Available: <https://www.integrasources.com/blog/high-speed-pcb-design-guidelines/> (visited on Apr. 22, 2023).
- [58] “20 Golden PCB Design Rules - PCB Antenna Design”. (Jan. 20, 2022), [Online]. Available: <https://pcbantennas.com/20-golden-pcb-design-rules/> (visited on Apr. 22, 2023).
- [59] V. Záhlava, “Návrhová pravidla”, in *Návrh a konstrukce desek plošných spojů: principy a pravidla praktického návrhu*, 1st ed., Praha: BEN - technická literatura, 2010, p. 123, ISBN: 80-7300-266-3.

Appendix A

Sensor platform drawing

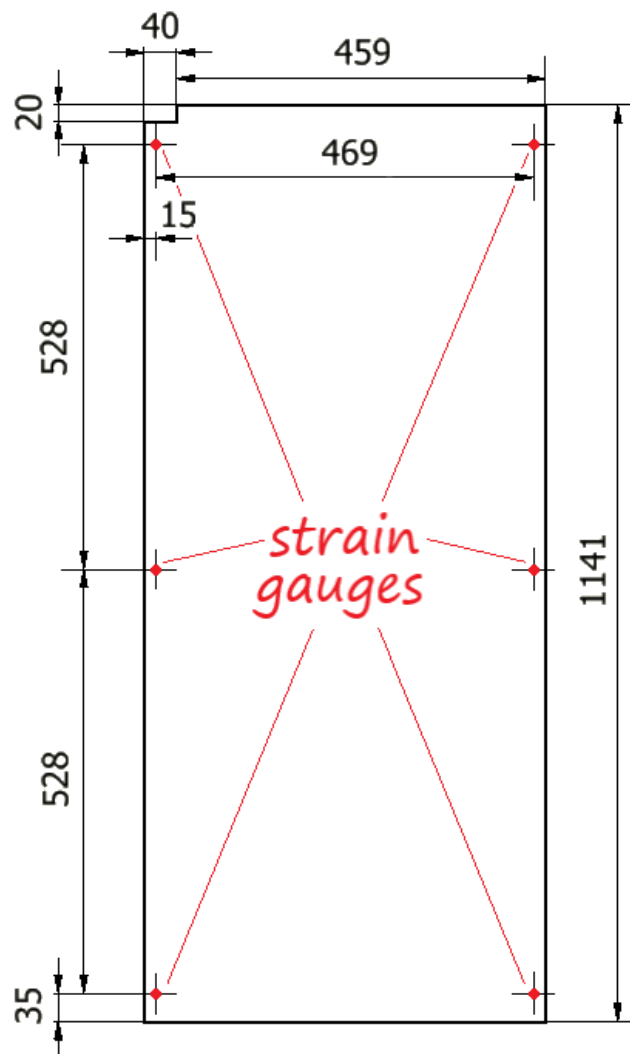


Figure A.1: Sensor platform drawing [mm]

Appendix B

Tablet 3D model

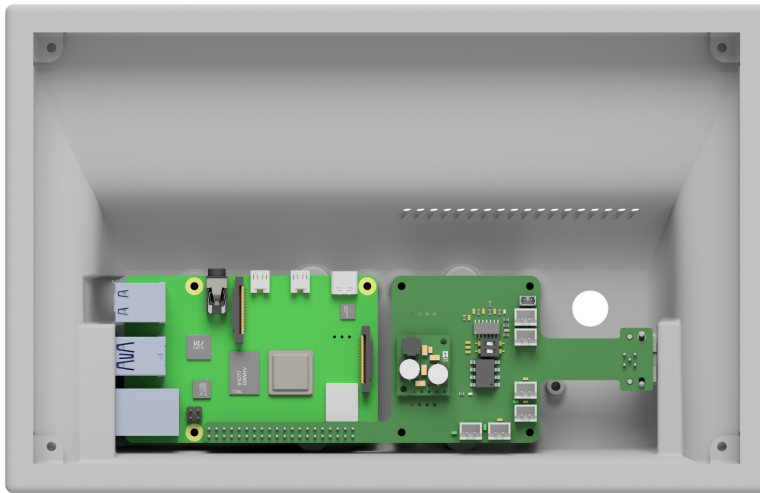


Figure B.1: Tablet 3D model - front view

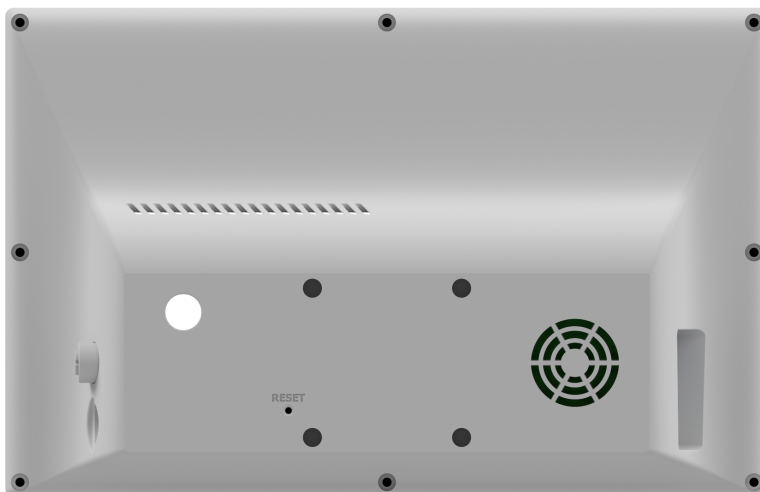


Figure B.2: Tablet 3D model - rear view

Appendix C

PCB 3D model

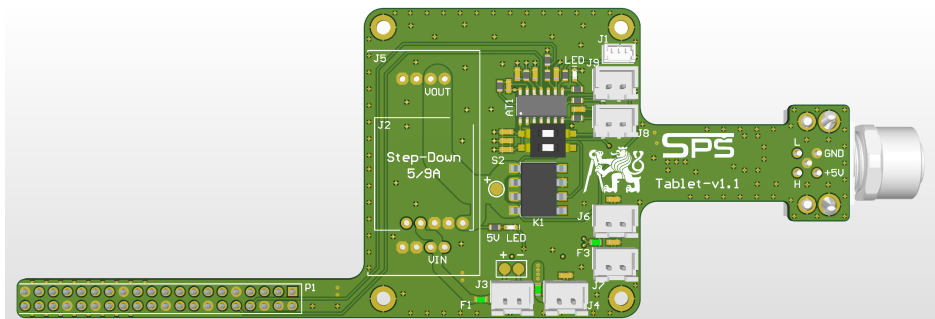


Figure C.1: PCB 3D model - front view

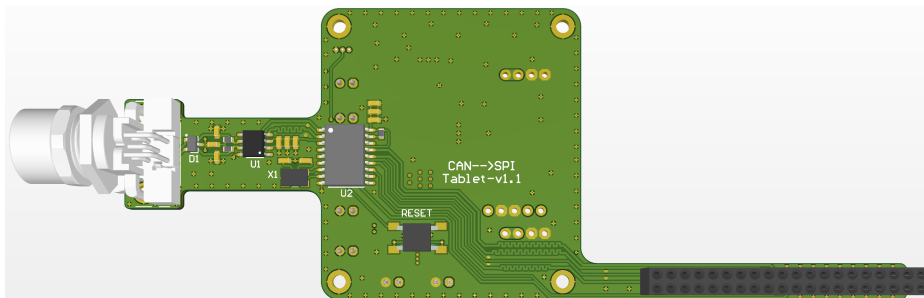


Figure C.2: PCB 3D model - rear view

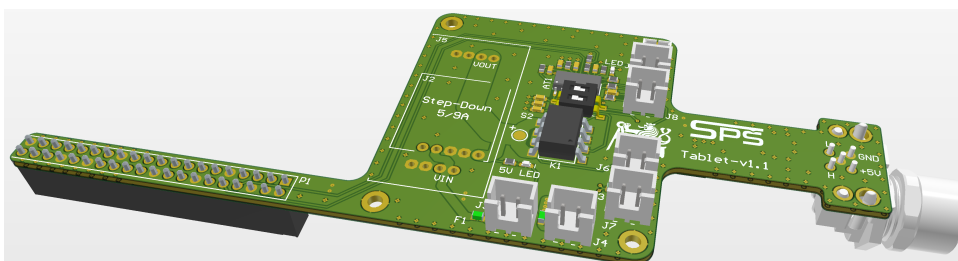


Figure C.3: PCB 3D model