Exploration of Agile Smart Footwear

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Declaration of Authorship

I, Student Marco GABRECHT, declare that this thesis titled, “Exploration of Agile Smart Footwear” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly conducted while in candidature for a degree at Technical University of Applied Sciences Lübeck.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

"Imagination is more important than knowledge.
Knowledge is limited. Imagination encircles the world."

Albert Einstein

TECHNICAL UNIVERSITY OF APPLIED SCIENCES LÜBECK

Abstract

Department of Electrical Engineering and Computer Science

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Exploration of Agile Smart Footwear

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Running on different undergrounds is common and typically burdens the joints and knee causing a variety of injuries torn ligament and ankle sprain. Common solutions are choosing consistent running paths or train the runner on changing undergrounds. Moreover, training can be dangerous and is temporary as it holds only a given time. By long running periods the problem is even more obvious. This Thesis presents a mobile smart insole system designed to change properties to simulate different Undergrounds and measuring impact parameters, such as Stance Time, Acceleration, gyroscopic forces. Furthermore, our prototypes are capable of simulating different undergrounds witch vibrations under the foot and inflatable pressure chambers. Our method has shown TODOOO

3. Collecting of existing papers in cyber physical and human system (CPHS), to build an artefact.
4. Building of an Artefact, that cant change properties and have similar properties like the other and can measure the same values.
5. Evaluation of the Artefacts to other studys.
6. Evaluation of the Artefacts with an user study.
7. Evaluation of the study.

The deliveries are:

- A Artefact with changing underground-simulation
- A Artefact with is capable of measuring different undergrounds
- A study that shoes the difference of the simulated underground artefact with real undergrounds artefact and no changing underground artefact.

Acknowledgements

Put your acknowledgements here! This is an example:

Acknowledgments by Horst Hellbrück I want to thank all staff members and students that have participated in this document by giving tips or by asking questions. When I have started this guide in 2009 with a vague idea in mind, I could not foresee that this document becomes such a great help for all the students. My special thanks go to Zhi Haolin and Ren Zhong from the international study program Information Technology at Technical University of Applied Sciences Lübeck together with ECUST in Shanghai. They have written most of the texts and provided references and figures. Without their valuable contribution this guide would have stayed at a conceptual level.

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The authors hope that students can benefit from the document and that more students may add contributions to this document to improve it.

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LIST OF ABBREVIATIONS

IMU	**I**antInertial **M**easurement **U**nit)
PCB	**P**oly**c**hlorierte **B**iphenyle
HCI	**H**uman **C**omputer **I**nteraction
PPG	**P**hoto-**P**lethysmo **G**raph
BT	**B**lue**t**ooth
EU	**E**uropean **U**nion
PWM	**P**ulse **W**idth **M**odulation
I2C	**I**nter-**I**ntegrated **C**ircuit
SPI	**S**erial **P**eripheral **I**nterface
RTOS	**R**eal-**T**ime **O**perating **S**ystem
FIFO	**F**irst **I**n - **F**irst **O**ut
MOSFET	**M**etal–**O**xide–**S**emiconductor **F**ield-**E**ffect **T**ransistor
LiPo	**L**ithium-**P**olymer-**A**kkumulator
LDO	**L**ow **D**rop **O**ut
CAD	**C**omputer **A**ided **D**esign
TPU	**T**hermo**p**lastic **P**olyurethane elastomers
WLAN	**W**ireless **L**ocal **A**rea **N**etwork
VR	**V**irtual **R**eality
AR	**A**ugmented **r**eality
API	**A**pplication **P**rogramming **I**nterface
3D	**three**-**D**imensional

Dedicated to my someone,
who you really appreciate to have in your life.

1 INTRODUCTION

1.1 Motivation

> *No matter what your mission is, have some notion in your head. Forget the model, whether it's government or nonprofit or profit. Ask yourself the more important question: Is my mission improving the world? Are you sure about it? Seek to disconfirm that all the time. And if you can, change your mission.*
>
> – *Jeff Bezos* [21]

To improve the World, it is necessary to find Problems in the World and address them. Only if the Problem is known, it is possible to find an solution. The Problem in this Thesis is relevant to almost everyone. We all uses shoes and don't want to get hurt. To create an Artefact, that trys to reduces the danger of injury's can be my part to make the world an better place.

writing why ———— Mehr motivation wissenschaftlich

1.2 Goal

This document and artefacts are intended to assist the world by creating better shoes. The goal of the document is twofold. On one hand, it serves as a basis to create an shoe that can simulate different undergrounds. On the other hand, this document is also a study to verify an change to the user by simulated changing undergrounds.

1.3 Organization

The rest of the document is structured as follows. Chapter 2 shoes different studies with smart foot-ware. Chapter 3 explains the artefact and the process to build it. Chapter 4 explains the study and the results. Chapter 5 summarizes the work, and suggests future work that could be done to improve the results.

2 RELATED WORK

– This chapter is about the research about injury's with non changing undergrounds and different attempts to create smart foot ware.

FIGURE 2.1: Different smart foot-ware prototypes

2.1 Smart foot ware

The topic of smart foot ware is not new and many Papers exist of measuring different things. Often these measurements are getting improved to detect human errors or illness. In some cases the measurements provide an input device for the user to interact witch something. Only a small amount of papers are giving Feedback to the user in the sole over the foot. And from these a very small amount is changing the properties of the sole. in the following pages there will be an overview over some interesting papers, that are interesting for the artefact that will be build. In Figure 2.1 some of them are shown.

2.2 Sensors

Sensors are used to generate measurements. With this measurements many theses are proven. The range of Sensors is huge. Mentioned here are only sensors, that are used in foot-ware. The following are only some Papers with Sensors, there are many many more.

2.2.1 Acceleration and Rotation

An IMU can measure movements and changing in the movement. With this values the smalls changing can be measured. With help of the Gravity the rotation to ground can be measured. This can be seen in Figure 2.2. This Sensor is used in “mobiLLD: Exploring the Detection of Leg Length Discrepancy and Altering Gait with Mobile Smart Insoles“[23] or many commercial products like Styrd.

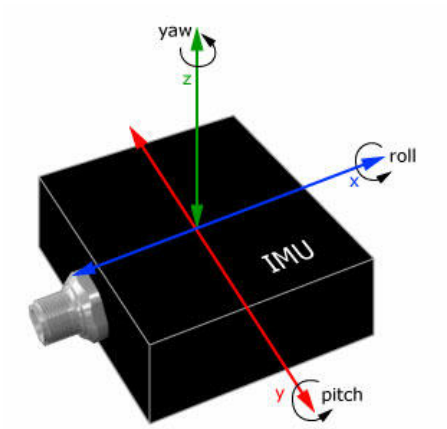

FIGURE 2.2: IMU

2.2.2 Pressure

The pressure in different regions of the shoe can visualize the ground contact or center of pressure like in “GymSoles: Improving Squats and Dead-Lifs by Visualizing the User’s Center of Pressure“[14]. This Sensor was also used to determine stress in “StressFoot: Uncovering the Potential of the Foot for Acute Stress Sensing in Sitting Posture“[12].

2.2.3 Heat and humidity

The interesting Paper “Arduino Controlled Cooling Smart Footwear“[27], contains many sensors, like an temperature and humidity Sensor. The most Humidity sensors have an temperature sensor combined to calibrate the sensor.

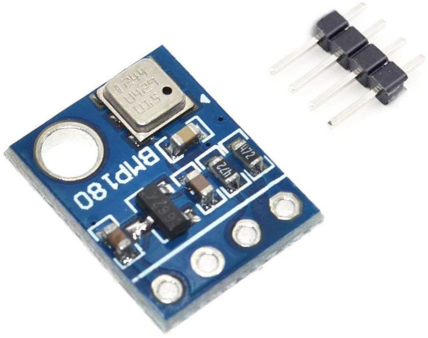

FIGURE 2.3: BMP180: Common Temperature and humidity sensor

2.2.4 Deformation

Restive Strips can be used to recognize stretch, bend and pressure changing, in the Paper “Wearable stretch sensors for human movement monitoring and fall detection in ergonomics“[8], this is shown witch some different sensor types.

2.2.5 speed with air

The Stryd sensor system can measure the foot speed with an heating element, by the cooling from the surrounding air. The sensor values of Stryd are proven in the Paper “Validity of the Stryd Power Meter in Measuring Running Parameters at Submaximal Speeds“[19]

2.2.6 GPS

The interesting Paper “Arduino Controlled Cooling Smart Footwear“[27], contains many sensors, like an GPS. The GPS values can be used to track the user and load values from the internet or measure height differences, speed and distance.

2.2.7 capacity

An Pressure layout was generated in this paper “ShoeSoleSense: Proof of Concept for a Wearable Foot Interface for Virtual and Real Environments“([24], and an self build capacity was used. A future Work of this approach is “CapWalk: A Capacitive Recognition of Walking-Based Activities as a Wearable Assistive Technology“[18] and this method was used to recognise different undergrounds in “CapSoles: who is walking on what kind of floor¿‘[22].

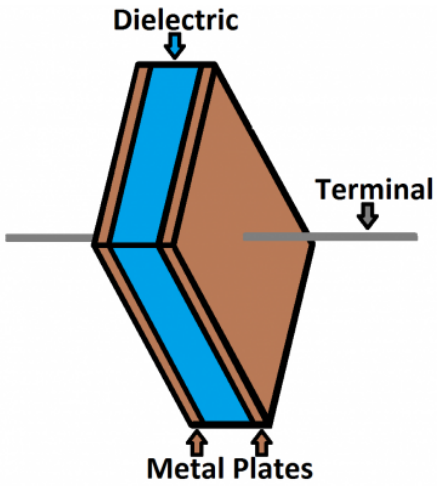

FIGURE 2.4: Principal of an Capacitor[6]

2.2.8 Infrared

With Infrared light heat and some blood values can be measured.[9][17] Blood sugar is one of these values. Other light(green) measurements, like the Photo-PlethysmoGraph (PPG) sensor, can measure blood movement and therefor blood

pressure and pulse.[44]

2.2.9 microphone

Microphones can detect some really lightweight signals, in the Paper “Estimation of temporal gait parameters using a wearable microphone-sensor-based system“[40] they try to estimate the Gait Parameters only witch an microphone.

2.2.10 camera

Camera systems can track the posture of the users and the angles of the joints, like in “Cluster analysis to identify foot motion patterns in children with flexible flatfeet using gait analysis—A statistical approach to detect decompensated pathology¿‘[4] or “Design of a bladder based elastomeric Smart Shoe for haptic terrain display“[41].

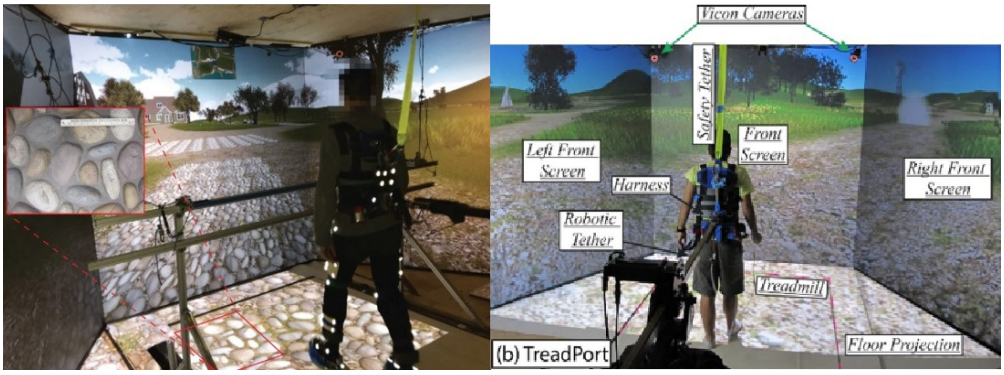

FIGURE 2.5: Camera tracking system with tracking markers on person to recognize the angle of the joints[41]

2.3 Feedback/Actuators

As Feedback there are the Acoustic feedback, visual feedback and haptic feedback. The hearing sense is the fastest sense[43] and the haptic sense is faster

than the visual sense[11]. Smell and taste is not considered, because the shoe in this paper is not in a good range to this senses.

2.3.0.1 Vibration

Vibration is an interesting Topic, because the reaction from the Human is fast and it is easy to produce. For example in this study "VIBROTACTILE DISPLAYS FOR IMPROVING SPATIAL AWARENESS"[34] the reaction time of an visual system with vibration have an significant increase in reaction time. The Paper "Application of tactile displays in sports: where to, how and when to move"[39] agrees, on the fact, that vibration is an effective actuator. in Shoes there are also vibration feedback prototypes, like in "mobiLLD: Exploring the Detection of Leg Length Discrepancy and Altering Gait with Mobile Smart Insoles"[23] This paper "Exploring Vibrotactile Feedback on the Body and Foot for the Purpose of Pedestrian Navigation"[25], have an interesting part where they measure the sensitivity of different parts on the body.

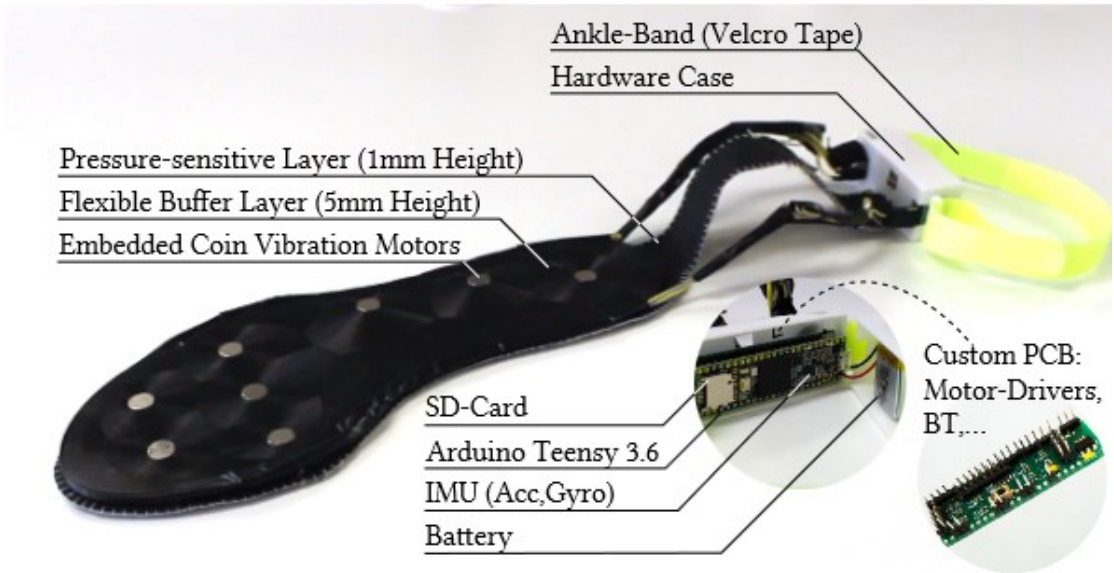

FIGURE 2.6: Prototype with vibration sensors[23]

2.3.0.2 Servomotor

Servomotors can move to an fixed position and therefore move against an human to generate an haptic feedback. The Paper “Auto-Moto Shoes: An Automated Walking Assistance for Arthritis Patients“[33], can compensate the underground height, what is really interesting, because it is nearly an simulation of a flat underground an on non flat underground.

2.3.0.3 solenoids

Solenoids have two states and can move something, touch against something or move their mass to make an shock. The most used way in foot-ware is the valve, this is more captured in 2.3.0.6.

2.3.0.4 other compression

There are several other actuators to compress something and squeeze as feedback. An interesting option is Fabric, that can compress like in this paper “ouch me Gently : Recreating the Perception of Touch using a Shape-Memory Alloy Matrix“[26].

2.3.0.5 auditive

2.3.0.6 Air Chambers

The use of Air-chambers is well known, an sphygmomanometer is basically an air chamber witch an sensor. An interesting actuation system of this concept is in this Patent, it have an Air-Chamber system, with passive pressure generation and changing chambers [45]. There is an comparable Paper to the goal of this paper. The Paper is “Design and Evaluation of a Soft Robotic Smart Shoe for Haptic Terrain Rendering“[41], this Prototype can simulate objects under the shoe, or different heights. The Tests with this Prototype showed, that the participants can recognise inflated chambers, but the real simulation of different

terrain is not part of it, but mentioned. The Terrain simulation is performed in this Paper “Augmenting Virtual Reality Terrain Display with Smart Shoe Physical Rendering: A Pilot Study“[42]. The Results are an increase of the realism on cobblestone.

2.3.1 other foot ware actuators

In this Paper “TickleFoot: Design, Development and Evaluation of a Novel Foot-Tickling Mechanism That Can Evoke Laughter“[15] an electric motor is used witch an tip, to tickle the foot. Another interesting Feedback, but a slow Feedbacl ist heat, like in “ShoeSoleSense: Proof of Concept for a Wearable Foot Interface for Virtual and Real Environments“([24]

FIGURE 2.7: Prototype with tickle mechanism[15]

2.3.2 Visual Feedback

An interesting foot-ware paper with an visual feedback is “GymSoles++: Combining Google Glass with Smart Insoles to Improve Body Posture when Performing Squats“[13], there are google glasses used to display feedback of the measured posture.

2.3.3 conclusion of other artefacts

There are many different actuators and foot-ware, and one of them is trying to simulate different undergrounds. Another paper, that i can find was an simulation of different frictions “DEVELOPMENT OF A COMPUTATIONAL MODEL FOR SHOE-FLOOR- CONTAMINANT FRICTION“[3], but not really what his Paper will tackle. The Papers around simulating VR undergrounds from Yue Wang, sowed, that the terrain simulation is an interesting Topic, there for this topic is worth to explore more. This Paper will simulate more the cushioning and damping and vibrations.

- There is a wide range of papers with Artefacts, that can measure parameters.
- There are some papers, that can change hardware properties.
- There are some papers, that can change the behavior of the human, by actuate something.
- The field of underground simulating is very small.

3
ARTEFACTS

– This thesis contains Artefacts, that will be needed in the following Chapter. This chapter walks through the building process of the artefacts from planning to production, and discusses the function and decision of each part. Sections 3.1 through 3.3.2 describe different iterations and development parts.

3.1 Overview of the Artefacts

There will be a three part Artefact at the end of this chapter. The Artefact will change the sole of an shoe and measure the impact of the changes. The study needs at least one dummy Artefact and one functional artefact, to compare measurements. The dummy is an sole, with no active changes within the running period. On the other side are the functional Artefacts, they will actively change properties of the insole to explore the effect of changing properties while running. Functional Artefact one(air-pressure Artefact) will have air-pressure-chambers and change the pressure in this chambers. Functional Artefact two(Vibration Artefact) will have vibration motors and will simulate a change in the insole with vibration, like other Papers[23]. The sensor system will be the same for all Artefacts, but this also needs to developed. To get an Idea of such an Artefact, an iteration can be seen in Figure 3.1.

FIGURE 3.1: One Prototype Iteration

3.2 Requirements

The Artefacts must meet requirements. The Requirements are categorized in following topics:

- Global Requirements (R1-R6)
- Requirements (R7-R17)
- Optional Requirements (R18-R22)

The global Requirements are Requirements that are equal for all Artefacts and define the overall physical limits and dimensions. Requirements are different for each Artefact. Optional Requirements are nice to have, but not totally necessary for this thesis.

3.2.1 Global Requirements

The Global Requirements are not sorted in the other Requirements, because they are equal for every Artefact.

R1 the dimension of the insole, they all need the same size (EU 42) and shape, for comparison reasons.

R2 They all need the same sensors system with equal sensor positions.

R3 They all need a measuring period of 10ms.

R4 The data needs to be transmitted to a server with an maximum delay of 5 seconds.

R5 They all must withstand the Force of an running person with 90 kg on asphalt, about 2000N

R6 They all need a working period of one hour or more.

3.2.2 Requirements

The Mechanical Requirements for the Functional Artefact one are:

R7 The Artefact one needs an active Valve System, to change the damping and height of the sole, noticeably.

R8 The Artefact needs functional Valves, that can let Air in each of the two pressure chambers

R9 The Artefact needs functional Valves, that can let Air from one chamber in the other and vise versa.

R10 The chambers needs to be relative airtight, that they can hold pressure over normal level for more than 10 seconds.

R11 The Valves need to close and open in less than the measuring interval (10ms).

R12 The Valves and chambers have to withstand more than 2000N pressure.

The Functional Artefact two needs less:

R13 The Vibration System have to vibrate noticeable.

R14 The vibration strength have to be adjustable

R15 The Vibration have to withstand continues Vibration for more than 10 minutes.

R16 The Vibration Motors have to arranged in the Front, middle and back.

R17 The Vibration Motors have to be controlled individually.

The Dummy Artefact don't need additional Requirements.

3.2.3 Optional Requirements

There are Optional Requirements, they will help with the study when they are meet, but are not necessary, they will increase the accuracy of the study.

R18 same weight - If the artefacts have the same weight the measured values are better comparable

R19 same medium damping - The standard damping and flexibility have to be the same to compare the Artefacts better.

R20 same weight distribution - The weight distribution may change the way of walking or measured impact.

R21 same optic (blind study) - No one should differentiate the Artefacts by sight. Therefor an influence can be excluded.

R22 all Artefacts are combined in the same body - Is they are the same, they cant be different and give the equals results.

3.3 Artefacts

At the beginning their are different concepts, they will be implemented in Artefacts. At the end all concepts will be merged in one Artefact. The process will produce many iterations of different Artefacts with improvements and changes. Not every change and Iteration will be shown, but in Figure 3.2 are some of the discarded iterations.

FIGURE 3.2: Some outdated Artefacts and material tests

3.3.1 designing the shape

To become a use full shape, there are many ways to start. Overall the shape of commercial insoles are well designed. With 3D-scanning a replica of commercial insole will be created and used for the outer shape. Because the other Artefacts need a specific thickness the biggest need thickness is chosen. The Version with the air pressure chambers is probably the thickest. The Design is created with Fusion 360, because it is free for Students and private use. Because of this the work can later be edited by a a huge group of people. All files will be free available. The artefacts will be designed for foot-size 42EU, because the

participant for the small user study will have this foot-size. Other Ideas was to generate an optimised shape with Gensole[16], this tool can generate an orthopedic correct shape. This artefact will be tested with different users and therefor an over customised shoe will be wrong for all other users. The designed Shape will be the same for all Artefacts and R1 is meet.

3.3.2 Dummy Artefact

If something gets compared there must something to compare to. The Baseline of the study will be the dummy Artefact. This artefact has no active changing functionality and contains only the needed measuring system(R2). Therefore a 3D-printed insole with the same shape as the following Artefacts will be produced.(R1) It will be 3D-printed, because it is a well used technology in prototyping[30][2]. With this technique this results are reproducible for many Researchers. Also the changing of characteristics are fast implemented. In Figure 3.3 the first Dummy artefact can be seen. The Straps are temporary and the Micro controller is in the yellow box, the sensors and battery are in the sole.

3.3.3 Vibration Artefact

The vibrations within an insole can change the behavior of a person [23], but it didn't change the real underground properties. This Artefact simulate the change of the underground. vibration motors are inside the insole in different positions(R16). Different vibrations strength(R14) and motors(R17) will be activated to simulate changes. An example of the first Vibration Prototype van be seen in Figure 3.4. The Mounting mechanism have greatly involved and the Micro controller in with the IMU(R2) and the battery pack in the sole.

3.3.4 Air-pressure Artefact

This Artefact will have two chambers within the sole, one in the back, to generate pressure while walking and running and one in the front, that can expand and

FIGURE 3.3: Dummy Artefact V1

change the properties withe the given pressure. The Artefact will change the pressure while running and simulate different properties of the underground. One Iteration Step can be seen in Figure 3.5. The Chambers are split from the insole and the electronics are separate. They can be changed with different stiffness and can have support structure, to prevent warping or force warping in different places. One of these prevention can be seen in Figure 3.11. The lines in the chambers hold the top and bottom together. They are also needed to support the surface while printing.[1]

3.4 Sensors

A critical part of all Artefacts is the validation. The validation is done with the Sensor values. If the Artefacts have an impact, than the sensor data have to change. Important is that the sensor data is reliable and meaningful. To measure important forces there are one accelerometer, one Gyroscope, and two

FIGURE 3.4: Vibration Artefact V1

pressure Sensors for the pressure chambers. This setup is chosen, because the it is possible to measure the force from the lower leg[5].

3.4.1 Building the sensor system

At the beginning the stable placement of the sensor is essential and the Sensors need a stable mounting system. The Sensor will be in the center of the sole pressed in place. The Acelerometer and Gyroscope sensor (MPU6050) is on the main PCB and the Pressure Sensors connected thou cables, because they have to measure the pressure directly at the chambers.

3.4.2 validate the sensor system

To Validate the Sensor system the measured Data will be proven against fixed actions. The Pressure will be tested with 3 Forces with knows weight and same

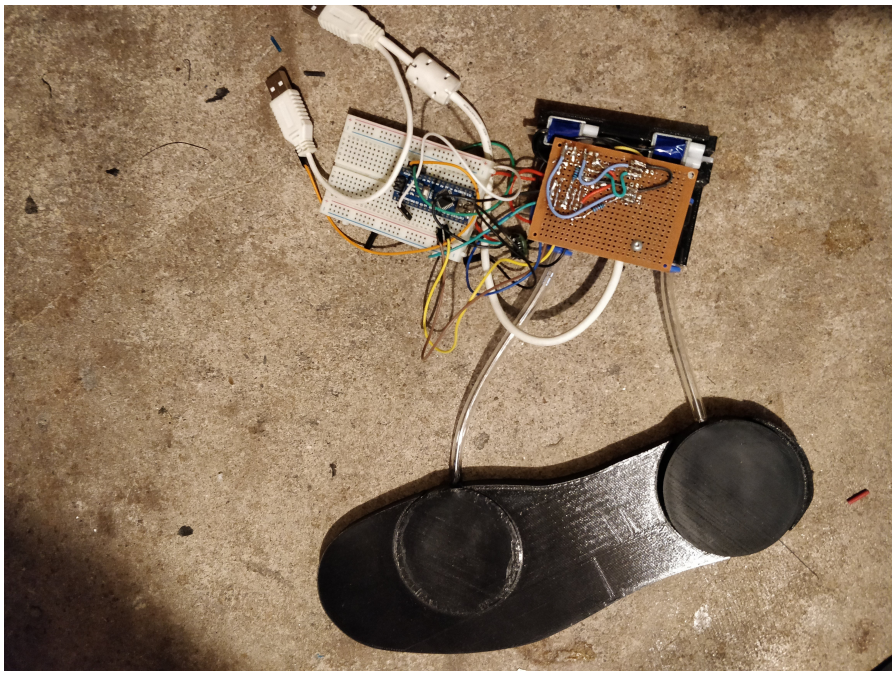

FIGURE 3.5: Air-pressure Artefact V1

footprint. The measured pressure values have to be linear, because the measured pressure is the force on the surface and the Sensor is linear [32]. The Acelerometer and Gyroscope will slowly rotated in every direction and the Earth gravitation have to display a constant measured force in one direction, because this is the strongest force.[28] The Sensor system have passed these tests.

3.5 Actuators

To change the properties, the two different mechanisms are controlled with an micro controller from an pc or roles on the micro controller. The Changing mechanism is in one artefact the vibration With 6 Points, as shown in Figure 3.6(R16), and different strength(R14), more in the next Section. The other artefact the pressure chambers, that inflate and deflate and change the stiffness of them in different levels. The Layout of these can be seen in Figure 3.11. More in 3.5.2

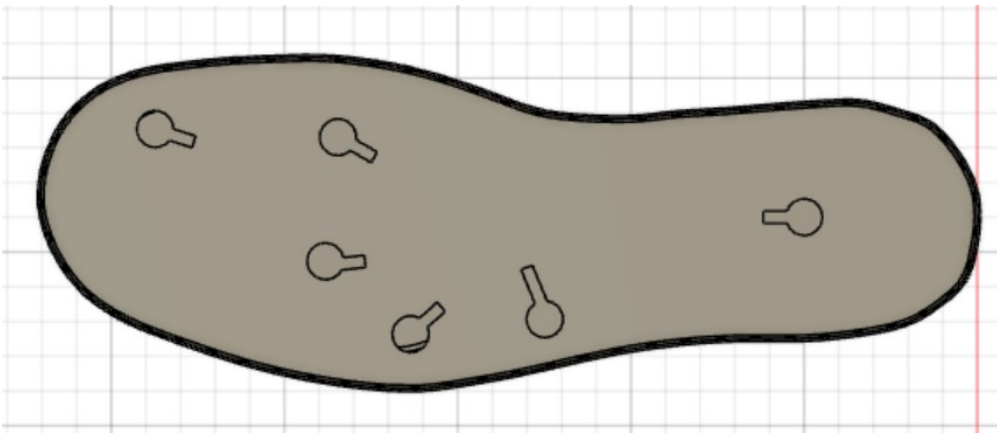

FIGURE 3.6: Layout of the Coin-Cell vibration Motors

3.5.1 Vibration mechanism

To vibrate in such an small space there are different ways. A Coin-cell vibration motor near by the foot is possible a good solution, like in the Paper mobiLDD[23]. This type is chosen, because the vibration is validated, that it has an impact of the human. To control them with different strength an MOSFET with a PWM signal can be used(R14)). To consider is, that the Load is an inductive load and the coin-cell-motor generates electricity. to overcome this an by-pass-diode and a small capacitor buffer will be added. Six of them will be in every sole(R17). aside from the holes and cable channels for the motors no extra hardware modifications are needed.

3.5.2 Inflate mechanism

The inflate Mechanism needs an pressure generator and valves to regulate the pressure. An commercial pressure generator is not suitable for the space and witch out generating vibrations and many wight. An other solution is to use the Mechanical energy from the running. If one chamber will be used to generate the pressure other chambers can be inflated with these pressure. the pressure in all chambers must be monitored and than the pressure can be controlled with fixed values. To achieve the monitoring an very fast pressure sensor(R3) in every chamber is needed and two valves for every chamber, one to let the pressure in(R8) and one to let the pressure out(R8). The Valves have to be very strong,

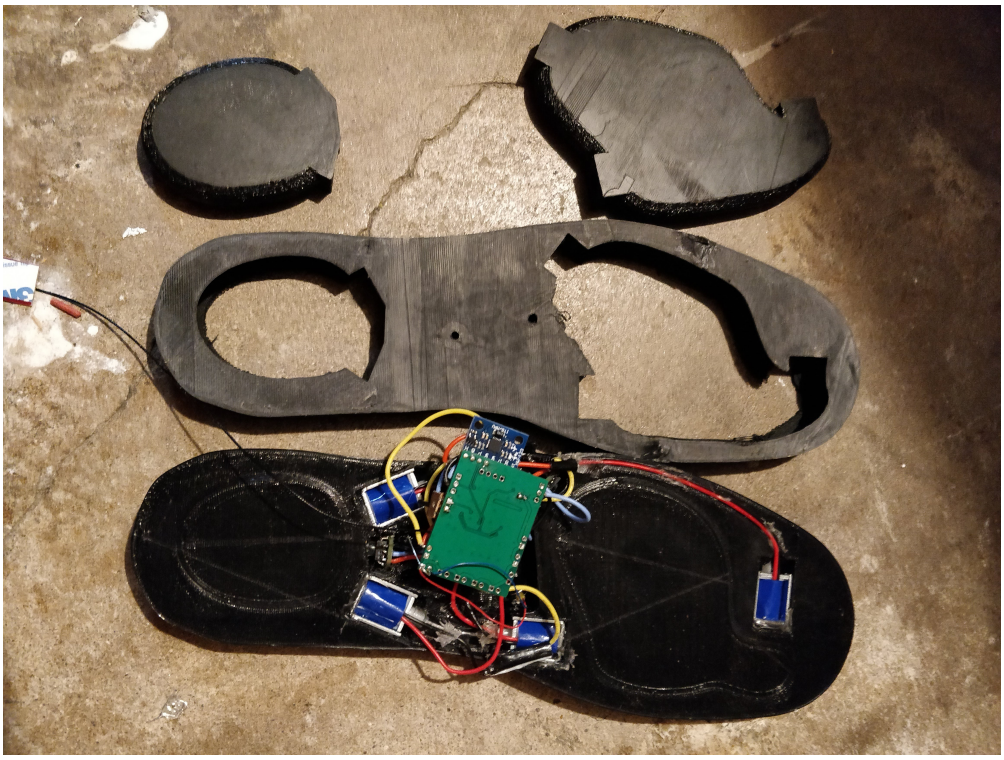

FIGURE 3.7: Air-pressure Artefact V2 and V3

light, fast and small. In such a tiny space it is not common to have all of it. The pressure will only be in one direction, out of the chambers, because of this fact it is possible to use Valves that are self closing in one direction, without external energy. This reduces the power-consumption of the system drastically, because the valves have the highest power consumption(400ma each) and are most of the time closed. The only problem is the connection between the two chambers(R9). The pressure is to strong to withstand forces in two directions, because of this there are two valves against each other. The Valves are inductive loads and will generate negative voltages if they releases. To overcome thes negative Voltages and save the micro controller the same system as by the vibration motors will be used and the Motors will use the battery pack directly and not on the same 5V system like the micro controller. The final Air chamber iteration can be seen in Figure 3.7. The Chambers are extracted to get them better airtight and thy don't break so fast(R10). The Material of the insole part was switched so Chinchilla.

3.6 Hardware decisions and implementation

The Hardware is an essential part of the Project. Witch changing Hardware also the results may change. Every part of the Hardware is open Source and can be replicated.

3.6.1 Electronics

The Electronic part consists of an Micro controller, an gyroscope, accelerometer, air pressure sensors, MOSFET stage, Coin-cell Vibration Motors and Valves. Every Part have to be suitable for the common task.

- Micro controller - The Micro controller is an ESP32 with an small form factor but every passive components build in. The ESP32-S2-MINI-1U-N4[37] is fast enough to do the readings(R3) and actions, he also have an WiFi option, to send and receive data(R4) and many pins to operate actuators and sensors. The FreeRTOS[38] on the ESP32 is an real time operating system, that can handle context switches to get precise measurements and upload data in background. He have I2C and SPI[36] to connect more sensors. The Analog readings are not precise, but precise enough for the pressure readings, because they are equally unprecice and we only compare the values. The Antenna is external and can be positioned elsewhere to get an better connection. This Micro controller is often used in many applications.[0][0][0]

- Gyroscope and Accelerometer - The Gyro and Acelerometer Sensor is the MPU6050[20], because this sensor is often used[0][0][0][0][0][0] and gives comparable Data to other Paper and findings. The MPU6000 have an SPI interface and is therefore faster, but it was harder to get and with the I2C interface in fast Mode the I2C was fast enugth (>0.800ms)(R3). If it is necessary an magnetometer can be added and the readings can be faster witch the FIFO on the chip. The Breakoutbord was used, because it is cheaper as the single chip and easy to solder.

- Air pressure sensor - The Air pressure sensor have to be fast, to read the Pressure and adjust it. The Sensor have to withstand huge forces(R5), because the user will accelerate his hole body mass if he is running and the Chambers will hit witch the complete force. The analog sensor XGZP6847A300KPGPN33 [7] is an sensor, that will withstand -100kpa to 300 kpa(R5) and map it to an analog voltage instantaneously(R3) and continues. The version we uses is an 3.3Volt version, because the ESP32 is an 3.3V micro controller. Other Sensors with the hx710b[35] Chip will take more than 100 ms to read one value[10]. The XGZP6847 is used in some other, none foot ware, papers with great measurement results.[0][0][0]

- MOSFET Stage - The MOSFET Stage have to deliver power for one coin cell vibration motor continues or up to two valves pulsed or a short duration. This prototype uses the SSM3K7002KFU,LF, with a very tiny form factor and can deliver up to 400ma continuous and 1.2A pulsed(R10). Because they will power inductive loads there is a need for an freewheeling diode parallel to the load to cut off the negative voltages generated by the inductive load. Additional there is an 680Ohm resistor and 10μF capacitor to reduce the effect even more. This MOSFET Stage have an pull-down resistor with 100kOhm and an limiting resistor to protect the pins of the ESP32 with 1kOhm to reduce the current flow to under 40mA, what is the maximum of the digital outputs of the ESP32.

- Coin-cell Vibration Motors - The Vibration motors have to fit in the insole and vibrate strong enugth with an voltage between 4.2V to 3.3V. The FIT0774 from DFRobot works with an Voltage from 1.5V to 4.2 V and are small enough with 10mm in diameter and 2.7mm in height. They only consume 40mA on full load.(R13, R14, R15, R17)

- Valves - The Valves have to withstand the same Pressure as the Air pressure sensors and have to be small. As mentioned in 3.5.2 this is a big challenge and the only small valves available in the pandemic, are 0520D Valves from fspump with 3V. They gets over driven from the voltage(R12) and consume up to 400mA each. Because they don't switch in the highest

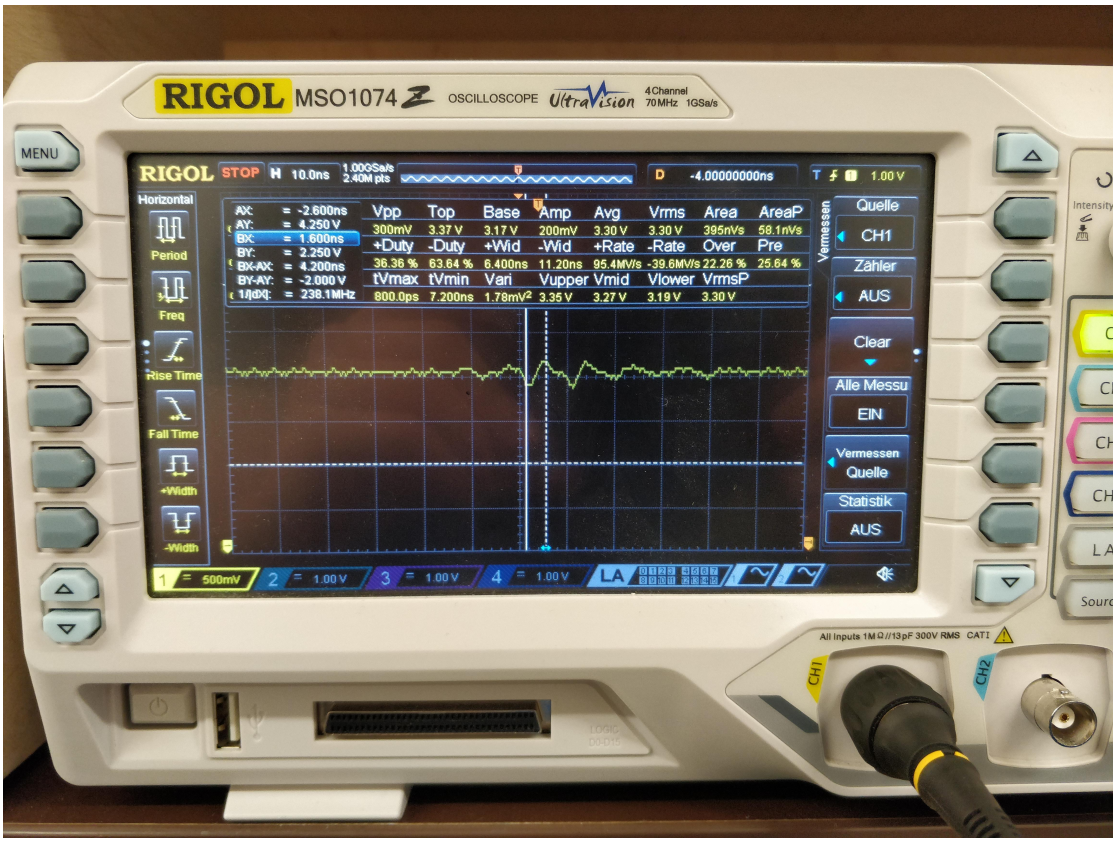

FIGURE 3.8: The 3.3 Volt line with an Oscilloscope, when all Valves gets open and closed.
The Voltage-drop and increase is at nearly 200mV

pressure moments, but in the negative moments and nearly equivalent moments, they have the power to open and close, without maximum power consumption.

- battery pack - The Power comes from an Turnigy 1200mAh 1S 1C Lipoly battery pack [31]. It has the same size as the space between the chambers and nearly the same surface as the components needed for the PCB. With the capacity of 1200mAs and an peak power consumption of 310mA while transmitting and 40mA vibration and sporadic use of 400mA Valves the average power consumption is estimated at 400mA. With this assumption the average up time is over 3 hours. This is more than an average training session. This battery pack is protected against short-circuit, under-voltage and over-charge. The maximum continues discharge current is 1200mA. The theoretical maximum current draw is about 1.6A for the

Valves, 200mA for the Vibration motors and 310mA for the ESP32-S2 and 3.7mA for the MPU6050 and two times 3mA for the pressure sensor. In total this is 2119.7mA and nearly double the continues rating. In normal operating only two Valves get activated at the same time and only for an short period of time. The ESP32 will not send continues and have an consumption of 30mA while not sending and spikes to 310mA while sending. On average the system will have an power consumption of 170mA for the ESP32, 9,7mA for Sensors, 100mA´for Motors and 100mA for the Valves in total 379,7mA, this is below the constant current rating.(R6)

- Voltage regulator - The Voltage from the Lipo is above the maximum Voltage of the ESP32. Therefor it must convert to 3.3V. The Gyroscope and Air pressure sensor have to communicate with the ESP32 between 2,8V to 3.3V and have an stable voltage, to give consistent readings. The Powersource losses Voltage with discharging. The NCV8187[29] is an LDO Linear Voltage Regulator with power good output. This Prototype uses the NCV8187AMT330TAG that will generate 3.3V for the logic system. The Chip can handle up to 1300-1750mA witch an dropout voltage of 150-220mV. The ESP32 will shutoff about 2,8V and the LiPo at 3.0V with the Voltage drop of nominal 150ma the regulator is perfectly to use the hole battery capacity. The Actuators will be power directly from the Power source.

The PCB was created in KiCAD, this is an Open Source Project and free of charge. The PCB can be seen in Figure 3.9.

3.6.2 Shoe

The Shoe is the Housing of the electronics and the connection to the human. This shoe exist of four parts.

- Sole - The sole is the heart of the shoe and contains the Pressure chambers and Electronics. It is made of chinchilla from ninjatek. In Figure 3.10 the object in the middle. The Pressure chambers are from Ninjaflex from ninjatek and can be seen under the sole.

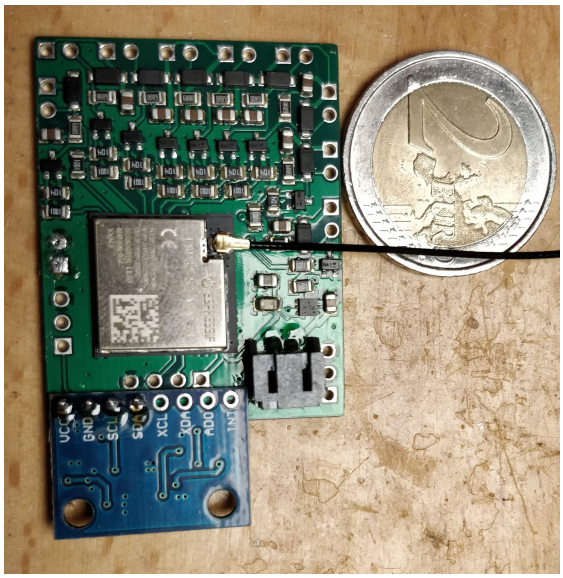

FIGURE 3.9: Artefact PCB.
The ESP32 is in the Center with the Antenna connector, the blue PCB is the IMU and on the top are the MOSFET Stages.

- insole - The insole will be softer than the rest of the shoe and have holes for the vibration motors. This part have direct contact to the foot of the human. It is made of Chinchilla from ninjatek. It is the secondtel object in Figure 3.10.
- Shell - The Shell contains the Sole and on-top of it the Insole, it have mounting holes for fabric of an existing shoe(R21). It is made from TPU V2 from dasFilament.
- Fabric - The Fabric is recycled from an shoe, witch was dissembled.

All 3D Printed parts are designed in Fusion 360, this have an free educational and hobby license. The ninjatek filaments are often used in other papers, because of the well suited properties.[0][0]

3.6.3 Software

One of the biggest parts of an hardware system witch logic is the software. The software was implemented in Arduino and on the FreeRTOS of the esp32. The

FIGURE 3.10: Artefact in parts.
Top: Shoe, Second: Vibration Inlay, third: Inner shell, fourth: Pressure Chambers and electronics, last: Shell

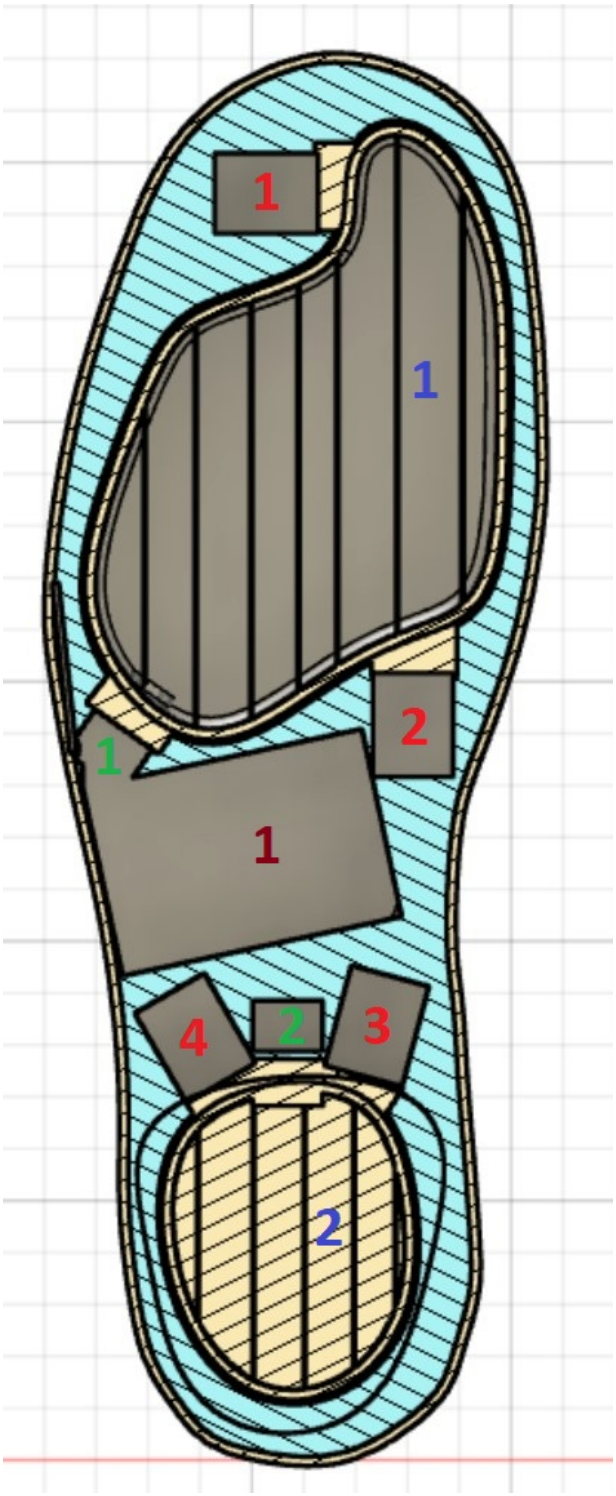

FIGURE 3.11: The cross-section of the CAD-Design
Blue: Chambers, Red: Valves, Green: Pressure-sensors, Brwon: MCU

Sensors are read every 10 ms, witch is realised with the OS functions to ensure quality reads. The sensor collection and actuation of the active parts needs around 1,2 ms. The reading from the I2C was the longest part witch more than 99 percent of the time. The I2C is in Fast Mode to more than double the reading speed. The Sensor data will be uploaded directly over WLAN to the cloud time series Database influx DB. An Web-server on the device can be used to update the System and control the functions and settings. FreeRTOS is used in applications and papers with real time constrains.[0][0][0]

3.6.4 Problems on the way

If the theoretical world collides with the real world there are unknowns problems, can occur. The first problem was the Corona pandemic and Ukraine war, because of them the supply chains are unreliable. Some parts are not on Stock and only available in more than one year. The MOSFETs ware on Stock but this was only an miss information on the supplier side. There have to be an replacement. They got replaced by similar or stronger MOSFETs. Another big problem was the printing of airtight chambers. 3D printing is not air or water tight and with some fixes and special mechanics the results are better, at the end the chambers are printed in more parts, to get the chambers alone airtight. The Cambers gets prepared with an iron to close the biggest leaks. The chambers are not totally airtight but mostly. The connections to to valves and Sensors are critical, because they are stiff and can break. An solution to this problem are more flexible tubes, that disconnects the chambers and Valves/sensors. The I2C connection was slow and a SPI connection are the better choice. If the Internet connection is to slow, the micro controller resets, because the buffer will fill up. An offline cache like an micro SD-Card can solve this problem. another big Challenge was the the connection to an existing shoe. Because the PCB have no off switch and the deep sleep is not save enough to disconnect the Battery. the next PCB will have an MOSFET to switch off the connection to the Battery. Without this switch there is a need to disconnect the Battery every time and change it if it is empty. There for the connection to the shoe have to be fast accessible and without much force on the stiff parts of the insole. The Electric and physical

connections are not designed to withstand many movement. The vibration motors, sometimes break their own cables, the pressure sensors will be pressed out of the shoe or the bending will disconnect some tubes.

3.7 Requirement Check

At the end there is only one Artefact left in size EU42, therefor R1, R2, R18, R19, R20, R21 and R22 has been met. The FreeRTOS will satisfy R3 with system delays and prioritizing. The Wifi connection will upload every 500ms and needs about 700-800ms, R4 is met. R5 was tested with an scale and the pressure sensor cant measure the values, but can withstand the force. The Valves are tight and the Sensors don't come loose with added hot glue. R5 is also met. With an maximum Power consumption of 2119ma the system will work for over 30 minutes, but the maximum power consumption cant be delivered, if the maximum power draw of the bms is delivered the System will hold an hour. The average power consumption will work for over 3 hour and R6 is met. The Chambers can inflate and bubble up to nearly the double height and can compress to nearly touching top and bottom. The Damping on high pressure is less than on medium. R7 is met. R8 and R9 is met with the two Valves for each Chamber, what can be seen in Figure 3.11. R10 is met, the pressure is falling relative constant, like in Figure 3.12, the value is 880 over normal and is falling by 184 (20.91%) in 11 seconds. XXXXXX R 11
R12 is met, none of the Chambers gets damaged or the Sensors gets damaged, by applying over 2000N. The measurement was taken with an scale and measured 150kg of force. The Sensor can handle 2X of the 300kpa. The Vibration System can vibrate noticeably and met R13, the Vibration Motors need some space and if the insole is to compressed, the vibration is minimized, but with the used insole it is noticeable. With the MOSFET Stages every motor can be controlled witch an PWM signal, this met R14 and R17, the MOSFET can power the 40ma without getting warm and the Battery can deliver enough power to vibrate all of them continues for more than 1 hour, this is way over R15 and met it to. The Arrangement in R16 can be seen in Figure 3.10. Therefor all Requirements are met and the Artefact is an success.

FIGURE 3.12: Pressure fall over more than 10 seconds

4 STUDIES

– If you think user research is expensive, you should look at the cost of building the wrong thing - Mario Maruffi

4.1 Study design

To validate the thesis, that it is possible to simulate the changing of the underground with this Artefact. There are Three Studies. The first two are Validation if the Artefact and only with a small number of Participants, because there exists similar studies, that validate this point. The last Studie is the main Studie, that showed if the prototype can simulate different undergrounds. The main changing point of the Artefact is the damping and vibration.

4.2 Pilot study: Underground detection

The first pilot study will validate if this system can recognise different undergrounds. The Paper “CapSoles: who is walking on what kind of floor? “[22], has an comparable study. The outcome of the study was, that it is possible to

FIGURE 4.1: Measured values of the three Undergrounds.
Top: Asphalt, Second: Grass, last: Sand.
pH: Pressure Heel, pV: Pressure Ball, pB: pressure Baseline, ax: accelerometer X, gz: Gyroscope X, ay: accelerometer Y, gy, Gyroscope Y, gx: Gyroscope X, az: accelerometer Z

distinguish different undergrounds. The difference in hard and soft floors can be considered as easily distinguishable. This study is only to validate, that this Artefact can differentiate different undergrounds, like the other Artefact. The other artefact have some differences, like other Sensors and mainly capacitive sensing and the accelerometer and gyroscope are in a different position, but this study will show, if the Artefact can differentiate between three undergrounds, only with pressure values and IMU values. The Undergrounds will be asphalt, grass and sand. This three undergrounds are chosen, because they have an big difference in the ground reaction. The participants will walk a defined path on the underground and the measured data will be analysed. In this study their were two participants and they walk nearly the same paths. The analysed data will be shown in the Figure 4.1. The most interesting part was the phase, where the Foot interact with the underground. The phase where the foot is still on the ground was most classifying, because the stability of the foot on the ground was different. The First graph shows the stand phase on asphalt. The measured values on Asphalt are nearly stable. The second is the grass, the values are a bit more unstable. The last one is the sand with a big unstable measurement. An

easy threshold classifier on the ripple of the signal have differentiate the samples to 100%. The samples are cleaned up. The first two steps and last two steps or incomplete steps and still standing phases are removed. The sample size was small with only two different participants and only one long walk on the ground. This study sowed, that the system can differentiate between different undergrounds. The stance time on soft undergrounds are longer (Sand 800ms, Grass 730ms), than on hard undergrounds(Asphalt 670ms). The quality of this study is poor, because of the low participant number and low sample size. But well enough for a simple validation of the sensor system and sample data that can be used to generate a simulation.

4.3 Pilot Study: User actuation

The second study will interact with the participant and is inspired from "mobiLLD: Exploring the Detection of Leg Length Discrepancy and Altering Gait with Mobile Smart Insoles". [23] This paper have vibration motors in the system and can alter the gait. The outcome of the study was, that he stance time increases with vibration. The Artefact is nearly identical, but have other pressure sensors, other TPU and an pressure insole with more pressure zones. To validate, that this Artefact can alter the stand time with vibration their are four tests with two participants. The participant will walk on the same floor(lenolium) and the Artefact will have each one of the following modes:

1. no active part on the shoe
2. random vibration by ground interaction
3. Full vibration by ground interaction
4. full vibration at that part, that is on the ground

The Results in figure 4.2, show the same 5 steps of the track of the 3 participants. The result is the time on the ground. The base stand time without vibration is 641ms to 658ms. With random vibrations, every 10ms, what is nearly equal than the half vibration strength, the stand time is increased to 690ms to 724ms.

The full strong vibration will stretch the stand time to 750ms to 822ms and the full vibration with the walking movement is from 770ms to 808ms. This mini study come to the same conclusion, that the stand time increases with vibrations. This clarified, that this actuation can change the walking of the participants. Interesting was, that the stance time of no vibration on asphalt, grass and sand are nearly the same stance time like no vibration, random vibration and fill vibration. An assumption is, that the vibration and softer undergrounds, make the participant's uncertain and the person take more time to stay save and stable.

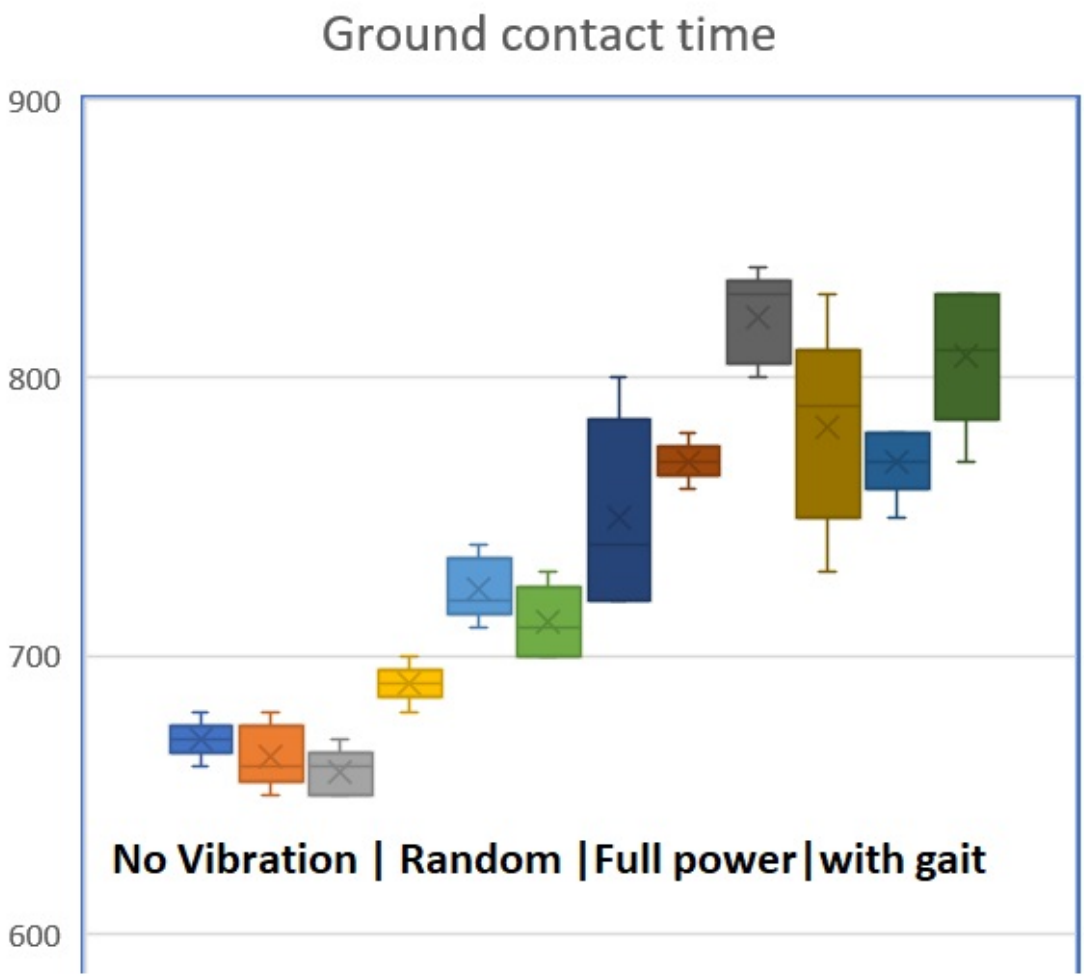

FIGURE 4.2: Ground contact time

4.4 Simulating Study

With the measurements of the first studies, it was possible to create an simulation of some undergrounds. This Study is inspired from "Augmenting Virtual Reality Terrain Display with Smart Shoe Physical Rendering: A Pilot Study"[42], but with much less sensor systems and with an focus on realism, like in Figure 12 from the Paper. The used AR/VR System is completely different, because this study will use an Oculus Quest headset with an video of an underground and the other study uses an VR cave with treadmill. The hole sensing part with cameras and other sensors are not relevant and not existent. This study will have X participants and have 2 Phases, the first one is with an VR-System and the Shoe. The participant will make two steps and on the VR-Headset is an terrain, that will be simulated. The User then will answer the following Questions.

1. How realistic was the underground? (0-10)
2. On what underground was the Steps?
3. How difficult was it to walk?
4. How different is the shoe to previous run (0-10)(normal shoes in first run)

The second Phase is the same, like the first on, but without the VR-Headset. The tested Terrains are:

1. Asphalt (Hard pressure value and short vibration on first hit)
2. Grass (Hard pressure, that will slowly be released to normal pressure and soft vibration on the hole stance time)
3. Sand (normal pressure, that will be released and some really light vibrations)
4. Linoleum (normal pressure, no vibration)

The measured Data from Stability and walking speed will be compared.

5 CONCLUSIONS AND OUTLOOK

In summarize, the Artefact was an success, with some downsides. The studies have recreated and proven other studies, but the last Simulation process have a bit lack of success in recreating known undergrounds realistic. The change in the properties of the insole is huge and this may can be used to train the body to run on different undergrounds.

5.1 Hardware Conclusion

The Artefact is only an prototype, a missing on/off switch is the biggest design flaw. The Chambers have to be more airtight and anther production way have to be found, because 3D printing have layers and therefor small gaps and layer lines. The Software have some bugs with an slow internet connection and an SD beck-up where the best option. The mounting to the Shoe can be improved, but therefore the power switch have to be accessible. The Akku have to be better protected and the stiffness of the shoe have to be optimized, to flex at the normal points. The Mechanisms worked sufficient. The use of one chamber to generate the pressure in the other was a problem, when both chambers should be used.

5.2 Study Conclusion

The first two study's came to the same conclusion, like the similar study´s and therefore are an success. An larger scale of them and an well designed machine learning approach to detect changes and classify the undergrounds can improve the quality. The last study can be improved with a larger participant size and some software tweaks, to make the simulation more realistic. The VR Support can be improved with an connected Game Engine or an AR/VR-Hive. An AR-Display can be used to generate the new underground on the given floor.

5.3 Future Work

With this Artefact it was possible to change some properties. But what is it good for?

5.3.1 Advanced Prototype

An exploration with an Pump or compressor, so, that the deflation can be performed with every step, sounds like an great extension. The Chamber system can be improved with silicon chambers, witch are more airtight, like in the reference Study[41]. More Chambers can be implemented to simulate obstacles[41] or change the tilt of the foot[33]. The known flaws of the Artefact can easy be removed, with an magnet switch and an MOSFET enable setup, like mentioned in 3.6.4.

5.3.2 Study's with more Sensors

Like in other Study's[41][42][22][27] the sensor system can be evolved, camera systems, motion tracking[0] and more IMUs can be used to get precise measurements of changing properties. The Gait analyse can show witch properties must change to generate the wanted gait.

5.3.3 training of changing undergrounds

If an person will run on changing undergrounds, the risk of injury will be decreased. An study witch explore if this prototype can train humans to reduce the risk of injury[0] is interesting.

5.3.4 VR/AR

This Prototype can be used as input and output device for VR and AR. Therefore an API have to implemented. The big dream of meta with the metaversum, needs more interfaces to transfer the user in the metavers.[0] An adequate pressure value of the foot can be used in games to trigger different events, like breaking things or undergrounds or simulate sink in sand. Actuation like in "Augmenting Virtual Reality Terrain Display with Smart Shoe Physical Rendering: A Pilot Study" [41][42] can be implemented to give the user more feedback and a better experience.

5.3.5 Energy harvesting

With the Camber system an energy harvesting solution is possible, their exist some Papers with this approach[0], but integrated with an fine adjust of the property's this can be an self-sufficient shoe. The energy of the ground reaction force is huge, compared to vibration or temperature harvesting approaches[0].

5.3.6 3D Profile

This Artefact showed, that is is possible to inflate Chambers to the foot, but interesting can be an inflation of an profile to the ground, to reduce or increase the slip. Different to the argumentation of the underground[42], an reaction to the environment and the adjustment of property's, can result in an big advantages for the human. Different shoe profiles and expandable cleats can improve the stability[0].

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