CHALMERS
UNIVERSITY OF TECHNOLOGY

Development of the RISE Vibration Monitor: RVM

Master's thesis in Industrial Design Engineering

TOBIAS EDHOLM
JESAJA S. HÖGBERG

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
DIVISION OF DESIGN AND HUMAN FACTORS

CHALMERS UNIVERSITY OF TECHNOLOGY
GOTHENBURG, SWEDEN 2022
WWW.CHALMERS.SE

Master of Science Thesis (IMSX30)
Development of the RISE Vibration Monitor: RVM
In collaboration with Research Institutes of Sweden

Cover Illustration: The RVM Instrument
Cover made by Tobias Edholm & Jesaja S. Högberg
The typefaces used in this thesis are ITC Avant Garde Gothic by International Typeface Corporation and Times New Roman by Monotype

Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Print: Repro Service Chalmers
Gothenburg, 2022

Master of Science Thesis 2022

DEVELOPMENT OF THE RISE VIBRATION MONITOR: RVM

Tobias Edholm
Jesaja S. Högberg

Company Supervisor: **Alexander Mann**
Chalmers Supervisor: **Andreas Dagman**

Department of Industrial and Material Science - Division of Design & Human Factors
CHALMERS UNIVERSITY OF TECHNOLOGY - Gothenburg Sweden 2022

ACKNOWLEDGMENTS

First of all we would like to thank our supervisor and examiner Andreas Dagman. His insight and guidance has been crucial in making the project successful. His never waiving optimism and support has made the project smooth sailing.

We would also like to show our gratitude toward RISE, whose support and expertise has been pivotal in making the project a success and direct a special thanks to our supervisor Alexander Mann for supporting us in this project, especially with his vast knowledge of mechanical design. We are also grateful for the help we have received from Fredrik Ahrentorp with regards to component selection and understanding the electronics, which has been vital for the success of the project.

We would also like to thank all the participants in our user research, especially the work environment engineers and work environment hygienists whose experiences have given us a great insight into their work and the challenges with vibration measurement.

We would also like to thank our fellow students who have been never-ending sources of inspiration and advice. Finally we would like to thank the CreaTD for providing 3D printers which have been essential in the production of our prototypes.

Without all of your support this project would not have been possible.

Jesaja S. Högberg

Tobias Edholm

ABSTRACT

Vibrations are responsible for the largest single part of workplace related injuries in Sweden. There is an ISO-standard which is used to estimate how harmful vibrations are and how long one can be exposed without risking damage, however it does not take into account ultra high frequency vibrations, those above 1250 Hz. Recent studies indicate that these vibrations might be more harmful than previously thought and that the current standard might not be sufficient to protect against all kinds of vibration-induced injuries. To remedy this problem the current ISO standard will be updated to better reflect the reality of what vibrations are harmful. However there is a lack of data to base the updated standard on.

To gather the necessary data the client, Research Institutes of Sweden - RISE, has created a prototype instrument used to measure the ultra high frequency vibrations which contemporary instruments cannot measure accurately. The prototype includes electronics, a 3D-printed case, and a MATLAB interface. The aim of this project was to improve the usability and user experience of interacting with this instrument. The electronic components were to remain as they were, but the other parts could be changed freely. Additionally some accessories were to be explored, a carrying bag and a remote trigger for the instrument. The deliverables should be of such a fidelity that they can be sent to a contract manufacturer with little to no work from the client.

The project was carried out in an iterative manner but began with investigations of the current state of the art of contemporary measurement instruments. This was followed by user research to understand the needs and wants of the users. Then followed concept ideation where different solutions to the needs and wants were investigated. The biggest part of the project was concept creation and refinement where solutions and ideas from the ideation were put together into a viable product which was then evaluated.

The outcome of the project is a concept called The Rise Vibration Monitor - RVM consisting of a new front-end built in MATLAB which can be connected to the current MATLAB back-end as well as a manufacturing ready design concept for the instrument body and a carrying bag. Some design has also been done to create a remote trigger but at a lower fidelity which will require more work before it can be sent to manufacturing.

These designs are meant to improve usability of the instrument which will hopefully in turn increase the quality of the measurements being created in the field. There is more work that can be done to improve the designs, especially on the hardware side. If the batch size were to be increased it would be worth looking at ways of miniaturizing the electronics which would allow for making the dimensions of the whole instrument smaller.

Keywords: User experience, vibrations, user research, UX/UI, work related injuries.

TABLE OF CONTENTS

1. INTRODUCTION

Vibrations are one of the most common causes of work related diagnoses, about a third of the diagnoses in the span 2014-2018 were from the effects of vibrations[a]. This means that prevention of these injuries is very important for the healthiness of the workforce. At RISE, Research Institutes of Sweden, work towards researching and providing solutions for minimizing vibrations in tools is performed. This is done to enable longer and healthier working lives for the working public. To be able to prevent vibrations, measurement of the vibrations is a key aspect, prompting the development of measurement tools and methods for quantifying the severity of vibrations and correlating them to diagnoses.

a Afa försäkringar (2020)

1.1. Background

The current accepted way of quantifying and measuring vibrations in hand held tools is governed by the ISO-standard ISO 5349[a]. However, vibrations with a frequency higher than 1250 Hz (called ultra high-frequency vibrations, UHFVs) are not currently included in this ISO-standard. Research[b] has however concluded that vibrations with frequencies higher than 1250 Hz can damage the body, even though they cannot be perceived by the human nervous system. Because these vibrations are not included in the ISO-standard, there are no current regulations around them, which is why work towards expanding the standard to include these is being conducted. As a part of the work towards expanding the standard, new measuring equipment needs to be developed to be able to measure the UHFVs, to enable research about their hypothesized harms.

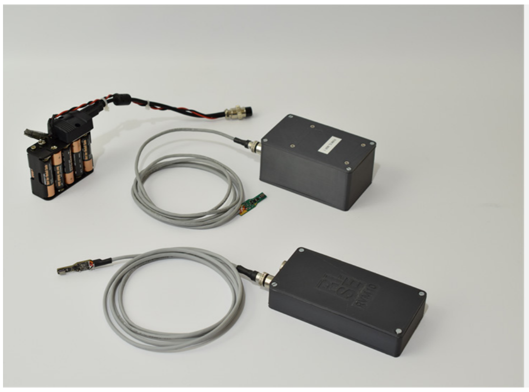


Figure 1.1. - Prototypes of the instrument

RISE has developed a tech-stack, including sensors, for a measuring instrument that can measure UHFVs in parallel with regular vibrations (under 1250 Hz) in three axes and implemented these into a prototype instrument, see Figure 1.1. The instrument is meant to expand the ability for vibration researchers to measure UHFVs in the field, and not only in controlled lab settings. Our part of the project is to ensure a good user experience of the instrument by designing a premium physical enclosure and an effective digital user interface.

1.2. Purpose

The purpose of the project is to build a new understanding of a wider range of vibrations and how they affect users of hand held tools. This will be done by providing researchers a user friendly and robust instrument to enable measurements in the field. The robustness of the instrument is key as breakage of the instrument can delay work and the user friendliness of the interface is also very important as incorrect readouts can interfere with the development of new standards.

1.3. Aim

The aim of the project is to aid RISE in the creation of a new instrument for measuring UHFVs. Our contribution will be a design for the enclosure of the instrument and a design for its software interface. This will be done in such a way that it ensures that the user experience of the researchers will be as good as possible. Focus will be on manufacturability and ease of development to ensure that the result can be used effectively by the company.

a International Organization for Standardization (2001)
b Gerhardsson et al. (2020)

1.3.1. Deliverables

The main objectives of the project will focus on three main elements of the measurement instrument for measuring UHFVs: *the physical enclosure of the instrument, the software interface, and a remote trigger for hands-free measuring*. User research and human-machine system understanding will be the first steps taken in the project to ensure an understanding of what the needs and requirements are, both from the users and the product. For the design of the enclosure and the trigger there will be a focus on durability, ease of manufacturing, and ease of use. For the software interface, the focus will be on usability, ease of use and ease of development. The hardware will be delivered in the form of CAD files, drawings, and a bill of materials for the components.

To summarize, the deliverables are:

- Creating an enclosure for the instrument, while:
    - Ensuring functionality.
    - Ensuring manufacturability.
    - Ensuring assembly.
    - Ensuring usability.
- Creating a desktop software interface for the instrument, while:
    - Ensuring a complete feature set.
    - Ensuring usability.
    - Ensuring ease of development.
- Exploring and creating peripherals for the device:
    - A remote trigger for hands free operation of the instrument.
    - A bag for mounting the instrument on an operator.

1.4. Research Questions

To achieve the aim of the project a number of research questions are specified:

- What is the current state of contemporary vibration measurement equipment?
- How are vibration measurements performed by professionals in laboratories and in the field and what are the needs present when performing vibration measurements?
- How will the possibility to measure UHFVs affect the users' demands on the measurement instrument and the companion software interface?
- How could a measurement instrument and its companion software interface be designed in order to fulfill the users' needs?

1.5. Delimitations

The project will not include the development of electronics, programming, or the creation of technical specifications. However, these factors are to be taken into consideration for the design of the enclosure and when conducting component selection. For the software interface, a prototype of how the interface should look and function will be created, but no production code will be written for it. The peripheral equipment will be investigated to a lesser fidelity. The sensor itself will not be designed as it is too complex, because of the geometry and materials needed to create good measurements.

2. THEORY

In the following chapter the theoretic background of the project will be presented. First, vibrations and relevant terminology will be explained. Then, the injuries that vibrations can cause and factors pertinent to vibration related injuries. Then a background on how vibrations are measured and quantified will be given. Lastly, a theoretical background on the design will contain explanations of general product development processes, usability and user experience design, ergonomics and anthropometry, and design semiotics.

2.1. Vibrations

A Vibration can be described as a "back-and-forth about an equilibrium position with a wavelike character of periodicity"[a], see Figure 2.1. The movement from one extreme to the other and back is called an oscillation and the number of oscillations in a specified unit of time is called the frequency. Vibrations can be measured both as the acceleration of the vibrating object, measured in m/s^2, and as the frequency of the vibration, measured in Hertz (Hz or s^{-1}).

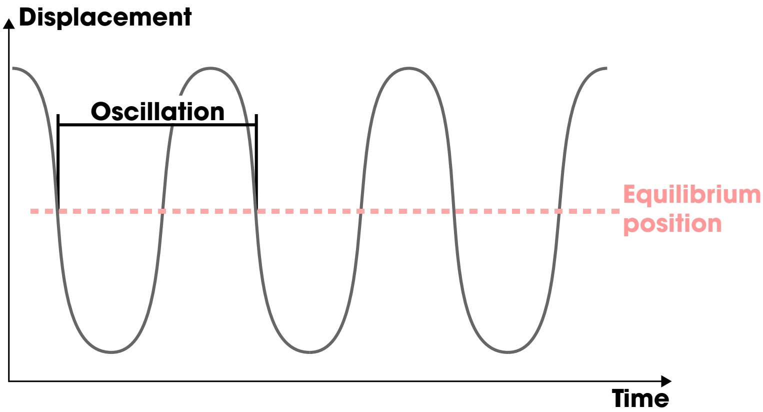


Figure 2.1. - A diagram of a vibration.

2.1.1. Transient vibrations

Transient vibrations are vibrations which only last a short period of time, between tens of microseconds to a few milliseconds.

When a dynamic system is excited by a non-periodic force, such as a suddenly applied impact, steady-state oscillations are not produced and the resulting motion is called a transient response[b].

One example of a transient vibration could be the operation of an impact wrench. When the internal hammer spins freely there is very little vibration until the hammer strikes the anvil which can create an enormous, but short lived, vibration shock, see Figure 2.2 for an example of how shocks are created in an impact wrench.

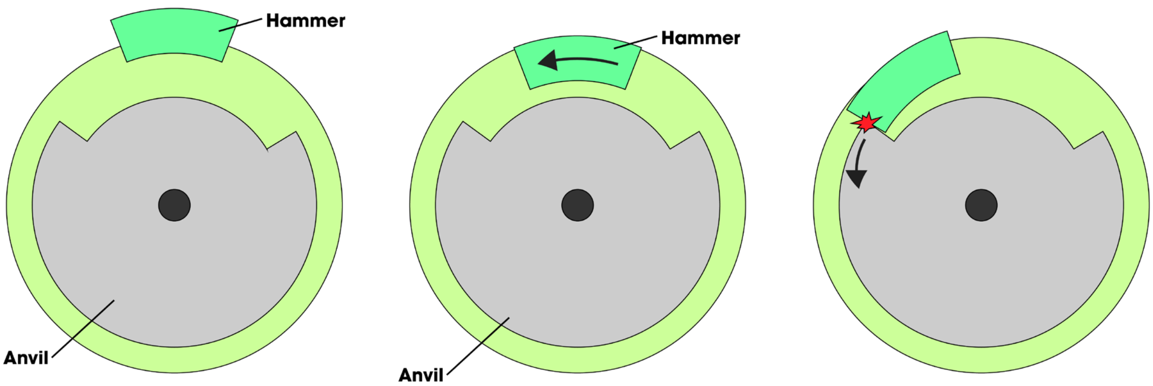


Figure 2.2. - The mechanism of a common type of impact wrench. The hammer rotates freely, building up speed. The hammer then strikes the anvil, transferring its momentum to the hammer, and in turn the screw. This impact creates a vibration shock.

a Dillion Dahleh et al. (2002a)
b Dillion Dahleh et al. (2002b)

There is currently no standard for measuring how transient a vibration is, but a method proposed to expand the standard is using Vibration Shock Index, VSI, to rate how transient the vibration is from a scale starting with 1 and going upward.

2.1.2. Ultra high frequency vibrations

An ultra high frequency vibration (UHFV) is in this context a vibration with a frequency above 1250 Hz, which is the upper limit of the frequencies that are taken into account when analyzing vibrations using the current standards. There are two main ways in which UHFVs are generated in a tool. The first, and perhaps most intuitive, reason is that the tool moves with a very high frequency, one such example could be a dental drill which commonly utilizes an air turbine to achieve speeds upwards of 400 000 rpm (or approximately 6600 revolutions per second)[a] and small instabilities cause it to vibrate once every revolution.

The second main reason for UHFVs are sudden impacts which can produce peak vibrations in excess of 10kHz. These are commonly found in tools where impacts happen repeatedly in its operation, like in the case of an impact wrench.

2.1.3. The governing standards

ISO 5349-1:2001 is the main ISO standard that govern how hand arm vibrations are classified and how they are to be measured[b]. It contains both the mathematical formulae for weighing the vibrations as well as instructions for how to measure vibrations. These are currently ratified by the 2002 EU directive[c] and the Swedish standards institute[d].

Currently the laws and regulations dealing with vibrations in Sweden are limited in the way that they approach transient vibrations. The Swedish Work Environment Authority is the regulatory authority which is responsible for the welfare of workers in Sweden[e]. The current regulation regarding exposure to vibrations in the workplace is AFS 2005:15, and in the regulation it is stated that ISO 5349 should be used to calculate the frequency weighted acceleration of a vibrating tool. The frequency weighted acceleration is then used in conjunction with the exposure time to calculate if the usage exceeds the daily allowed vibration exposure. Since the current ISO 5349 standard requires usage of the root mean square, the effects of transient vibrations on the measurements will be diminished. The use of frequency weighting and exclusion of vibrations with higher frequencies also affects how transient UHFVs are regulated. As an example, an impact wrench can produce vibrations reaching above 10000 m/s^2. However, since these vibrations are so short-lived an RMS analysis might calculate it to be just a few m/s^2 over the duration of the measurement, and the exclusion of the highest frequencies will further reduce the estimated vibration.

2.1.4. Exposure

The exposure time of vibrations is an important factor in how much damage vibrations cause. This means that for longer exposures, the permissible vibration must be smaller. In Sweden this is regulated as the A(8) value, which is the level of vibration a tool can have if it is to be used for an 8 hour work day. This means a vibration acceleration of 2.5m/s^2 or less for a hand held tool to pass without necessitating any time limitations.

---

a Hunter (2021)
b International Organization for Standardization (2001)
c European Agency for Safety and Health at Work (n.d.)
d Svenska institutet för standarder (n.d.)
e Arbetsmiljöverket (n.d.)

2.2. Vibration-related injuries

Vibrations can affect the human body in a number of ways. Many of the ways that vibrations affect the human body are not yet fully understood, but it is certain that it can cause considerable long term harm[a]. Conditions caused by vibrations can be insidious since they develop very slowly and can therefore be hard to attribute to their root causes and might not be noticed until they have already developed to a more severe degree. Vibrations are commonly dealt with in different ways depending on if they are whole-body vibrations (WBV) or hand-arm vibrations (HAV). The measurement instrument will be used to gather information about HAVs and therefore the medical aspects discussed below will be those affecting the hand and arm. HAVs occurs when a person is gripping a vibrating object[b].

2.2.1. Nerve damage

One of the ways that vibrations affect the human body is that they can cause damage to the nerves. Studies on rat-tails, which have a very similar resonance frequencies as human fingers, have shown that nerve damage can occur at a wide range of vibration frequencies[c]. Nerve damage can lead to a number of issues, among them loss of feeling, trouble with fine motor skills, and vasoconstriction.

2.2.2. Raynaud's syndrome

In 1862, Maurice Raynaud described a condition where a patient suffered from a condition where the blood circulation in the fingers was cut off and became numb and white when exposed to moderate cold[d]. Since then, this cut-off of blood circulation, numbness, and whiteness of the fingers have been referred to as Raynaud's syndrome or colloquially as White fingers. Raynaud's syndrome can have a number of different causes, with one of them being repeated exposure to vibrations[e].

2.2.3. Hand arm vibration syndrome

Hand Arm Vibration Syndrome, HAVS, is a broader condition which incorporates the occurrence of Raynaud's syndrome related to vibration exposure as one part. HAVS can also include a number of other symptoms for the people affected[f]:

- Attacks of whitening (blanching) of one or more fingers when exposed to cold
- Tingling and loss of sensation in the fingers
- Loss of light touch
- Pain and cold sensations between periodic white finger attacks
- Loss of grip strength
- Bone cysts in fingers and wrists

HAVS is the most common occupational injury in Sweden[g] and is often a chronic condition[h].

2.2.4. Ultra high frequency vibrations in relation to injuries

Ultra high frequency vibrations, UHFVs, were previously believed to be of limited harm to humans since they are quickly absorbed and will not reach deep into human tissue like lower frequencies will. Recent studies have, however, indicated that they might cause nerve damage

a Gerhardsson et al. (2020)
b Coggins et al. (2010).
c Govindaraju et al. (2008)
d Wigley & Flavahan (2016)
e National Heart, Lung, and Blood Institute (n.d.)
f Canadian Centre for Occupational Health and Safety (n.d.)
g Afa försäkringar (2020)
h Research Institutes of Sweden (2020)

or injuries that cannot be explained by regular vibrations[a]. Since vibrations at frequencies above 1250 Hz seem not to be able to propagate more than a couple of millimeters into human tissue, their effects might be limited to the outer layers of the skin, or just beneath them, but this is deep enough to damage nerves and capillaries. These issues seem to need a lot of time to develop, though since it seems that the body has a robust way of countering the damages, but when the system gets overloaded the damage can likely not be fully reversed, even if the exposure is halted[b].

2.2.5. Exposure times and trigger times

One of the key factors affecting if and how quickly people will develop vibration-related injuries is the time during which they are exposed to the vibrations. This is the exposure time and in the context of HAVs it is also commonly referred to as trigger time. The trigger time is important to separate from the total time a tool is being used, as vibrations are only caused when the tool is operating, or when the trigger is pressed.

2.2.6. Transient vibrations

It is not entirely known how transient vibrations are affecting tissue, but studies in rats are indicating that they might cause nerve damage[c]. Studies have also suggested that transient vibrations might still cause damage even though the RMS-values remain under dangerous levels.

2.3. Measuring vibrations

One important factor dealing with UHFVs is that they are not perceptible by humans. It is also hard for humans to perceive any detailed information about vibrations in the ISO 5349 frequency-range. Therefore, there is a need for instrumentation to allow for measurment of vibrations.

2.3.1. Root mean square

The root mean square value, RMS value, is used to get the average acceleration of a vibration; it is directly related to the energy content of the vibration. Since it is related to the energy content, it can be used as a measure of the destructive capabilities of the vibration and is therefore a useful metric for understanding the harmful effects of the vibration on the human body. It is calculated by taking the square root of the sum of the squares of all the measurement data.

$$RMS = \sqrt{\sum_{n=1}^{\infty} x_n^2}$$

Using the RMS value does however have the disadvantage that it tends to downplay the severity of transient vibrations. This is because the transient vibrations only last a short time and thus their accelerations, although very large, will have a lesser impact on the RMS value.

A proposed way of solving the issue of underestimating transient vibrations is to use 6 as the exponent in the formula and then take the sixth root of the sum instead. The use of a higher exponent will make the large acceleration of the transient vibrations extremely large which will make the resulting value after the sixth root operation better reflect the transient contents of the measurement.

a Gerhardsson et al. (2020)
b Zimmerman et al. (2020)
c Zimmerman et al. (2020)

2.3.2. Fourier transformations

To get a better understanding of which frequencies are most prevalent in a vibration a Fourier transformation can be used to break the signal down into several sine waves of different frequencies and amplitudes. This can then be analyzed to see which of these are most prevalent and get an understanding of which frequencies are most important to look at in a scenario.

2.3.3. Frequency weighting

In ISO 5349, the effects of each frequency are weighted. This is because it was believed that frequencies below and above thresholds of what the body can feel are less harmful for the body. However the occurrence of damages in dentists[a], who use tools that vibrate with frequencies above the threshold, suggest that higher frequency vibrations are associated with risks.

2.4. Design theory

The project is a product development project and therefore follows a product development process. In the following chapter historic and impactful product development will be described to give a better understanding of the structure of the process.

In the end of the chapter important theoretical aspects of design will be explained as these have been used in the design process. Usability and ergonomic principles have been used to ensure the products usefulness and appropriateness and anthropometry has been used to make sure that it will work for most users. Design semiotics have been an important part of making the product look the way it ought.

2.4.1. Product development

There are numerous different approaches when it comes to describing and defining the product development process. Many of these share some common aspects, namely that they all begin with an understanding and analysis of the current situation. After the current situation is understood, concepts are developed to solve the problem or task that was identified, the concepts are then evaluated in some manner to see if they solve the problem in a satisfactory way. Most methods are also iterative in the way that they approach the problem solving process.

Cross[b] describes a simple and broad process consisting of four main steps:

- Exploration
- Generation
- Evaluation
- Communication.

The first step aims to understand the issue at hand, the second generates ideas and solutions, the third evaluates if the solutions will indeed solve the issue, and the fourth communicates it to the important stakeholders. The process will also iterate between generation and evaluation until a satisfactory result is achieved. This is a good way of quickly outlining the process and giving a rudimentary understanding, but there is value in having a more detailed process description that can better guide the designer.

a Rytkönen et. al (2006)
b Cross (1995a)

Pahl & Beitz[a] describe a slightly more elaborate process with six steps that give a more thorough understanding of the general problem solving process. The steps in this process are:

- Confrontation
- Information
- Definition
- Creation
- Evaluation
- Decision

Roozenburg & Eekels[b] also describe a similarly structured basic problem solving cycle applied to design containing five main steps. This is stated as *the most fundamental model of designing*, and meant to be easily accessible. The five steps in this process are: *Analysis*, *Synthesis*, *Simulation*, *Evaluation* and *Decision*.

The steps *Confrontation*, *Information*, and *Definition* by Pahl & Beitz could be seen as analogous to the first step, *Exploration*, in Cross' process. Pahl & Beitz also propose another process which is specifically adapted to design which is based on the general problem solving method. This process has two main components, working steps and decision making steps. This process is split into four main phases:

- Planning and Clarifying the Task
- Conceptual Design
- Embodiment Design
- Detail Design

Planning and Clarifying the Task has the goal of understanding the current situation and what requirements the finished solution must fulfill. The three subsequent steps are all aimed at generating a design with increasing level of fidelity, ranging from a principle solution in the conceptual design phase, to design ready for production in the detail design phase. One interesting aspect that Pahl & Beitz mention is the decision to stop development if it ceases to be viable. It is not explicitly mentioned in the decision steps but should always remain a possibility to minimize the risk of sinking resources into a design which is unfeasible.

Pahl & Beitz were also heavily involved in the development of the design process for VDI, Verein Deutscher Ingenieure [Association of German Engineers], VDI 2221[c]. The development of this process had the goal of creating a "general methodology for designing technical systems and products and to support a methodical and systematic designing, in order to produce a more efficient working style"[d], and the process is essentially an amalgamation of the work by many different researchers in the field and the previous standard, VDI 2222, which was created by a working group led by Fritz Kesselring and Friedrich Hansen in the 70s[e]. This process is based around seven stages that each have a specified output, but the stages do not necessarily have to be done sequentially and are often done iteratively.

a Pahl & Beitz (1995a)
b Roozenburg & Eekels (1995)
c Pahl & Beitz (1995b)
d Jänsch & Birkhofer (2006)
e Jänsch & Birkhofer (2006)

Ullman[a] proposes a rigid design process aimed at being efficient and being able to deal with complex problems regardless of the product being designed. This process is an iterative one with several steps which can be read as a flow chart that leads one through the process. It consists of 5 main phases and around 20 smaller subtasks.

The double diamond design process was created in 2005 by the British Design Council[b] and is based around two main diamonds, in each diamond the scope first diverges and then converges again. The first diamond starts with the *discover* phase where the problem is understood, then follows the *define* phase where the challenge is properly formulated and specified. In the second diamond the first phase is *develop* where solutions to the challenge are created, and the final phase is *deliver* which involves validating and improving the solutions. The first diamond could be seen as an understanding and research phase and the second diamond as a design and solution phase.

One criticism that applies to many of these process descriptions is that they stem from a problem-focused approach rather than a solution-focused one, which goes against how designers usually think[c].

2.4.2. Usability and User experience

As with the product development processes there are a number of different frameworks and theories which can be utilized when working with user experience. Within this project cognitive ergonomics were seen as especially important since it is a product which is used by professionals in environments where distractions are numerous and the product should not occupy all the users' cognitive resources.

One of the most prolific UX researchers is Jakob Nielsen, who proposes a *Discount Usability Engineering Method*[d], which is intended to provide a framework that produces good enough results without overwhelming practitioners with "strange terminology and elaborate laboratory setups". The method is based around using 4 techniques:

- **User and task observation** - letting the users work as they normally would without interference and observing them.
- **Scenarios** - Creating prototypes which are not fully implemented, but rather only work when the interface is used in the way that is prescribed by the scenario. Since not all parts of the interface need to be simulated this allows for quick and frequent changes in response to user feedback since they are cheap to implement.
- **Simplified thinking aloud** - Thinking aloud is a method where users are asked to perform a given set of tasks while asked to verbalize their thoughts, what they are doing and why they are doing it. Traditionally it is videotaped and analyzed, but in the discount usability method the researchers only rely on notes taken during the test since re-watching and analyzing tapes is time-consuming and that time could be spent on doing more tests instead.
- **Heuristic evaluation** - These are a set of rules that can be run through by the developers to ensure that the most common usability problems are avoided. The ten rules are in short: Dialogue should be simple and natural, language familiar to the user should be used, the users' memory load should be minimized, the interface should be consistent, the interface should provide appropriate feedback, there should be clearly marked exits

a Ullman (1997)
b Design Council (n.d.)
c Cross (1995b)
d Nielsen (1994a)

from unwanted system states, provide shortcuts and accelerators for advanced users, provide good error messages, prevent errors, and provide help and documentation.

Nielsen also describes five main attributes which a system needs to have in order to have good usability[a], mainly related to software systems:

- **Learnability** - it should be easy for a novice to learn how the system works. This also includes that users that have previous experience with similar systems should be able to start on a more advanced level than a novice, given that the system is reasonably consistent with the other systems. One important factor which affects learnability is the ability for users to learn the system in an exploratory way. Some key elements of a system that affect exploratory learning are: easy-to-understand error messages, possibility to do useful work without having fully learned a system, availability of undo, and confirmation questions before execution of risky commands.
- **Efficiency** - the system should be designed in such a way that when the users have learned the system they should be able to achieve a high level of productivity.
- **Memorability** - it should be easy to remember how the system works and how to interact with it, so that a user does not need to learn it all over again after not having used it for some time. Improvements in learnability will to some extent also improve memorability.
- **Errors** - the users should make as few errors as possible during the use of the system, and if they do make errors the system should make it so that they can easily recover from them.
- **Satisfaction** - the users should feel subjectively satisfied when using the system. It refers to how pleasant it is to use the system. One factor which can affect this is called approachability, meaning that a system should not seem too daunting when first approached by a novice user since that might make the users dislike it from the very start.

Unger & Chandler[b] split the necessary principles for UX-design into three separate areas: Visual design principles, Interaction principles, and Psychology principles.

The visual design principles focus on the look and feel of the product, incorporating concepts such as hierarchy, balance, and variety.

Interaction principles break down the user interaction into three constituent steps: understanding the ability to act, acting, and then getting a response. According to Unger & Chandler there are three main rules that should be followed when designing interactive objects to ensure users understand that an element is interactive and what it does:

- Associate the elements with an object from the physical world that provides clues on its usage (such as tabs or buttons)
- Be consistent with how interactive elements are usually designed, such as making links a different color.
- Consider how the users will perceive the usage of the element, i.e. if the properties of the object indicate how it should be used.

When the user has understood that something is interactive and what the interaction does, another important aspect is *economy of motion*. Economy of motion relates to how much time

a Nielsen (1994b)
b Unger & Chandler (2012)

and effort the user has to expend in order to interact with the element, such as moving the mouse a far distance or clicking a small button.

The final aspect of the interactive principles is *response*, which deals with the feedback that the users get after they have interacted with the element. This can be improved by good performance, error handling, and proper feedback. Conversely the response can be worsened by having poor performance, error handling, and feedback.

The final principle described by Unger & Chandler are the psychology principles. These principles seek to understand the psychology behind why and how users interact with products and services. One psychological aspect is that an attractive product is both perceived as easier to use, easier to trust, and can even increase creativity.

Jordan[a] outlines 10 principles for good usability design. There are a lot of similarities with the two previously detailed authors, but also some differences. The 10 principles are:

- **Consistency** - the product should be consistent in how tasks are to be carried out. For example, if there is a menu system similar actions should be ordered in the same sub-menu.
- **Compatibility** - this principle aims to ensure that the product is consistent with any expectations that users might have from interacting with similar products in the outside world. Both consistency and compatibility are important since they both rely on the fact that people are likely to solve tasks in the same way as they did before if they recognize a situation from before and if that is not possible it might cause frustration and errors. There are also compatibility aspects that need to be considered in relation to cultural differences, as an example switches are traditionally flicked up to power something on in the US whereas in the UK flicking a switch downwards is standard for powering on.
- **Consideration of user resources** - different interactions will place different demands on the users' cognitive resources and it is important to ensure that the tasks that users need to do does not overwhelm them.
- **Feedback** - providing meaningful and timely feedback to the users after an action is performed is crucial as to keep users informed of what is happening with the product or system.
- **Error prevention and recovery** - products should be designed so that the occurrence of errors is minimized and that users can quickly recover if an error is made.
- **User control** - allowing the users to control as much of their interaction with the product as possible is preferable. Providing appropriate default settings but allowing the users to change them is a good way of doing this as it allows users to quickly undertake tasks while still allowing experienced users to customize parameters that they might need to change.
- **Visual clarity** - information should be readily available to the users, quickly and easily readable. This could involve decisions such as font-size, color, and placement of elements.
- **Prioritization of functionality and information** - when there are a lot of functions and information available in a system it is important to prioritize what is available to the users to avoid overwhelming them.

a Jordan (1998)

- **Appropriate transfer of technology** - adopting and utilizing technologies developed in other contexts can improve the user experience if done properly.
- **Explicitness** - the design of a product should make it clear how it should be interacted with.

Fitts's law is a model for predicting the accuracy of human motor skills first described in 1954[a]. There are numerous variants of the law, but they all describe the relationship between how long it takes to hit a target, depending on how long the distance moved is and the size of the target[b], dealing with 2 dimensional hand-movements. The law has been shown to work with many different input devices[c] and is often applied when designing user interfaces, either by increasing the size of the targets, i.e. creating larger buttons, or by decreasing the distance, e.g. by grouping similar interactive elements together.

2.4.3. Ergonomics

Ergonomics can encompass both physical and cognitive aspects of products. Physical ergonomics mainly focus on dealing with different aspects of human anatomy, as well as some anthropometric, physiological, and bio-mechanical aspects of the tasks examined[d]. Cognitive ergonomics on the other hand examine how mental processes, such as perception, emotion, memory, reasoning, and motor response affect how humans interact with different systems and products[e]. Both cognitive and physical ergonomics can be crucial in creating products and systems which minimize the risk of work-related injuries[f]. To aid in the creation of ergonomic designs there are a number of different frameworks addressing both the physical and cognitive aspects of design, such as RULA, REBA, ACTA, etc..

2.4.4. Anthropometry

Anthropometry is the science of measuring the human body, it is used to ensure that equipment and products are properly dimensioned to their users[g]. There have been numerous studies conducted to gather anthropometric data about different populations around the world that can be used to create suitable designs. Anthropometric dimensions vary quite drastically between different countries, but also between different sexes[h]. In Sweden there have been one recent anthropometric study on adults[i]. When using anthropometric surveys it is common to dimension the products so that they are suitable for a certain percentage of people, as creating products that suit everyone would likely be unreasonably resource intensive in many cases. It is common to design for people between the 5th and 95th percentile, or 1st-99th[j].

---

a Fitts (1954)
b Interaction Design Foundation (n.d.)
c MacKenzie et. al (1991)
d International Ergonomics Association (n.d.)
e International Ergonomics Association (n.d.)
f Occupational Safety and Health Administration (n.d.)
g Bridger (2003a)
h Bridger (2003b)
i Hanson et. al (2009)
j Bridger (2003c)

2.4.5. Design semiotics

Semiotics is the study of meaning formation and communication. This can be applied in many fields such as linguistics, philosophy and also in design. Semiotics, the study of signs, can be split into three components: *semantics*, the study of the meaning of signs; *syntax*, the study of the relationships to other signs, and *pragmatics*, the study of the use of signs in different contexts. When designing products it is especially important to consider the semantic functions a product can be imbued with. Monö describes four semantic functions relevant for product design:

- **To describe** - purpose, mode of operation
- **To express** - properties,
- **To exhort** - reactions,
- **To identify** - a product, its origin, kinship, location, nature or category[a].

Describing

A product can be described in many ways, the most obvious being by using words to label it. However products can also describe themselves by their form, by giving the product a shape that brings in mind other products of the same type. This associates the product with the others and helps the individual contextualize it correctly. Another aspect which the product can describe is its mode of operation. By emphasizing certain aspects of the geometry it can guide the user to pay attention to these parts and by giving it clear interaction points they can identify how to use it.

Expressing

All products have an expression, a way in which they impress their qualities on the viewer. Expressions in products can be achieved by modifying and emphasizing the geometry in different ways. By increasing the contact area between the geometry and the ground a stable expression can be created, chamfers can create a more closed and robust form. Darker colors create more heavy expressions.

Automotive design works a lot with expressions: most cars, although in reality very similar in terms of performance and functionality, have very different expressions. The cars in Figure 2.3 are similar in both size and performance, but the white car has a sporty and more aggressive expression, whereas the gray one is friendlier and more rugged looking.

Figure 2.3. - A white sportier car (left) and a gray more rugged car (right).

The harmony between the functionality of the product and the expression is also very important, because if there is a mismatch the expression can seem dishonest and be detrimental to the product.

---

a Monö (1997)

Exhorting

Products can by using cues to call upon certain actions from users. Blinking lights can command attention, arrows direction and signs rules. Using this in conscious product design can create products that make their use more clear.

Identifying

Products have aspects that can be identified. Companies that have a portfolio of products often have an interest in having their brand represented on the products. Showing the origin can be done in the most elementary way by adorning the product with a logotype. It can also be done more comprehensively by including colors and form elements as well. The purpose of the product can also be identified through the design, a product can be understood as medical by using white colors and smooth surfaces and another product can conversely be identified as a tool by its use of strong colors and complex surfaces.

3. PROCESS & METHODS

The process for the project has been inspired by the product development processes described in chapter 2.4.1, but adapted to better fit the project, see Figure 3.1 for process diagram. The main difference is that it has been divided into four iterative phases, but the contents in the process are similar to the other processes, just arranged in a slightly different way. First the needs relating to the product were investigated. Second, solutions corresponding to the needs were developed in an ideation phase. After solutions, or design concepts, had been created they were evaluated during the evaluation phase. These solutions were then reviewed, refined, and finalized in a final phase to prepare for delivery to the client. In this phase designs were iterated with the client multiple times to ensure that it fulfilled their demands, but also that it could be manufactured. In design it is very important to work in an iterative way, going back and forth between the different phases. This allows both for an increase in fidelity as the process is iterated with increasing levels of detail as well as allowing for increasingly good ideas to surface when iterating earlier phases with the knowledge gathered during the process.

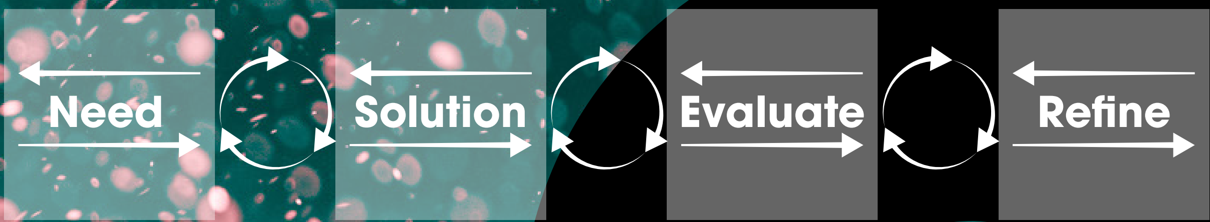


Figure 3.1. - Process diagram for the project.

3.1. Needs recognition

There were two phases of studies, the first one acted as the main knowledge-gathering phase for the project and the second one, which occurred a few weeks later, allowed for filling of the knowledge gaps which were discovered during the early stages of the concept development. This information was used to get an understanding of the user and what their needs and requirements are when interacting with an UHFV measurement instrument. This information was then used in ideation and creation concepts to ensure that the ideas and concepts created aligned with what the users needed and wanted.

3.1.1. Literature review

To get a better understanding of the current situation and the factors affecting it, a literature review was conducted. The goal was to give insight into what causes vibration related injuries, what the consequences are, how vibrations are currently measured, and what can be done to prevent them. This was done to provide a basic understanding which in turn aided in communicating with the different stakeholders and using the correct jargon when doing so.

Additionally a literature review into design theory was conducted to design and structure the process and methods were investigated in order to select suitable methods for the project. Usability and user experience principles were researched in order to anchor the design of the interface in literature. Ergonomic and anthropometric factors were investigated when relevant to the design of the physical instrument and the peripherals.

3.1.2. Interviews

Interviews were one of the main methods by which information about the user and their relationship with measurement instruments was gathered. The interviews were semi-structured with rough outlines of talking points. This was done to ensure that all the important aspects relating to the project were discussed and allowing for easier categorization of the answers later on. Digressions from the questions by the interviewees were allowed and probing questions were used to further explore subjects that were interesting. Because there were many unknowns, an overly structured interview could have risked excluding at the time unknown aspects. An unstructured interview allowed for more input from the interviewees to fill in potential knowledge gaps.

The interviews were held with three types of vibration measurement professionals: work environment engineers, occupational hygienists and lastly with researchers specializing on vibrations and their prevention. Of the interviewed participants, only the researchers were a part of the user group for the instrument in development, but since the purpose of the interviews were to gain an understanding of the processes and workflows of vibration measurements it was deemed relevant to have an expanded scope in the interviews. A total of 9 interviews were carried out.

The contained 12 main talking points, see *Appendix 1 - Interview Template*, ranging from the process of taking measurements to the analysis of the measurements. The interviews were concluded by discussing a preferred visual identity for a measurement instrument by using moodboards as mediating objects.

3.1.3. Moodboards

A moodboard[a] is a visual communication tool that can be used in many different contexts. Moodboards consist of collections of pictures that collectively are supposed to evoke a specific mood or image. These can be used to create a common visual language with a user.

In the project, they were used as mediating objects during the interviews. Three moodboards were created in advance which were meant to represent three different use environments for a vibration measurement instrument Each moodboard represented the expressions *heavy industry*, *medical technology* and *advanced industry*. See Figure 3.2 and for enlarged versions of the moodboards see *Appendix 2 - Moodboards*. This was done to get a grasp of what design language was preferred by the interviewees.

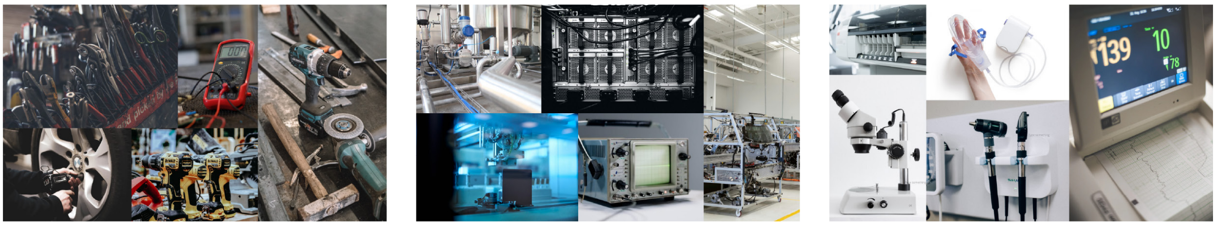


Figure 3.2. - Moodboards used as mediating objects.

3.1.4. Benchmarking

To understand the current state of the art in the field of measurement equipment, an online benchmarking study was done on other vibration measurement equipment. Their functionalities and designs were the focus of the study. As the industry of vibration measurement devices is quite small, the scope was expanded to include other measurement instruments. Keywords related to hand-arm vibration measurement instrumentation, general vibration measurement instrumentation and general measurement instrumentation were used to find as many potentially relevant devices as possible.

Additionally as the amount of interaction points on the instrument was expected to be limited a study on other devices, where the main purpose of the enclosure is housing electronics, rather than housing various interface elements, was conducted. The aim was to gather a good understanding of how enclosures can be designed to display different expressions. The devices studied for this ranged from computer cases, portable DACs (digital-to-analog converters, a type of audio peripheral) and portable SSDs (solid-state disk, a type of data storage device).

3.1.5. Observations

A user observation was done both to explore how the user interact with the current incarnation of the measurement instrument, and how interaction with other types of instruments for vibration measurement. This observation was done with a vibration researcher, the identified target demographic. The study also explored the context of vibration measurement in a laboratory environment, something not covered in the interviews, where most measurements were conducted in the filed. Methods such as “think aloud protocols”, “user narration”, and “cognitive walkthrough” were used to further enhance the effectiveness of the observations. More observations could not be performed due to time limitations, Covid-19 pandemic restrictions, patient privacy concerns and because there is a very limited number of hand-arm vibration researchers within an accessible distance.

Participatory observations were also done in the early stages of the project to get a hands-on understanding of the operations of the instrument in its current incarnation and to understand the current incarnation of the user interface.

---

a Österlin (2003a)

3.1.6. KJ Analysis

A KJ analysis, also known as affinity diagram, is a great tool for organizing large amounts of ideas and data. The KJ analysis was used to better structure and understand the large amounts of qualitative data generated by the interviews and observations. The KJ-analysis was carried out as described in Universal Methods of Design[a], adapted to allow for discussion during the categorization.

The quotes were categorized three times in total. Initially they were grouped quite crudely by which question they were related to, but this proved unsatisfactory since many of the interviewees went on relatively lengthy tangents and would sometimes stray far from the initial subject of the question due to the quite unstructured nature of the interviews. The second categorization was done to better represent what the quote was in relation to and proved far more useful since it gave a much better representation of what the different areas of interest were. The third and final categorization was done in the same way to create smaller, more precise, categories.

3.1.7. Needs analysis

Understanding the needs of the users is central to a user-centered design process[b]. Therefore, analyzing them and listing them creates an important resource for future ideation. In the needs analysis, the different needs were classified by which component it affected, if applicable, which stakeholders had the need, in which environment it was relevant, and when in the stakeholders workflow it occurred.

3.1.8. Function listing

Function analysis is a method that is used to formulate and list the desired functions. These are then categorized as either main, part, or support functions based on how important it is perceived to be for the functioning of the system. Additionally, they can be categorized as either necessary or desirable.

Based on the list of needs, a list of corresponding functions was created, however some needs were judged to be out of scope for the measurement instrument and therefore their corresponding functions were excluded from the list of functions. Each function was categorized as either a part or supporting function to the main function 'Register Vibrations'. To highlight the hierarchy of the functions in relation to each other they were then organized into a tree of functions, see *Appendix 3 - Tree of Functions*. The hierarchical view enabled a deeper understanding of which functions depend on one another.

3.1.9. Design specification

A design specification is a document which lists all the specifications a product must meet and how this will be verified. This can contain obligatory specifications like maximum size and desired specifications like optimal size. The desired specifications were rated for importance on a five point scale. The specifications can be numerically determined like dimensions or weight, or non-quantifiable like expression or usability.

The list of functions and the list of needs were complemented by other specifications derived from measurements of components and other requirements from the client, and used to form a design specification, see *Appendix 4 - Design Specification*. The design specification was then sent to the client to verify that it was aligned with their thoughts and needs regarding the project and revised to include these factors.

---

a Hanington & Martin (2012)

b Österlin (2003b)

3.2. Solution ideation

The aim of ideation is to create a rich set of ideas for how to solve the problems and fulfill the needs discovered in the user research. Ideation was executed multiple times for the different aspects of the product and was also repeated after evaluations. For the ideation, a number of well-known methods were chosen. These have a good basis in literature and practice and are intended to allow for more creativity during the ideation phases.

3.2.1. Sketching

One of the most common, but still very powerful, tools for designers is sketching. It can be done in a free-form manner or it can be more stringent with methods such as braindrawing[a]. Either way, sketching allows for quick and easy communication of ideas between project members and as a way of documenting the design process. The act of sketching can also help with creative problem solving by unlocking spacial and visual thinking.

During the project sketching was utilized throughout most phases. It was used as the first step for designing all the separate parts of the product: the exterior casing, the component layout, the interface and the peripherals. It was also used throughout to quickly communicate ideas and solutions to problems.

3.2.2. Brainstorming

Brainstorming is used to generate a large number of ideas which can later be improved upon. Brainstorming can be done in a multitude of different ways[b, c, d], but the main tenets are always roughly the same:

1. **Never criticize**. Do not consider realizability, cost, or other practical factors.
2. **Strive for wild ideas**. A creative state of mind is important and allowing crazy ideas to surface can help with that.
3. **Combine and build upon ideas**. Combining and improving upon each other's ideas can lead to interesting results.
4. **Quantity**. The more ideas there are, the bigger the chance that some of them will be good.

In the project, a brainstorming mind set was applied throughout the early phases of design. Brainstorming sub-methods were also used for specific cases.

Braindrawing

Braindrawing is a brainstorming method in which individual drawing is utilized, instead of the more forum-like open discussions of brainstorming[e]. Traditionally sketches are passed around between a greater number of participants, but in the project it was applied to explore ideas in tandem.

---

a Wikberg Nilsson et al. (2016a).
b Wikberg Nilsson et al. (2016b)
c Österlin, Ö. (2003c).
d Johannesson et al. (2004a)
e Wikberg Nilsson et al. (2016c)

Crazy 8s

Crazy 8s is a brainstorming method in which eight concepts are made in eight minutes[a]. It is common in the field of Human computer interaction to create early and diverse interface concepts.

In the project this was done for 3 rounds to generate some holistic solutions and some interface component solutions. Some concepts included mobile interfaces, but most were computer interfaces. The resulting ideas were then used as a basis for continued ideation around interfaces.

3.2.3. Morphological chart

A morphological chart is used to combine technical solutions to create a whole idea. It allows for the rapid creation of many ideas. It uses the different criteria that were identified in the functional analysis by creating a series of different ways to fulfill those functions and then combining them to create different concepts.

After a number of ideas were created using brainstorming, an adapted morphological matrix method was used to create a more diverse set of ideas. Instead of exploring the complete set of concepts that could be generated using the morphological matrix a subset was deemed sufficient to explore these. The basis for the categories in the matrix were a combination of functions from the list of functions and functions created during the brainstorming sessions. A total of 8 concepts were generated using this method, with a focus on creating a set of concepts housing all technical solutions. Some of them were quite similar, but enough variation was present to be able to evaluate them individually.

An interesting aspect of the result of the morphological chart was that most of the technical solutions could be implemented in any concept simultaneously. This meant that it was fairly easy to cherry-pick the best parts from each concept and improve other concepts with these ideas.

3.2.4. Pugh

To evaluate what ideas have the most potential a Pugh matrix can be used. This method allows for a rapid and non biased way of evaluating the concepts. In a Pugh matrix the evaluation criteria are traditionally derived from the desired specifications in the design specification. However when applied in the project, functions were used as a basis instead. This was done as the design specification was not written to cover specific features, to keep the design space broad.

The method was done twice, in the first round the existing solution was selected as the reference and in the second the winner from the first round was selected as the reference. Going through the process twice allowed a more nuanced evaluation, by using a new reference it exposes its strengths and weaknesses relative to the other concepts. For an overview of the concepts and results of the Pugh matrices see *Appendix 5 - Pugh-matrices*.

Another aspect which is important to consider when conducting a Pugh matrix is if any weight should be put on whether a concept is consistent or not, should a concept with many positive aspects but some negative be valued in the same way as a concept with fewer positive aspects but no negative ones? It was chosen to only go by the final score since it was deemed to give an adequate score without risking to induce biases.

There was one main issue with the results of the Pugh matrix, it heavily favored concepts which had a screen and some way of interacting with it. This was because there were a number of evaluation criteria which were almost impossible to achieve without a screen and buttons

a Google. (n.d.-a)

and no criteria which were adequate in rewarding feasibility. Therefore the winner of the Pugh matrix was a concept with a large screen and a lot of buttons, which would not be feasible to implement and would not likely not provide an advantage in relation to the development cost. To remedy this issue a second Pugh matrix was done with only the concepts that had no screen. From this the highest scoring concepts were chosen and their best features were combined into three main concepts. This created a set of concepts which implemented a broader set of features without focusing too much on some aspects.

3.2.5. Interface prototyping

In this chapter the prototyping of the interface will be described, from the first prototypes in paper to the functional digital prototypes.

Paper prototyping

To quickly generate interfaces paper prototyping was used to lay out interface concepts created during the Crazy 8's. Each interface element was drawn on a separate piece of paper to allow for exploration of different layouts, see Figure 3.3 and for all components see *Appendix 6 - Paper Prototype Components*.

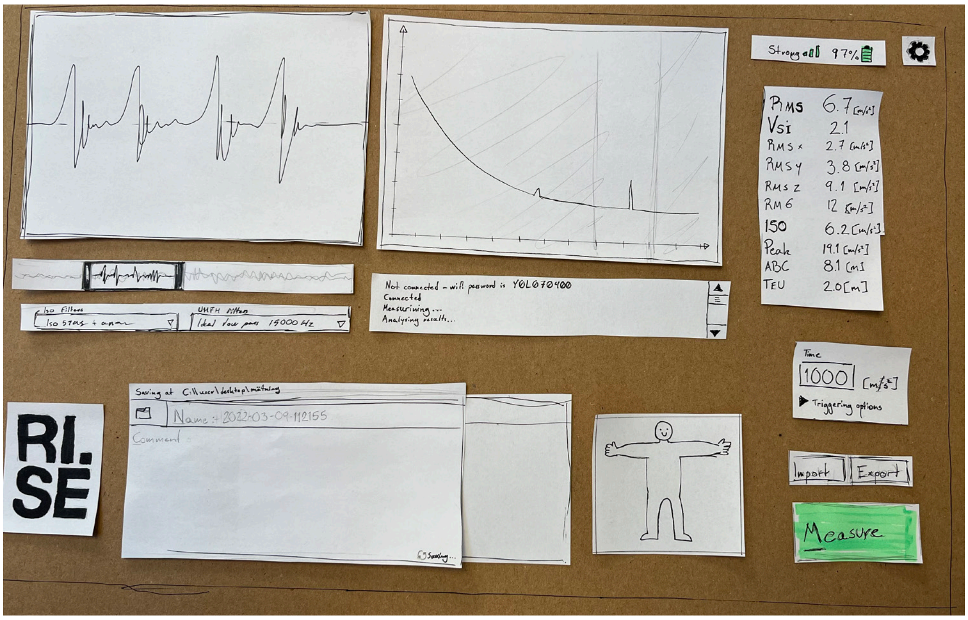


Figure 3.3. - A paper interface concept created in the project.

Digital prototyping

The interfaces generated as paper prototypes were duplicated using digital tools with a focus on creating the information fields present in the interface. This generated a better insight into the information density of the interface, by using realistic font-sizes and padding between elements.

This created a number of interfaces, some were 'one-page' interfaces, where all controls and all information was laid out on one page, and some were 'wizard'-style interfaces, where the user is stepped through the measurement process. A mobile interface was also created. When the interfaces were discussed with the company, who strongly favored a laptop one-page interface, citing the expert nature of the user as well as the developmental ease of creating the application for laptop computers, see Figure 3.4 for the favored interface.

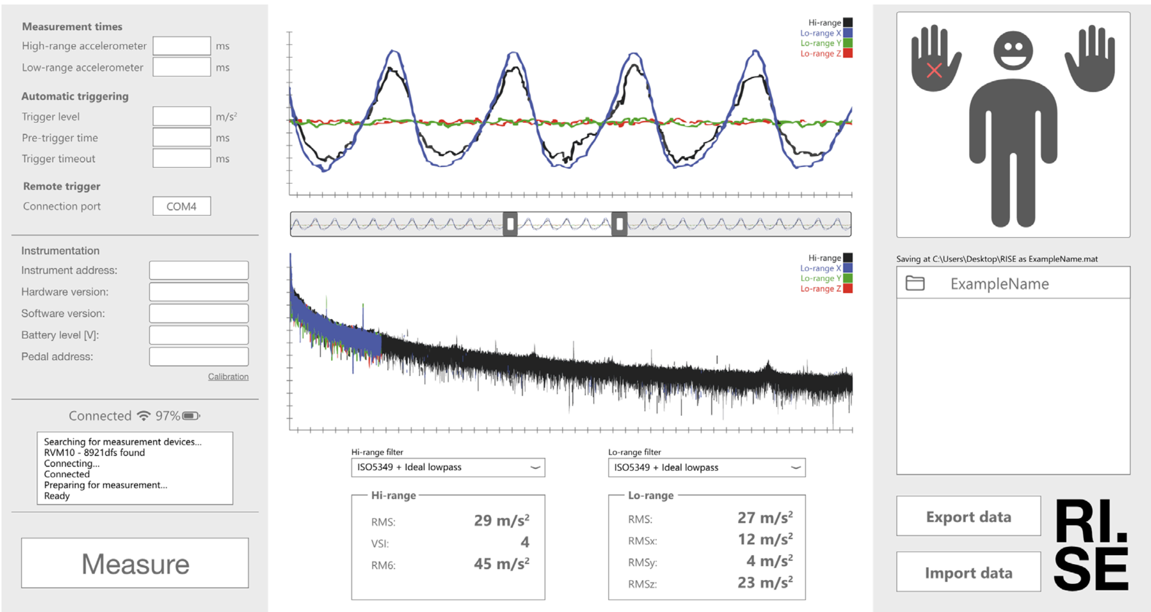


Figure 3.4. - The final interface layout after the digital prototyping.

3.3. Concept evaluation

After the ideation phase, one concept was selected for further development with the aim to be able to test these concepts and validate the designs against user criteria. At this stage, ideas were taken from the earlier phases and tangible concepts were created from them. These concepts were then evaluated to confirm the best fit to the demands and needs.

3.3.1. Prototype and scenario

After a basic concept for the interface was selected a higher fidelity prototype was built to map out the workflow of using the application and the instrument. This prototype was built to test out a scenario in which a participant simulates using the instrument in a realistic scenario. The act of building the prototype in tandem with a scenario also aids in the design of the interface by clarifying what steps are present, something often omitted in static interface concepts. The prototype was largely self-controlling and made using Figma and communication to the instrument was simulated by the Wizard of Oz principle, by a wireless keyboard and an operator. Due to time limitations the scenario was only tested on design students.

3.3.2. Semantic differential

A semantic differential is a method for the evaluation of the semantics of a design. It is constructed using adjectives on linear scales that are then evaluated with the potential users or other people. This data can then be used to understand whether the semantics of the product achieves the desired goal.

In the project this was used to determine the successfulness of the semantic expression of the physical product. Participants were shown five scales with the ranges *medical-industrial*, *playful-professional*, *durable-frail*, *elegant-rough* and *appropriate-unsuitable*. The results were a professional, durable and appropriate product. Most experienced the product as predominantly industrial, but some found it a bit medical as well. On the elegant-rough scale there was a larger spread in the results, with a weight towards elegant, for a visual representation of the results see *Appendix 7 - Semantic Differential*. A separate scale was also used to evaluate the experience of using the interface.

3.3.3. Ergonomics analysis

Cognitive ergonomics was an important part of the development of the instrument. The goal of the design was to create a product which uses as few of the users' mental resources as possible. There are numerous methods for evaluating this, and design guidelines to create ergonomic interfaces. The focus in this project was on creation of an interface which would be easy for the users to use, which it could be argued improves the cognitive ergonomics of the product since they are intimately connected. To achieve this, the interface was evaluated against Nielsen's[a] heuristics.

The physical ergonomics was also an important part of the project. The main factor affecting the physical ergonomics would be the weight since the users will carry the instrument in a pocket or in the carrying bag most of the time. The physical ergonomics were evaluated using a RULA.

Rapid Upper Limb Assessment, RULA, is a method used to provide a rating of musculoskeletal loads where mainly the neck and upper limbs are concerned[b]. It can be used to provide a "snapshot" of the risk the task poses, on a scale from 1(low) to 7(high).

A RULA was done to evaluate the task of turning on the instrument, pairing it with a computer, and then putting it either in the carrying bag or on a surface. It was assumed that the person using the instrument would hold it in their elbow bent around 90° and look down on it, slightly bending their neck. It was also assumed that this position would not be held for more than a couple of minutes since the pairing process is relatively quick. With these assumptions about the usage of the instrument, the final RULA score was calculated as 2, which is on the lower end of the spectrum and according to the RULA evaluation does not need any intervention, for the filled our RULA see *Appendix 8 - RULA*. This low RULA score was seen as a confirmation that the musculoskeletal aspects of the instrument would not be an issue, both due to the low weight and the short usage times.

3.3.4. CAD and CAID

For the evaluation of the form CAID, computer aided industrial design, was used as a method to translate rough sketches to modeled forms with proportions relative to the internal components. These models were then 3D printed to verify the expression and ergonomics of each form.

After this initial step of form giving, the focus shifted onto CAD, computer aided design, to ensure that the product would be possible to manufacture. In this step many iterations of the design were tried to make sure that the form could feasibly be created using a CNC mill and assembled by hand. To verify the former the design was discussed with various experts and to verify the latter the designs were 3D printed and assembled by hand.

a Nielsen (1994a)
b McAtamney & Corlett (2004)

3.4. Concept refinement

When a final design was chosen it needed to be refined to the point where instructions can be sent to the company's manufacturing partners. This meant that the design needed to be designed in such a way that accounts for, among other, the possibilities and limitations of different manufacturing processes, manufacturing costs, assembly possibilities, and look and feel.

3.4.1. Visualizations

To make sure that the product had the desired expression when finished, it was important to make visualizations to indicate how the different design decisions affect the final result. These were created using visualization software where materials were selected to mimic those of the components and then rendered in various environments.

3.4.2. Simulation and feasibility testing

To make sure that the finished product would be satisfactory, simulation of its properties was important. This could be done in software, by using finite element method, as well as physically and both are necessary and have advantages in product development[a]. Virtual prototyping had the advantage of quickly being to try different variants as well as being able to simulate different properties of the finished product such as mechanical strength or weight. Virtual prototypes were also used to check how parts and components fit together as well as how they could individually be manufactured. Physical prototyping on the other hand enabled the validation of the ergonomics and the assembly.

3.4.3. Component selection

In the project, an important task was to select components for the physical instrument as only some parts were already specified. The components included buttons, connection ports, batteries and antennae and the selection was done with the support of the design specification. This meant that the aesthetics of the components, their internal and external dimensions, as well as their performances for example tough environments were considered.

3.4.4. MATLAB Mockup

To create an interface with a visual fidelity equal to the fidelity of the final production interface a mockup to the interface was created in MatLab, using the MatLab App Designer. The MatLab App Designer is the tool that will be used to create the user interface in production, which means that creating a mockup in App Designer eased the handover to the development team and reduced the amount of non implementable interface ideas.

---

a Johannesson et al. (2004b)

4. RESULT

In the following chapter the result from the various parts of the project will be described and outlined. First the results from the user study will be presented by describing the needs of the user and second the physical design will be explained in detail. Lastly the design of the digital interface will be presented.

4.1. Benchmarking

To understand the field of vibration measurement, a benchmarking of current vibration measurement devices was conducted, mainly for hand-arm vibrations. From the benchmarking, conclusions about the roles of the devices could be done. There are two main categories of devices: instruments with screens and instruments without screens. The instruments with screens are usually more advanced and are to be held by a measurement professional. The instruments without screens are to be worn by the operators of tools and data will be unloaded from them at a later time by the measurement professional. This makes the approach of having an instrument with no screen and a companion software interface fairly unique, but necessary from a development standpoint. A stand out device is the Svantek HVM 106A, which is a device similar in purpose to the one designed in the project. In mode of operation, it does however differ as it features a screen for displaying the data and several buttons for configuring the measurements. None of the devices support measurements of ultra high frequencies as these measurements are new for human vibration measurements. Existing technology for measuring vibrations at ultra high frequencies is limited to heavy laser equipment, which is not well suited for measuring on handheld devices and cannot be brought for field measurements.

4.2. User study

The results of the user study was a greater insight into the process of how vibration measurements are conducted in the field by professionals. The results directly affected the development of the design specification which dictated the design decisions.

The context for measuring vibrations is variable, some measurements are done on-site whereas others are done in more controlled lab circumstances. For the on-site contexts there are two main types: medical sites, such as dentist offices, and industrial sites like production floors, workshops and building sites. The medical context places demands on the equipment to both look and be clean enough. The industrial setting does instead have demands on robustness and resistance to wear. What is common between both contexts is that the individual conducting the measurements is not the same as the one creating the vibrations and that they have to continue their work as the measurements are collected. This places many demands on speed and flexibility as the measurement process has the potential to interrupt the work of others, which in turn can have tertiary effects of delaying work or disturbing patients. As the context is someone else's place of work the individual measuring cannot influence what tools they can measure at any time, meaning that if they want to measure a specific tool in a specific context they have to wait and be ready for when this situation arises. This means it's important to quickly be able to set up for measurements. Another aspect of on-site measurements is that it might not be suitable for the one conducting the measurements to be physically near the vibration operation, it can for example be hazardous when using an angle grinder. This means that the operation of the device must be able to be performed from a distance and that the instrument must be able to be securely placed on or near the operator.

For usage in the lab the demands are slightly different. The operation of the vibrating tool as well as the measurement of the vibration is done by the same person. This means that measurement needs to be able to be done while operating heavy machinery with both hands.

4.3. Physical design iterations

The creation of the physical design of the instrument went through several iterations. These will be detailed in the following part. It was decided that a screen would be too costly to implement in terms of work needed. The two concepts without screens that fared best in the Pugh matrix were concept D and F and these were used as a basis when moving to creating designs which would be able to be manufactured, see Figure 4.1, for more concepts see *Appendix 9 - Early Sketches* and *Appendix 10 - Refined Sketches*.

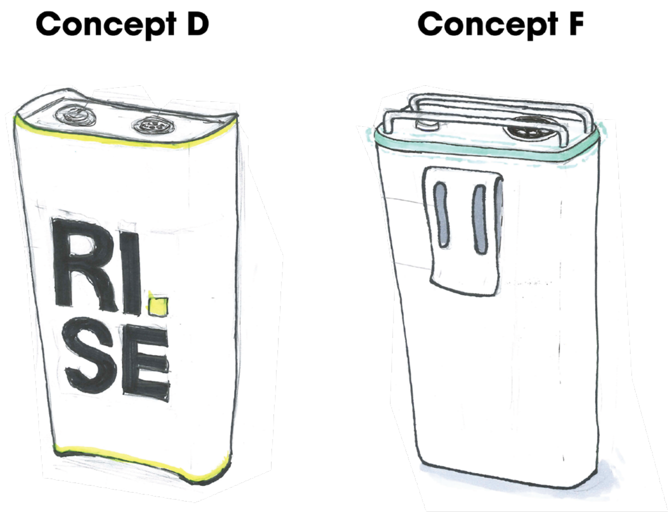


Figure 4.1. - Designs without screens.

Initially it was attempted to create a design which was a mix between D and F, but the metal bars on top of concept F were quickly disregarded as they were seen as making it far too hard to clean the device properly if it were to be used in a medical setting. The first step taken was to create quick models to get an understanding of the geometry and sizes involved. First a series of wood blocks were created, representing the maximum size of the product, the size of the electronics package, and some preferred sizes, see Figure 4.2. After that paper and foam models were created to test some geometry, like a slight indentation along the length of the body where providing a resting place for the thumb, see Figure 4.3.

Figure 4.2. - Wooden size representations.

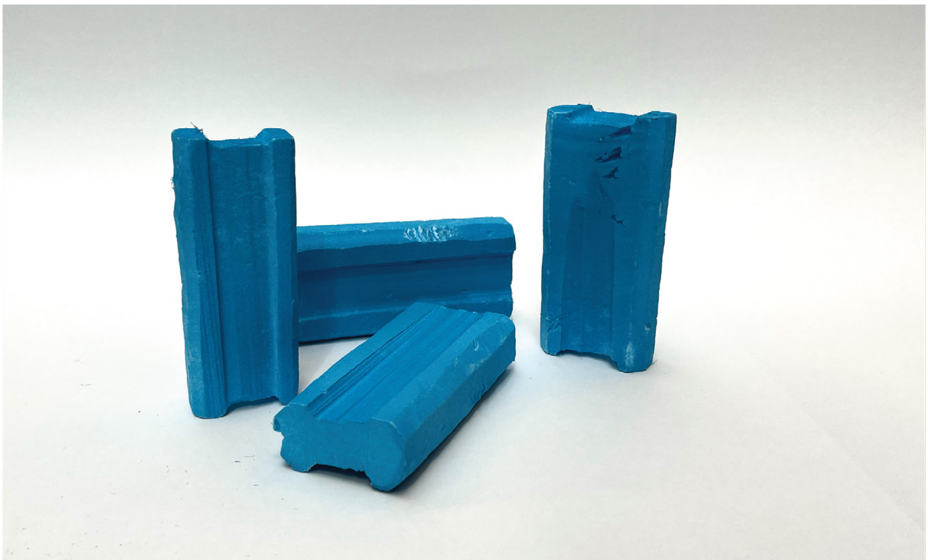


Figure 4.3. - Foam models.

After the models were evaluated the work moved to CAD. Since the device needed to be CNC-machined and be waterproof there were several challenges that needed to be overcome, in this stage the biggest challenge was how to fit an O-ring and where to place the split line. The first attempt can be seen in Figure 4.4.

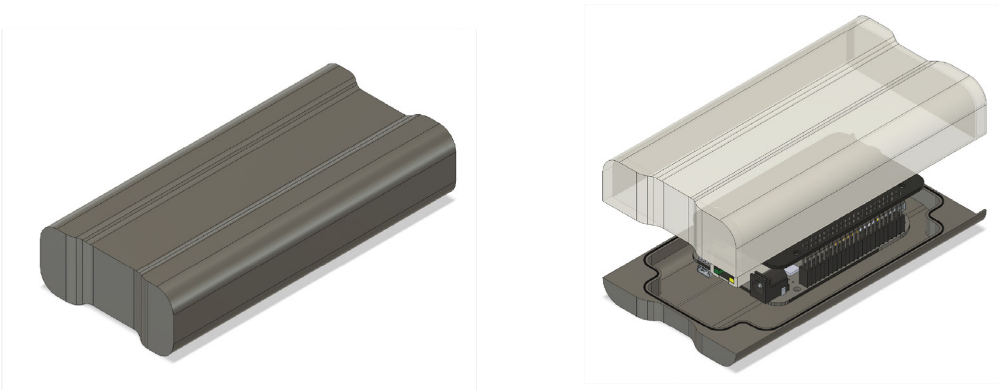


Figure 4.4. - Early attempt att manufacturable product.

This was not seen as a viable way of manufacturing the device since it would be very complex and the O-ring would be placed in a very strange manner.

The second attempt was created to make placing the O-ring easier by making a more straight slot for it. This concept still retained the idea of having two large parts, one base and one lid, see Figure 4.5. This idea would make assembly of the electronics easier since the large lid gives ample access to the internals of the device. But it creates a large area which needs to be sealed with the O-ring. This concept was also discarded since it would be very complex to machine due to the placement of the slot for the O-ring, and would be relatively flimsy due to the thin lid.

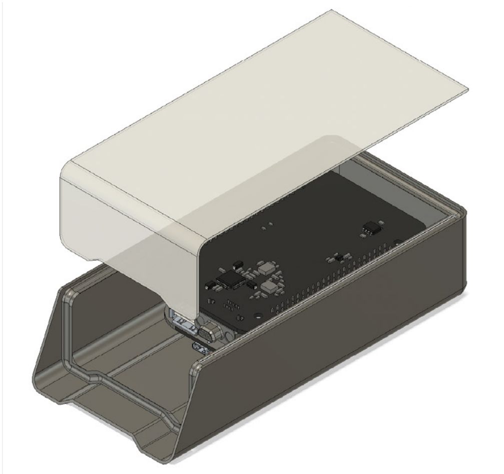


Figure 4.5. - Second concept for manufacturability.

The third attempt was approached the problem from another angle, by having one large base piece and a smaller lid, see Figure 4.6. This makes the area that needs to be sealed with an O-ring much smaller and makes the design more rigid since the base is made from one piece. This design would however make it much harder to assemble the internal electronics since it was only accessible from the narrow top.

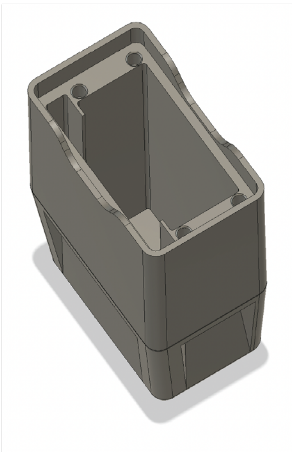


Figure 4.6. - Third concept.

To explore ways of making the internal components easier to assemble a fourth concept was created. This was based around a sled where the electronics could be assembled and then the entire sled could be inserted into a protective shell, see Figure 4.7. This would make assembly much easier, and would allow for only changing the sled if the electronics were swapped out for others with differing dimensions. This concept did however reintroduce the issue with complex O-ring placement. There was also a fear that the thin dimensions of the protective shell would make it susceptible to bending, exposing the internal components.

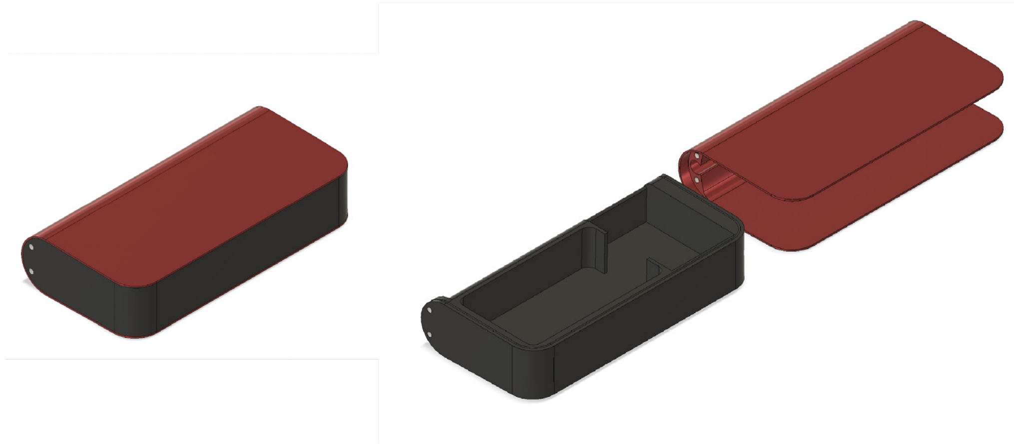


Figure 4.7. - First concept with a sled-like structure.

The concept with a protective shell and a sled was seen as having good potential and was further explored. This lead to the creation of the concept which was chosen to be further developed and which is the precursor to the final version presented later in the report. The concept could be seen as taking all the best parts of the previous attempts. The concept is based around a protective shell and a combined lid and sled, see Figure 4.8. This gives it the benefit of being easy to assemble since the electronics are mounted in the sled before, while retaining the structural rigidity of the shell. Since the shell has material all around its perimeter it is much stronger than the earlier sled concept.

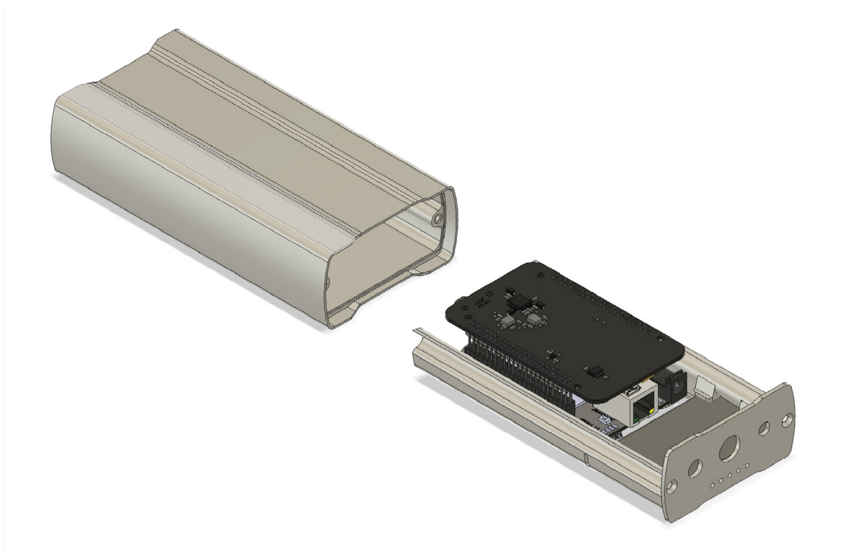


Figure 4.8. - The first concept with clear likeness to the final.

The remaining work with between the concept stage and the final design was mainly with making it easier to manufacture as well as sourcing different components and ensuring that everything fit together.

Simultaneously with designing the concepts in CAD several 3D-prints were also made, this made it easier to get an understanding of how the parts would actually fit together. It was also a great way of getting a feel for the size of the product, something that is easy to lose grasp of when only working in CAD. For pictures of the 3D-prints of different concepts and iterations, see Figure 4.9 for models used to explore many different concepts and Figure 4.10 for models used to refine the design.

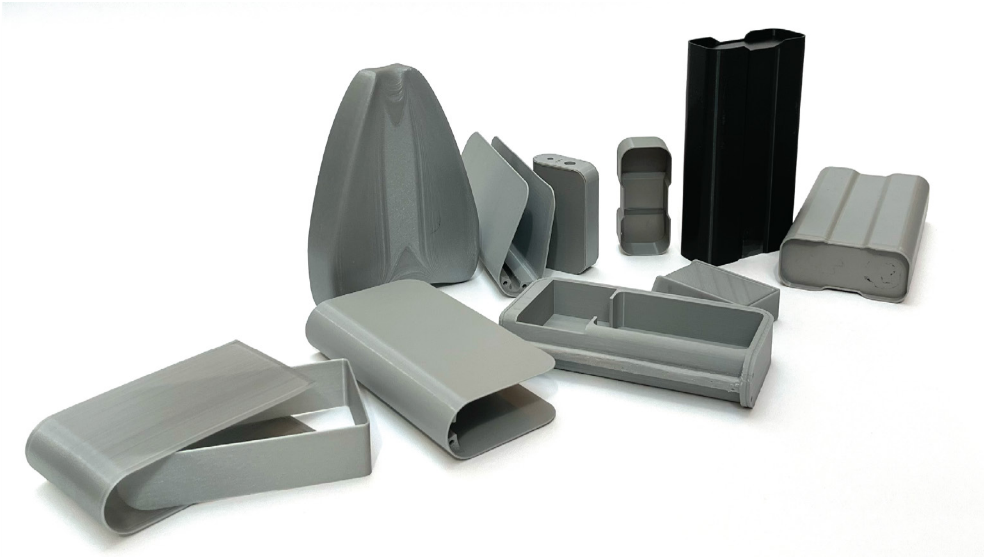


Figure 4.9. - Early 3D printed models.

Figure 4.10. - Later, more refined, 3D printed models.

4.4. Physical design

The physical design can be separated into 3 different parts, see Figure 4.11: the electronics enclosure which houses the single-board computer as well as the battery, the remote trigger which is used to operate the instrument when both hands are occupied, and the carrying bag which is used to fasten the instrument to the operator if there are no suitable pockets.

Figure 4.11. - All three parts, electronics housing on the left, carrying bag in the middle, and trigger on the right.

4.4.1. Electronics enclosure

The electronics enclosure is the main physical part of the product, it houses the BeagleBone Black, which is the computer responsible for controlling the accelerometer and communicating with the researcher's laptop. The final design is the balance between meeting the demands of the users and the environment, the ease of manufacturing and assembly, and the creation of a premium and professional expression.

Meeting the demands

As the instrument will be used in all environments that the researchers operate in, it is important that it functions well in them. The three main environments that the instrument will be used in are industrial settings, medical facilities and in research laboratories. These environments pose radically different demands on the instrument. In the industrial setting, the product needs to be rugged enough to withstand a lot of physical violence and harmful chemicals. In the medical setting the product must be easy to clean so as to not contaminate the facilities, this means that it should not have any places where grime and dirt can get stuck, but also that it must withstand some common disinfectants. In the laboratory setting, it will be common that a single researcher will conduct experiments, it is therefore important that it allows for single person operation.

Durable products usually feature reinforcement or additional protection in certain areas which are deemed more prone to damage, this is commonly done by adding rubber which will help absorb shock and prevent damage to the material underneath. This does however create spots where dirt and other contaminants can gather and was therefore not seen as a viable alternative for this product. To make sure that the enclosure would be both durable and easy to clean, aluminum was chosen as the primary material for the exterior. Aluminum is strong and durable, which combined with a natural corrosion resistance makes it ideal for industrial settings where it can handle both physical violence as well as many chemicals. In these environments there is also no guarantee for aridity, which creates a need for the product to be water resistant.

In industrial settings the operation of the tools that are to be measured can be hazardous to bystanders: an angle grinder sprays hot sparks that can damage clothes and eyes. This creates the need for the instrument to be operable from a safe distance. Because of this, in addition to being wireless, the dimensions, shape, and weight of the instrument are carefully considered. The dimensions are 30 mm in height, 80 mm in width and 160 mm in length, and have been selected to fit the internal components without making the product either too long or too high to fit inside the pockets in work-wear clothes. The dimensions also makes the product holdable with one hand, with the indentation along the top and bottom providing a more grippable surface, see Figure 4.12.

Figure 4.12. - The RVM held with one hand.

The weight of the product has been carefully considered to not be too heavy for when the product is carried on a person, but also be sufficiently heavy to make the product lay still when placed on a table. To ensure this stability, the underside of the product also features four rubberized feet to increase the friction. The formula to calculate how much force the friction between to objects can create is[a]:

$$\mu = \frac{F}{W} \Rightarrow F = \mu W$$

Where is the coefficient of friction, F is the friction and W is the load perpendicular to the sliding plane. The weight of the product is around 400-500 grams, corresponding to roughly 4-5N. 4N will be used in the calculation since it will provide the weakest friction force. The coefficient of friction will depend on the materials of the two sliding bodies, for rubber the coefficient of friction wi2ll commonly range between 0.4 and 1 depending on the material it slides against[b]. This means that the force F required to start pulling the instrument will be:

$$\mu_{min} W \leq F \leq \mu_{max} W \Rightarrow 1.6 \leq F \leq 4$$

The lower value of 1.6N represents rubber sliding against metal and the upper value of 4N represents rubber against asphalt. The sensor chip with cable weighs around 40 grams. Therefore the lower friction force of 1.6N could resist around four times the length of cable hanging freely without moving, something that is deemed sufficient as it will likely not occur. The more common issue would be someone or something yanking on the cable, the friction could handle some light pulling, but could of course not resist any significant pulling force.

a Hutchings & Shipway (2017)
b Grahn & Jansson (2002)

Construction anatomy

Inside the enclosure there is, aside from the single board computer, a battery to power it and connections to the components on the outside of the device. The components on the outside of the device are: the power connector, the connector to the sensor, the connector for the antenna and the power button. See Figure 4.13 for all the components, for an enlarged version of the figure see *Appendix 11 - Exploded*. All of these components were chosen to be IP67 rated to ensure that the instrument could be operated without damaging it in humid conditions. Inside the device there is also a board holding five LEDs that communicate the status of the instrument with the user. For a full list of all components see *Appendix 12 - Bill of Materials*.

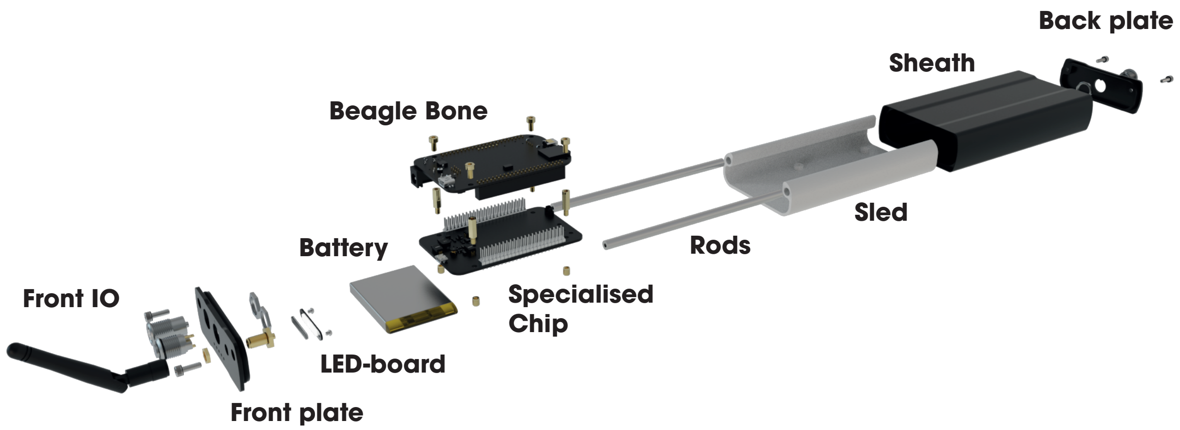


Figure 4.13. - Explosion diagram of the instrument.

The I/O components are fastened to the front and the back plate. The battery, BeagleBone and the specialized chip are fastened to the internal ABS sled for ease of assembly. Since the sled is made from ABS there are threaded inserts made from brass inserted into it so that the screws holding the BeagleBone are securely fastened. The internal sled is fastened to the outside of the enclosure via two metal rods screwed into the front and back plates. The plates are held in place by the rods as well as geometrically by the an internal lip on the sheath. An o-ring is mounted on both the front and back plate, creating a seal between the inner wall of the sheath to protect against water ingress, see Figure 4.14. For drawings see *Appendix 13 - Drawings*.

Figure 4.14. - The outer parts: The o-rings are mounted in grooves on the front and back plates.

Manufacturing & assemblage

The shape of the exterior sheath has been explicitly designed to be millable. Since the pocket that is to be milled is fairly deep, around 150mm, the radii inside the pocket must be at least 10mm. The front and back panels are also designed to be milled.

To allow for the more complex shape of the sled it will be produced by 3D printing in ABS. This makes the sled durable enough to hold the components and because the sled held by metal rods connected to the shell it will not receive most of the forces absorbed by the shell. 3D printing also allows the design to be more easily changed as it is a flexible production method with no tooling costs. This makes it simple to exchange batteries as the supply of batteries can be unpredictable.

The design of the product has been planned to allow for the assemblage of the product. By mounting the components onto the sled and to the front panel, and mounting the sled and the front panel onto the rods the components can be easily connected together before sliding the sheath over them. On the back panel only the power connector needs to be connected to the rest of the assembly before being mounted and screwed into place. The sled ensures the rods are parallel which aligns the screw joints.

Expression

As the product is a professional and premium tool it has been designed with an expression to reflect this, see Figure 4.15, Figure 4.16 and Figure 4.17. The material selection of anodized aluminum associates the product with other premium products, as well as gives the product a weight which gives it the heft of a premium product. The aluminum is also well suited to the environments the product will be used in, which is a key part in making the material appear professional. The dark coloring of the aluminum will, in accordance with chapter 2.4.5, make the product appear heavier, which combined with its large contact area with the ground will give it a stable expression.

Shape-wise, the product has a fairly large body, conveying advanced internal components. The depressed surface on top and bottom, and the convex surfaces on the sides makes the product shape more interesting than a more traditional flat shape, thus resulting in a more premium design. The sheath extends beyond the front and back panels which functions to hide the gap between the panels and the sheath. The device also exhorts the user to give it attention by having an LED-array which can blink in different patterns to grab the users attention and convey important information to them.

Figure 4.15. - The front and the back of the instrument.

Figure 4.16. - Side view of the instrument

Figure 4.17. - The expression of the instrument

4.4.2. Remote trigger

To ease single person operation of the instrument, a supplemental remote trigger is developed in the form of a foot pedal, see Figure 4.18. In order to reduce development costs and manufacturing complexity the pedal it's based on the main board of a Bluetooth mouse, with a new metal button soldered onto the board for durability. These are then mounted inside a plastic case with a similar form language to the main instrument.

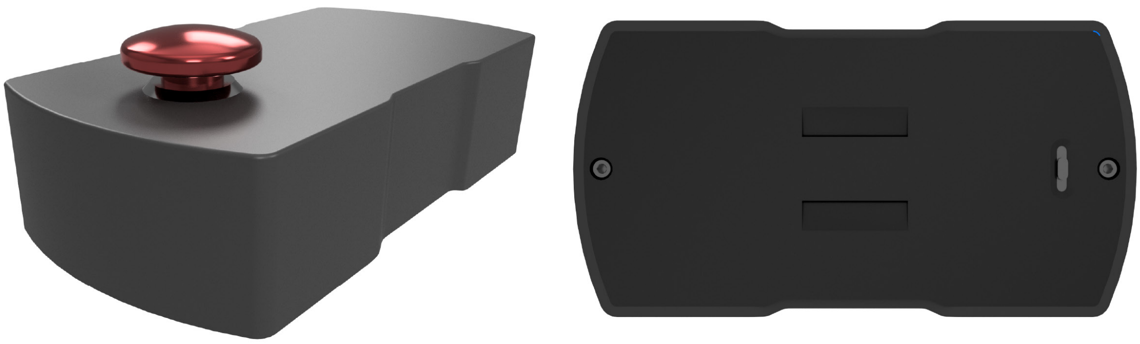


Figure 4.18. - The pedal concept for remote triggering.

On the underside of the device there is a combined on, off and Bluetooth pairing switch as well as a hole that allows for insertion of cargo straps to allow the trigger to be mounted onto surfaces.

Using a standard Bluetooth mouse as the basis for the trigger makes the software compatible with any Bluetooth mouse as a remote control for the instrument. This allows for flexibility of how the users want to use the device, as well as choosing other accessories if desired. This is done by allowing the user to select a COM-port as the trigger input in the interface.

4.4.3. Carrying bag

To make hands-free operation of the instrument easier, a carrying bag was developed. The aim of the design for the carrying bag was to allow it to be as flexible as possible in the way it is attached to the tool operator to allow it to be used regardless of the operators' clothing, operators' physical size, and the task carried out.

The basic form of the bag is constructed from three pieces of durable fabric, one backing, an u-shaped piece, and a flexible front piece, see Figure 4.19. This construction was chosen because it is relatively easy to construct, and creates a very durable design. The strength of the design stems from the fact that the u-shaped piece will take most of the weight from the instrument and since the connectors for the strap are connected to that piece it minimizes the number of weak points when using that strap. It also creates a long seam between the u-shaped piece and the back which will also allow it to withstand considerable force when worn with the belt loops attached to the back piece.

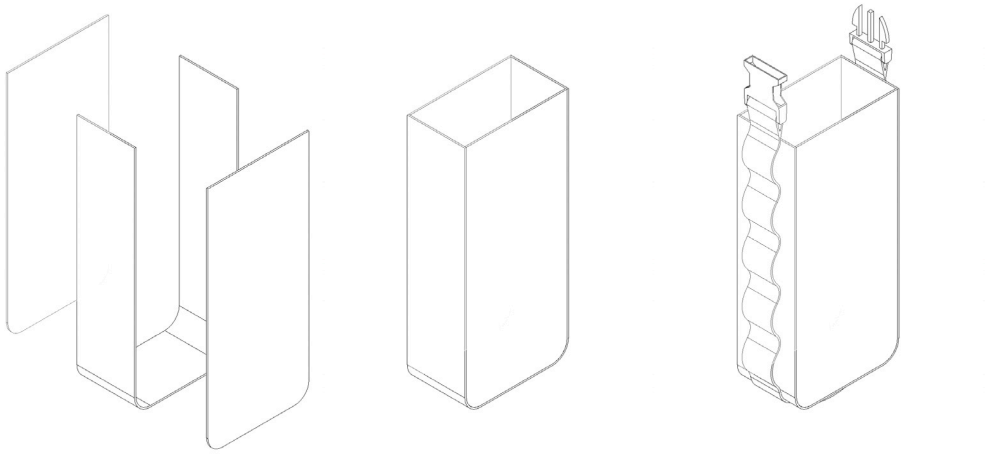


Figure 4.19. - The anatomy of the carrying bag.

The closing principle used to stop the instrument from falling out of the bag was initially a lid with buckle to close it, this was however deemed too cumbersome and instead the flexible material was chosen for the front side of the bag. This stretch material will be sown so that the bag will have a circumference that is smaller than that of the instrument when it is unstretched. When the instrument is inserted it will stretch the front material which will create a very snug fit, this snug fit and friction will be what keeps the instrument in place. It is not as secure as a mechanical closing mechanism such as a clasp, but this trade-off was deemed necessary to make it more streamlined to use and thus improving the user experience. If the bag is used in an environment where the operator will move around a lot or perhaps be upside down there is of course a higher risk that sufficient force will be produced to make the instrument fall out of the bag. In this case the bag can be worn with the belt loops on the back and the side release buckles used for the shoulder straps can be locked into each other to create a sort of lid which secures the instrument a bit more than just the flexible material, see Figure 4.20.

Figure 4.20. - The buckles of the bag securing the instrument.

To ensure that the bag would be useful in a wide set of circumstances the carrying bag was equipped with two flexible attachment systems:

Messenger bag

In this configuration the bag is used as a messenger bag with a long strap over one shoulder, see Figure 4.21. This allows it to be used by nearly anybody, regardless of physical dimensions or clothing worn since the only prerequisite is that the strap fits, which it will likely do even if the operator is very large or wearing a lot of bulky equipment, although it might ride a bit higher up on the body than intended. It is however less securely fastened than in the other two configurations since it is only slung over the shoulder. The strap is attached to the carrying bag using side release buckles.

Figure 4.21. - The bag slung over the operator's shoulder.

Belt loop

This configuration relies on the belt worn by the operator, see Figure 4.22. It uses two nylon loops on the back of the carrying bag which the belt will be fed through. Two loops were used to ensure that the bag will stay upright since a larger part of the bag is supported between the loops and thus insensitive to outside forces, see Figure 4.23.

Figure 4.22. - The bag carried in the operator's belt loop and secured around the thigh.

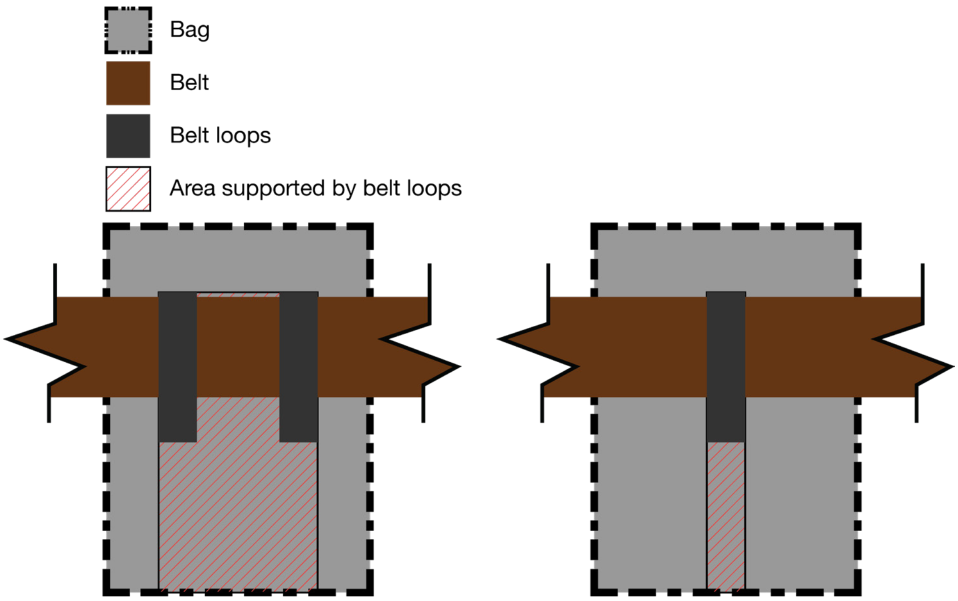


Figure 4.23. - The difference in area supported by the belt loops of two loop compared to one.

The drawback of the attachment method is that it requires a belt or similar attachment point. This is solved by including a separate strap which can be fed through the loops and then attached around the operators' thigh. To ensure that it does not slide down the leg in this configuration another, shorter strap is also included which uses the side release buckles for the shoulder strap. This shorter strap can then be looped around a suitable point on the operators' clothing, such as a belt loop or belt to secure it. Alternatively, the thigh-strap can be used simultaneously with the shoulder strap which also makes it very stable. Additionally, the carrying bag has been outfitted with a series of nylon strap loops going around the sides and bottom of the bag. These can be used to secure the bag in a number of ways, e.g. a carabiner could be used to fasten the bag to a belt loop or to a backpack, or rope could be used to secure the bag. The loop on the bottom of the bag is also helpful when removing the instrument from the bag as it provides a good grip if the outside of the bag has been made slippery by contaminants in the environment. Since there are many versatile attachment methods available on the carrying bag, it is also possible that the users will be able to come up with novel ways of using the bag which were not envisioned, this has both advantages and disadvantages. Allowing the users to fasten the bag in novel ways can help the product be useful in many cases which would have been hard to predict in the development phase, but there is also a risk that it could be fastened in ways which might be risky, both in terms of material and physical damage. It could for example be fastened with a sole carabiner in the lower loop so that it hangs upside down, the elastic textile material in the front of the bag would likely keep the instrument from falling out, but if the operator were to jump it could fall out and either be broken or hurt someone.

To make sure that the carrying bag can be used by as many operators as possible anthropometrics were used. The measurements used were from Hanson et al.[a]. For all the measurements values were chosen so that people above the 5th and below the 95th percentile were included. For the shoulder strap length, the diagonal across the chest was calculated using the *Shoulder height, sitting* and *chest depth, standing*, as these were the most accurate found, see Figure 4.24. Upper bodies were then assumed to be perfect rectangles, this makes the measurements slightly larger, but it was seen as negligible as it is likely countered by the fact that bags are not carried at the very edge of the shoulder. The formula used to calculate the strap length was *chest diagonal * 2 + chest depth* which gave a lower value of 1484 mm and a upper value of

a Hanson et al. (2009)

1982 mm, to make manufacturing easier it was decided that it should be adjustable between 1.5 and 2 m. The length of the strap around the thighs were calculated by using the *thigh clearance* (height from the chair to the top of the thigh when sitting) and assuming that thighs are perfect cylinders. This makes the formula for the length of the thigh straps *thigh clearance* * π which sets the lower value to 383 mm and the upper value to 578 mm. This was also simplified to between 0.4 and 0.6 m to make manufacturing easier. The calculations are fairly rough and require some assumptions, but it will likely fit the majority of operators.

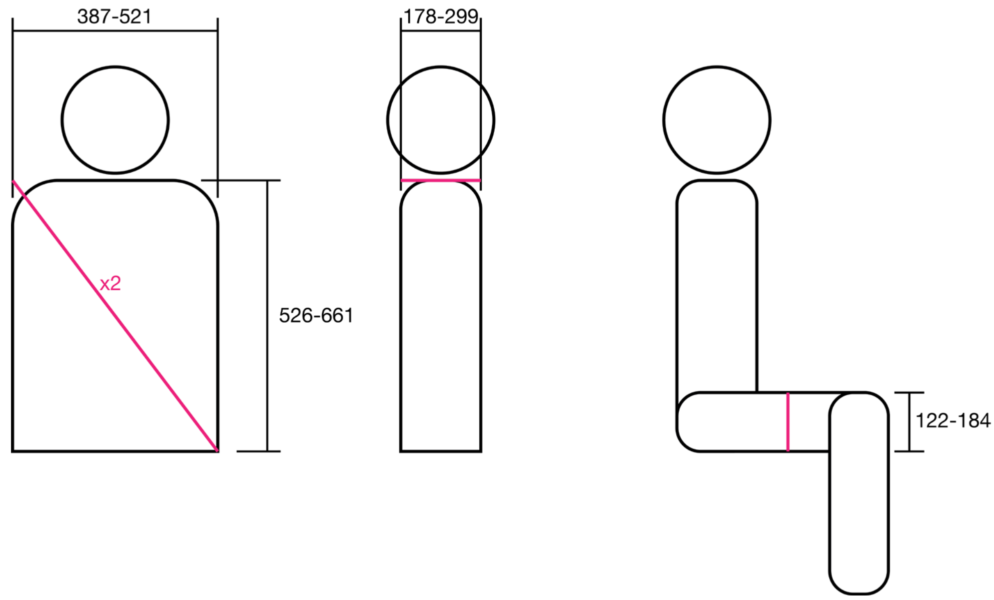


Figure 4.24. - The relevant measures on the human body, strap locations marked in pink.

To make sure that the bags would work as expected and be able to be manufactured in a reasonable way a series of prototypes were created using the a basic industrial sewing machine.

4.5. Digital interface

The digital interface is the main way that interaction with the instrument is conducted. When designing the interface, the frameworks and theories from chapter 2.4.2 have been used extensively. The heuristic rules described by Nielsen were used as guidelines to create a user interface with good usability, where applicable. Nielsen also describes 5 attributes that a system should possess for it to have good usability, the goal with the design has been to fulfill as many of these as possible. But due to the expert nature of the target users, they will be measurement professionals with extensive knowledge of vibration measurements; the interface prioritizes speed for these users. The guessability within the interface will not need to be very high, since the user group can be expected to read some documentation before using it. However the interface does employ clear language to convey the meaning of different interface elements.

The interface also utilizes some of the design principles described by Unger & Chandler. One of the more important principles used is that the interactive elements in the interface should be designed to be consistent within the system, e.g. all text entry fields are white with a gray border, making it easier for the user to understand that they need to enter text or numbers in them. Another principle used is economy of motion, that the user should not have to expend time and effort to interact with the system. The system is designed in such a way that the user in most cases first fills in the left pane from top to bottom, then moves on to the middle, and finally fills in the right pane and fills it in from top to bottom. This creates a very efficient route where the mouse does not have to move long distances. This is also related to Fitts's law, which states that it is easier to hit objects which are close and large, meaning that the short distance the mouse needs to move makes it easier to interact with the elements.

Many of the 10 principles for good usability design described by Jordan were also employed. Consistency is very similar to the concept of consistency described by Unger & Chandler. Compatibility, that the system should be consistent with other systems the user is familiar with, was fulfilled by creating an interface which uses elements which are standard within most digital interfaces. Examples of such elements are tick boxes which toggle functionality and drop-down menus which are both well established and understood by most computer users. Another very important aspect is feedback, to ensure that the users are aware of what is happening with the system, this is done in several ways in the system. There is for example a reed-out feed which tells the user what the system is doing, e.g. trying to connect. Another feedback example is that there are also several ways that the middle pane changes to different empty-states to reflect both what the system is doing and what the user needs to do.

4.6. The layout

The interface is divided into three columns, each centered around one key task, see Figure 4.25, for a larger image see *Appendix 14 - Interface* The columns are ordered in such a way that the most common order of interaction with them goes from left to right - the western reading direction.

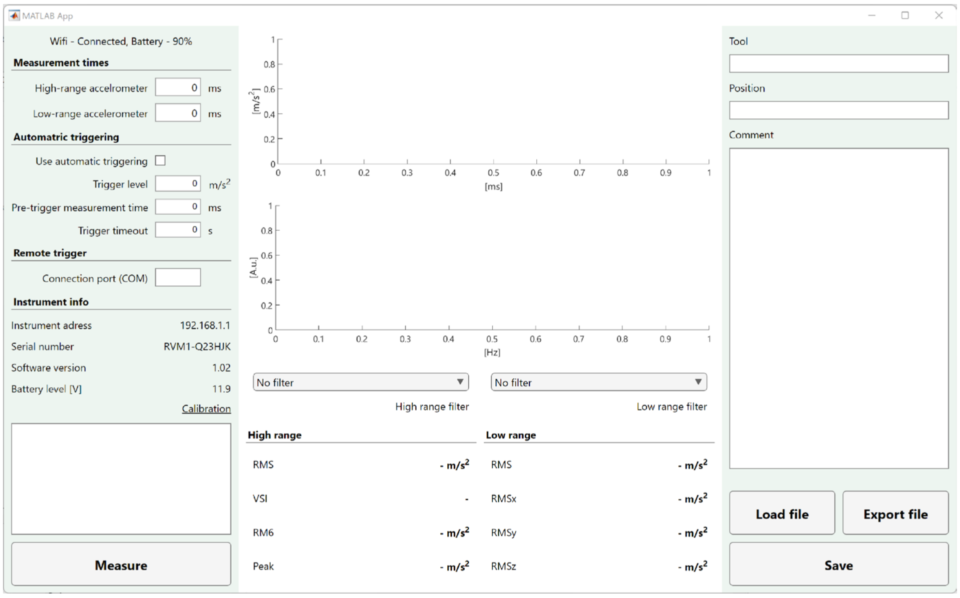


Figure 4.25. - The interface for controlling the instrument.

The leftmost column is the setup pane: it contains all the settings necessary to set up a measurement before conducting it, see Figure 4.26. Interactive elements which are related are grouped together, for example all elements relating to measurement time are grouped next to each other. At the top of the column is a small status bar showing connection strength and charge, underneath that are the settings for measurement time, below that are the settings related to the use of automatic triggering, which is used when the user needs to operate the machine alone. Underneath the automatic triggering is the setting related to using the remote trigger, which is also used when the user is operating alone. Below the automatic triggering is the information about the instrument, this cannot be changed by the user, but information such as software number or battery voltage can be useful, for example when troubleshooting. Underneath is a read-out feed, which displays the current status along with a history. On the bottom of the pane the measure-button is located.

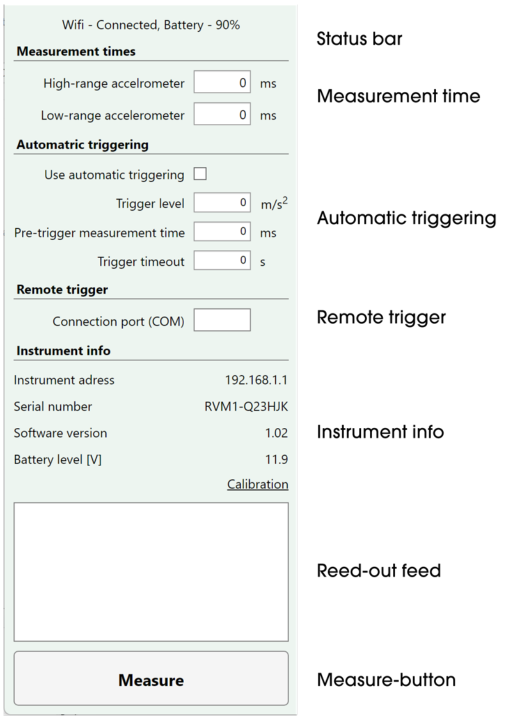


Figure 4.26. - The leftmost column - the setup pane

The middle column is for analysis of the measurements, see Figure 4.27. It contains two major elements, a set of two graphs and a set of two data fields. One graph shows acceleration-time axes and one shows acceleration-frequency axes. The graphs are separated by channel allowing the user to filter out only the channels they are interested in. In the data fields the most important values from the measurements are displayed, showing the RMS (root mean square), peak and VSI (vibration shock index) values. The pane also offers filtering of the data using mathematical filters, such as low-pass or ISO filtering.

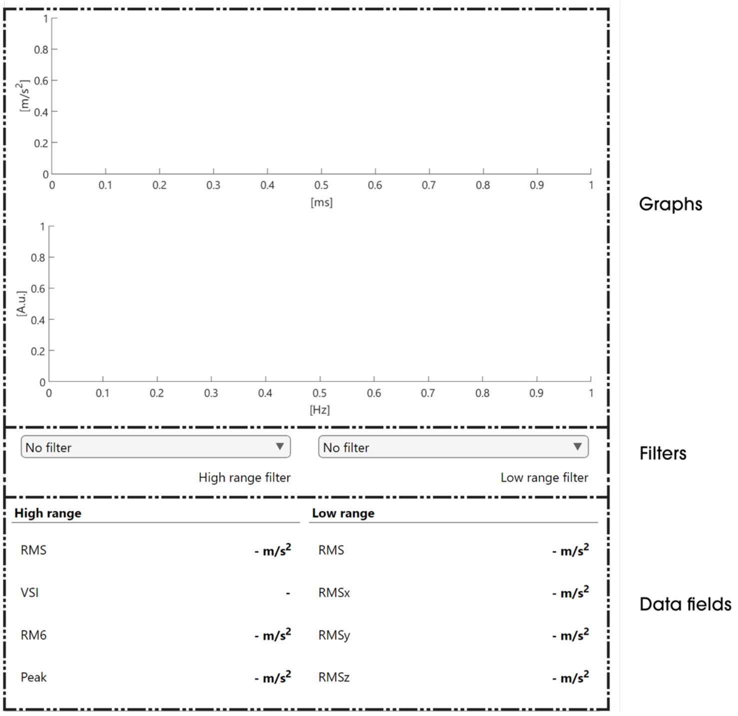


Figure 4.27. - The middle column - the data analysis pane

The right column contains tools for annotation of the data, see Figure 4.28. This makes it easier to analyze the data later since information about the context of the data is available. Without annotated data it is easy to forget valuable details about the measurement after some time has elapsed. It contains three fields for text input, the first one is for the name of the measured tool. The second is for the position of the sensor on the tool. The third is for general comments, where any other information about the measurement conditions, tool usage patterns and tool conditions can be written. This box also contains a button for attaching an image, which can be used to further describe the measurement.

At the bottom of the column the load, export and save buttons are located. The save button will save the data to a file which can then be opened in the software and the export button allows for exporting to common formats for data like .xlsx and .csv so that the data can be analyzed in other software like Excel. The load, export, and save buttons all open their own separate pop-ups, the load and save button will enter directly into the operating system save/open dialogue box. The export button will first open another popup where necessary settings about the output file can first be chosen, then the operating system save dialogue box will open.

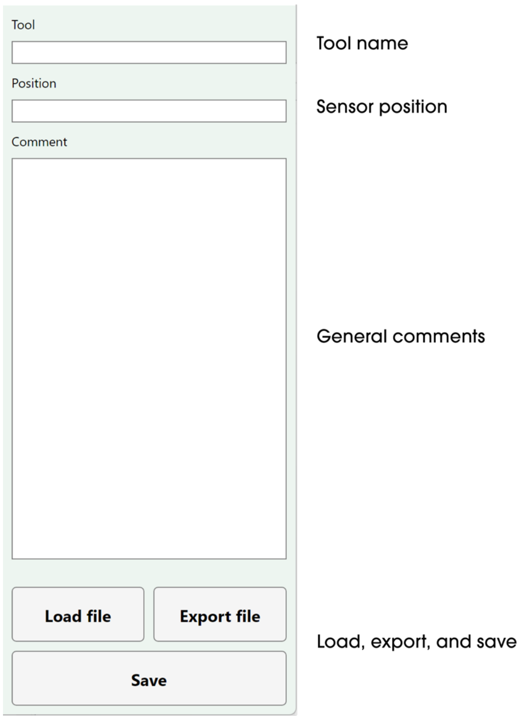


Figure 4.28. - The rightmost column - the annotation pane

To optimize the system for people with decreased color vision, the system does not use color coding except to differentiate the three different panes. The leftmost and rightmost pane both have light green backgrounds to make it easier to understand that there are in fact three distinct areas of the interface. Since the color is just used in two large blocks it does not matter what color they actually are to understand their meaning, this makes it usable for people with decreased color vision since it would provide the same function even if it is another color, or even gray. Light green was chosen instead of the light gray commonly seen in control system interfaces. This was done for two main reasons: Light green is also a color frequently used by RISE in their marketing material, making the interface feel connected to RISE in a subtle way. It is also a color which makes the interface a bit more fun and interesting to look at and gives the system a more modern look compared to the standard gray which can be associated with the 1990s.

The color provides good contrast to the black text making it easy to read, but is less straining for the eyes than an all-white background.

The interface is typeset in Segoe UI, the typeface was chosen mainly due to the fact that it is the standard typeface for text in Microsoft Windows, which will be the primary platform that the software is used on. This makes it consistent with the rest of the system and makes sure that the typeface will be installed and available on the computer used. There are three variants of the typeface used: 14pt regular for most text and labels, 14pt bold for headers, and 18pt bold for the four main buttons.

4.6.1. The content

The users of the interface are expected to be scientists and researchers who are experts in the field of vibration measurement. This means that they can be expected to have high demands on the performance of the tool. Optimizing the interface for guessability is therefore less important since operating the interface efficiently will be more important for the users.

The text inside the application is written to correspond with expected terminology regarding vibration measurements, and complemented with tool-tips that explain the functionality and meaning of interface elements or data-representations, see Figure 4.29.

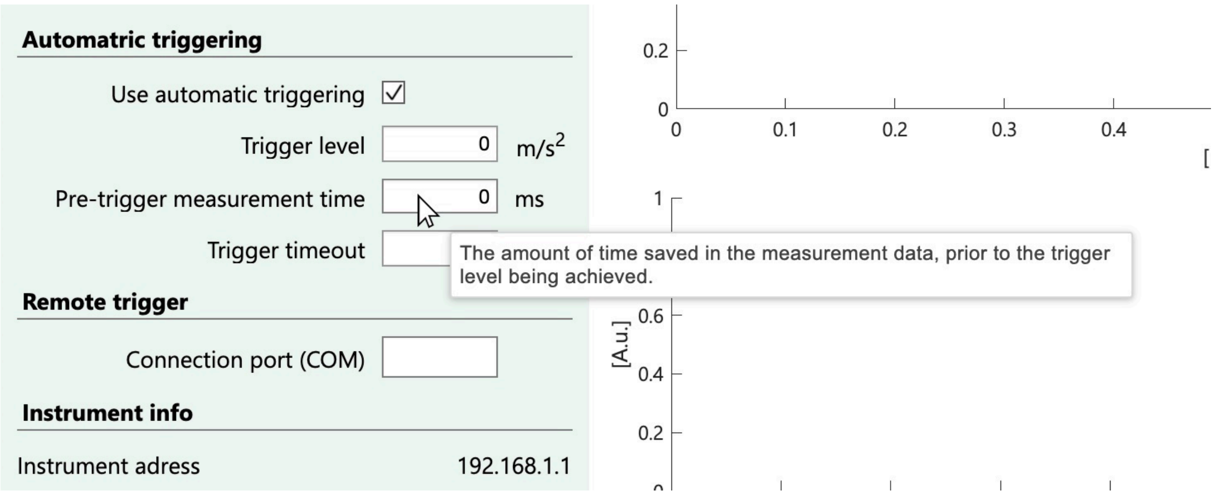


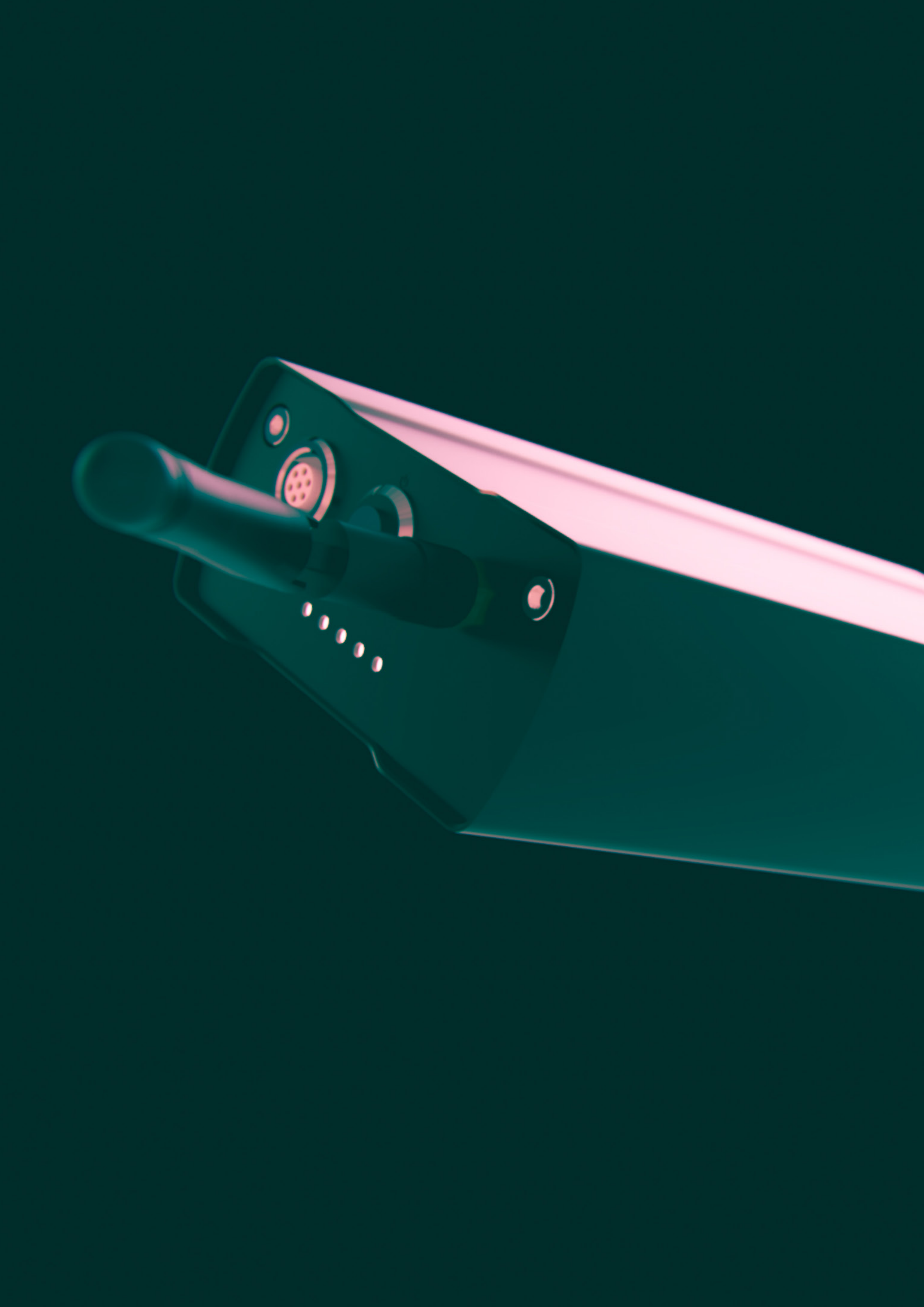
Figure 4.29. - Tool-tip explaining potentially unclear input field

To optimize the interface for speed, most options are shown at once. This might cause information overload in inexperienced users, but it enables faster operation of the instrument when the user has experience with the interface.

Figure 4.30. - Empty states explain what state the instrument is currently in.

In order to give feedback to the user without interrupting their flow within the application "empty states"[a] are shown in place of the graphs, see Figure 4.30. These occupy the middle column, when no graphs can be displayed. These provide feedback on what is happening with the instrument or show information on what input it expected from the user.

a Google. (n.d.-b).



5. DISCUSSION

In the following discussion ethical and sustainability aspects will be examined and justified. Then the process and its implications on the end result will be discussed. Some implementations and results of the methods will also be discussed as these provided interesting aspects to consider. Finally, the results will be discussed.

5.1. Ethics and sustainability

When evaluating the ethical aspects of a project there are two questions that need to be considered:

- What are the likely outcomes of the project? Will someone be affected by it, and if so, how?
- How will the project be carried out? Will someone be affected by the project itself, and if so, how?[a]

When using methods that require participation of people from outside the project, such as interviews or user testing, it is important to ensure that they are comfortable and safe during the entire process. There were minimal safety concerns since no hazardous elements were present in either the physical or digital design, and all evaluations were carried out in facilities where no actual industrial machinery was present. The most dangerous element was the test where users interacted with a drill, but this was strictly controlled and posed no real danger.

To ensure that the participants felt comfortable they were reassured that the subject for the tests were the designs and not the participants. This was done to ensure that the participants felt that they were not themselves being judged. The participants were also told at the beginning that they could at any time discontinue their participation in the test. Allowing the participants a quick way to exit the test allows them to feel more comfortable in that if they were to ever feel uncomfortable they can easily remove themselves from the uncomfortable situation.

5.1.1. Sustainability

The main environmental impacts from the project itself has been consumption plastic for 3D-printing. In total there were around 20 3D-printed prototypes made, each using a bit under 100 grams of plastic, therefore the total weight of plastic used is estimated around 2kg. The vast majority of the prints were made from Addnorth E-PLA, a plastic filament which is made from polylactic acid (PLA), a material that can be produced from renewable plant materials instead of petro-based plastics such as ABS[b]. PLA is also technically biodegradable, but the infrastructure needed is uncommon today[c]. PLA emits between 1.7 and 3.7 kgs of co2 equivalents for each kg of plastic produced, depending on how it is processed at its end of life[d]. This would give the 3D-printing and environmental impact of between 3.4 and 7.4 kgs of co2 equivalents. This is equivalent to about a tenth of a percent of the environmental impact of an average Swede in 2019[e] and could be seen as negligible under the circumstances.

The outcomes of the project are much harder to predict. There will be an increased environmental impact from the production of the instruments. The main factors affecting the environmental impact of the product are the aluminum in the enclosure, the plastic sled, and the electronics. The aluminum enclosure is CNC-machined from a piece of aluminum that is at least 80 x 30 x 160 mm, this gives it a volume of approximately 384 cm3. Aluminum has a density of 2.7g/cm3 which would make the raw material needed weigh around 1kg. Producing one kg of aluminum from the typical mix of virgin ore and recycled material emits between 8-9.5 kg of co2 equivalents[f]. The final weight of the enclosure is 250 grams, and thus 75% of the material needs to be machined away. Machining aluminum emits 0.115-0.127 kg of co2 equivalents per

a Axelsson (2018)
b add:north (n.d.)
c add:north (n.d.)
d Ansys (2021)
e Naturvårdsverket (n.d.)
f Ansys (2021)

kg of material removed, therefore the machining only stands for about 1% of the total emissions for the enclosure.

The sled is made from 3D-printed ABS plastic, due to the nature of 3D-printing the material usage will only be slightly higher than the final weight of the part, which is around 50 grams. Given that ABS of a typical grade has production emission of 3.4 - 3.8 kg of co2 equivalents per kg produced plastic[a], the raw material emissions for the sled will be around 200 grams of co2 equivalents.

The battery is a lithium-ion battery with a stated capacity of 7.4Wh. Typical co2 equivalent emissions for lithium-ion batteries are 19-50 kg/MJ[b]. 1 Wh is equal to 0.0036 MJ, and thus 7.4 Wh = 0.02664 MJ. This means that producing the battery emits between 0.5 - 1.3 kg of co2 equivalents. The electronics are much harder to predict accurately than the other parts since they themselves contain a myriad of different components and materials and the supplier provides no environmental data. Therefore, the electronics have been excluded since they cannot be analyzed and cannot be changed in this project.

The choice of aluminum for the exterior has by far the biggest impact on the environmental impact of producing the product. Choosing aluminum can however be justified by the fact that it is an extremely durable material which will last much longer than if it was to be made from, for example, ABS. Aluminum also provides a sense of luxury which is expected when buying an instrument in this price range. Another aspect which favors aluminum recyclability, aluminum can be recycled indefinitely and recycled aluminum only requires a fraction of the energy compared to virgin materials, about 4.5 to 5.7 times less[c]. The instrument will also only be manufactured in a very small batch size, between 10-100 units. This means that the environmental impact will be quite small compared to the benefit of learning more about, and preventing, vibration induced injuries.

The environmental impact of using the instrument is likely negligible in the context. The electricity used to power the BeagleBone is 5V at 2A = 10W. Power generation in the Nordic countries average around 50 grammes of co2 equivalents per kWh of electricity[d], this would mean that running the instrument emits around 0.5 grammes of co2 equivalents per hour. Perhaps the actions taken by companies to remedy the sources of vibration injuries might cause further environmental impact if new products need to be manufactured. But at the same time the need for healthcare might be reduced, and since healthcare is responsible for around one fourth of the greenhouse gas emissions from the public sector in Sweden[e],[f] there are large gains to be made even if only a minuscule part of the need could be lowered.

5.2. Process

One of the most interesting aspects of this project is that the client will in large part be the user of the instrument. This led to some interesting situations, for example, during meetings where they were acting as both clients and users. There was some initial confusion and in the beginning of the project they were not really recognized as users of the product, and were therefore interviewed as project owners instead. This led to some confusion and lost time in the beginning of the project but was identified and rectified rather quickly.

---

a Ansys (2021)
b Ansys (2021)
c Ansys (2021)
d Vattenfall (2020)
e Teghammar (2019)
f Wange (2019)

Another interesting characteristic of the project is that the deliverables would be at a high enough fidelity that RISE could with little or no additional work send the files to a contract manufacturer and get a finished product back. This meant that a lot of work needed to be done in the concept development phase of the project to reach a high enough level of maturity of the product, which necessitated some time saving measures in the earlier phases of the project. Concept refinement was planned to be the biggest phase of the project and grew even larger when the project was actually carried out. This large focus on concept refinement and handover meant that other parts were not conducted as thoroughly as might have been preferable, e.g. there are likely user needs that were glanced over or ideas that could have been further explored. This likely means that the final product does not meet all requirements that could have been found and solved if the earlier stages of the project had gotten more time, but the trade-off was seen as worth it since it allowed for a more developed final concept.

When performing the user research there was a major issue with finding the actual users of the product, there are only a few specialized scientists working with this kind of vibration measurement. To get a larger set of users to work with, the decision was made to also interview work environment engineers. They are not as specialized and in general have less knowledge. But they were seen as a good resource since they work with the current vibration measurement instruments and therefore are a good source of knowledge about what is important for a vibration measurement instrument to have good usability. Since a lot of the procedure for measuring regular vibrations is the same as when measuring UHFVs it is believed that a lot of the knowledge is applicable. But it would of course have been ideal to have a larger set of intended users.

5.2.1. Method implementation

During the course of the project a lot of different methods were used, a lot of these were implemented by the book, but some were deemed to work better with some slight modifications or in applications that they were not initially intended to. There are a few methods that had some more interesting aspects which will be discussed here.

Interviews

One interesting take away from the interviews is that the more knowledgeable interviewees were much more prone to digress from the question at hand. Some of them even started to talk about their experiences with measuring vibrations without any prompt at all in the beginning of the interview and talking until they felt that they had said most of what they were thinking about the subject. But even though these were the least organized, they were the interviews that gave the most insights. Whether this is due to them being more knowledgeable or the fact that they spoke more freely is hard to know.

All interviews were carried out through the videoconferencing service Microsoft Teams, this had both benefits and disadvantages. One major advantage was that it allowed for a much broader set of participants as it negated any geographical barriers which would have otherwise prohibited their participation in the study. It was also more time efficient as no travel was involved for neither the project team nor for the participants. However it becomes much harder to hold a natural conversation as it does not show body language in the same way as an in-person conversation and also becomes much more stilted since it is harder to pace when to speak due to the slight delay that is created.

Moodboards as mediating objects

In the interview studies with vibration measurement professionals, moodboards were used as a mediating object. As work environment engineers were judged to straddle the boundaries between 'blue collar work', 'engineering' and 'medical' it was deemed relevant to understand their attitude towards the product identities of the tools of each field. They were therefore shown three moodboards with objects and environments associated with the three fields and asked to talk about how they would want their vibration measurement instrument to look in relation to these. The usage of the moodboard as a mediating object in the pre-study phase yielded varying results, the participants understood the instructions in different ways. There was an introduction to moodboards and their usage which was read by the interviewer before the moodboards were shown but it was not sufficient to avoid all confusion. Several interviewees initially thought that the aim was to find a finished concept for the measurement instrument among the pictures and since the moodboards were the last part of the interview, there was not always time to do it correctly. However, even though there were some misunderstandings about the method, the discussions generated by the moodboards proved to be fruitful nonetheless as many interesting thoughts and ideas were introduced in this stage.

5.3. Results

The fact that the company had already begun developing the product imposed some constraints on what ideas could feasibly be created. This was mainly due to the fact that the internal electronics were already finished and making any major changes to them would be very labor intensive and therefore costly. The electronics enforced a minimum size that the product needed to be since it needed to fit both the electronics and a battery inside. Since the production run would be limited to only a small number of units the electronics were based around a BeagleBone Black which is a low cost development platform. The BeagleBone is outfitted with a custom made *cape* which is which is an add-on board which provides extra functionality[a], in this case to interact with the sensors and battery. The BeagleBone and the cape is a fast and easy way to develop electronics, but is not very space efficient. This means that the internal volume occupied by electronics is relatively large, which in term makes the outside dimensions of the instrument larger than what might be preferred.

When exploring different solutions during the ideation phase, there were a lot of concepts which incorporated screens as well as more advanced input methods. These more advanced ways for the user to interact with the instrument could have advantages for the user, but would require significantly more work to be implemented and was therefore not seen as feasible in this project, but could be worth further investigating in the future.

Because RISE is not a product centered company and is instead a research focused institute, they do not produce products with the same goals as other companies. For the client, the success of the instrument is not measured in how many units they can sell and how much revenue each unit generates, instead the important goal is for the instrument to provide valuable measurements for its users to be able to work on new standards and regulations. Because of this the constraints on the instrument are not concerned with high unit costs as the profitability is not in focus. However, because of the low batch size, methods using any kind of tooling, like molds or extrusion dies would be too expensive. The leniency for high unit costs is twofold, as the instrument is novel it can have a high price, but more importantly the quality of the instrument is of utmost importance. The instrument is on the cutting-edge in its field and needs to convey that to its customers, not succeeding doing that could damage the perception of both the instrument and the client.

In the semantic evaluation, the product was experienced as somewhat less medical than initially hoped. This is probably an effect of both the form language expressing strong and reinforced shapes as well as the color being dark, something which is not very common in medical devices. A white version of the device would be more medical but due to the large size

a BeagleBoard.org Foundation (2021)

of white pigment it is impossible to make white anodized aluminum[a], other methods such as acid-etching could be used, but do not create pure white colors. Making the device in a silver-colored anodized aluminum could be an option, however the risk of this device looking dirty is higher, so this would make the device only appropriate in the medical setting. Another option could be opting to manufacture a ‘medical-only’ variant in white plastic, but this would require further investigation into manufacturing. An advantage of this variant would be that the external antenna could be removed, as the plastic would not block the wifi-signal.

a Mojica (2011).

6. CONCLUSION

To conclude, the project has managed to achieve the goal of creating a basis for production for the measurement instrument. The companion interface has also been finished into a state ready to guide the development. The carrying bag for the instrument will allow for easy attachment of the instrument to operators of tools and allow the researcher to operate the instrument from a safe distance.

6.1. Research questions

Connecting back to the research questions, in short:

What is the current state of contemporary vibration measurement equipment?

It's not currently possible to measure UHFVs in the field.

How are vibration measurements performed by professionals in laboratories and in the field and what are the needs present when performing vibration measurements?

Vibration measurements in the field are generally performed under some time pressure and the tool the measurement is conducted on is operated by an operator. In the field there can be hazardous situations which makes it important for the measurement professional to be able to keep a safe distance. In the lab, the measurement professional is often alone which makes it important to be able to operate the instrument while operating heavy machinery with both hands.

How will the possibility to measure UHFVs affect the users' demands on the measurement instrument and the companion software interface?

The possibility to measure UHFVs will have effect on the users' demands, namely that currently a lot more data need to be displayed as there are no rigid standards as of yet to relate to. A secondary effect is that measurements of UHFVs can be done in new contexts, e.g. medical, which creates greater demand for the instrument to be clinically viable.

How should a measurement instrument and its companion software interface be designed in order to fulfill the users' needs?

The demands from field measurements result in the instrument being wireless and to be attachable to the operator of a tool - to allow for measurements from safe distances, being waterproofed and in rugged and thick aluminum - to withstand the harsh environment of a work site, and being relatively easy to clean - to allow for sterilization for use in medical contexts. It also needs to allow for some sort of remote triggering to be usable when alone.

6.2. Recommendations

For the measurement instrument the recommendation is to produce a prototype based on the results from the project to ensure the fit of the components before conducting a full production run.

To develop the interface the MATLAB-mockup could potentially be used as a new front end to the existing program, with some adjustments to the back end to support the added functionality. In case this is not possible development could be guided by its layout and functionality.

Production of the carrying bag can be done by using the existing prototype as a blueprint for new bags, when communicating with contract manufacturers.

The recommendation for the remote trigger is that further work is needed. The idea of having a remote trigger to enable unaccompanied measurements is sound, however the development of such a device using existing electronics, such as the board from a Bluetooth mouse, and encasing it in a new shell has some issues. Firstly this creates the need to re-solder many buttons on the mouse to allow for Bluetooth pairing and setting power states as well as re-soldering a button for the triggering action. Secondly the material of the new shell must be plastic, as an aluminum shell would block the Bluetooth signal. However a plastic shell could prove not sufficiently durable. This makes the creation of a bespoke trigger not viable in its current design, as it will be more expensive than the mouse which components it houses without providing benefits outweighing the costs. Therefore the recommendation is to allow for the functionality of remote triggering in the software, but not include such a device in the package. This allows the customer to remotely trigger, without having to include a costly and potentially fragile design. An alternative could be sourcing a Bluetooth operated foot pedal from a third party, but this is not a product category with a great selection. A final option which could allow for single person measurements could be making a countdown option in the interface, so that the person measuring could start a countdown to when the device will start measuring, allowing them time to operate the tool.

If the batch size was to increase in the, future it would be beneficial to investigate if the electronics could be made smaller. It would likely be able to fit all the components from the BeagleBone Black as well as the cape on a single board. This would allow the whole instrument to be made smaller which would make it easier to fit in pockets and carry around. The decreased size would also lead to a lower environmental impact due to the lowered amount of aluminum needed for the electronics housing, as well as a reduced weight for the use.

SOURCES

add:north. (n.d.). *Sustainability*. Retrieved May 17, 2022, from https://addnorth.com/sustainability

Afa försäkringar. (2020). *Allvarliga arbetsskador och långvarig sjukfrånvaro* (p. 61). https://www.afaforsakring.se/globalassets/forebyggande/analys-och-statistik/arbetsskaderapporten/arbetsskaderapporten-2020/f7060_arbetsskaderapport_2020.pdf

Ansys (2021). *Granta EduPack* (Version 21.2.0) [Computer software]. https://www.ansys.com/products/materials/granta-edupack

Arbetsmiljöverket. (n.d.). *About us*. Arbetsmiljöverket. Retrieved April 12, 2022, from https://www.av.se/en/about-us/

Axelsson, M. (2018). Ethics for engineers Swe 1. In CHALMERS Play. https://play.chalmers.se/media/Ethics+for+engineers+Swe+1/0_2qev1eqx/

Balachandran, B., & Magrab, E. B. (2004). 5.6 Acceleration Measurement: Accelerometer. In *Vibrations*. Brooks/Cole.

BeagleBoard.org Foundation. (2021). *BeagleBoard.org® Capes*. Https://Beagleboard.Org. Retrieved May 17, 2022, from https://beagleboard.org/capes

Bridger, R. (2003a). *Introduction to Ergonomics, Second Edition* (2nd ed. pp 58). CRC Press.

Bridger, R. (2003b). *Introduction to Ergonomics, Second Edition* (2nd ed. pp 60). CRC Press.

Bridger, R. (2003c). *Introduction to Ergonomics, Second Edition* (2nd ed. pp 72). CRC Press.

Canadian Centre for Occupational Health and Safety. (n.d.). *Vibration*. Health Effects : OSH Answers. Retrieved April 14, 2022, from https://www.ccohs.ca/oshanswers/phys_agents/vibration/vibration_effects.html

Coggins, M. A., Van Lente, E., Mccallig, M., Paddan, G., & Moore, K. (2010). Evaluation of hand-arm and whole-body vibrations in construction and property management. Annals of occupational hygiene, 54(8), 904-914.

Cross, N. (1995a). *Engineering Design Methods*. (pp. 19-20). Wiley.

Cross, N. (1995b). *Engineering Design Methods*. (pp. 29). Wiley.

Design Council. (n.d.). *What is the framework for innovation? Design Council's evolved Double Diamond*. Retrieved May 17, 2022, from https://www.designcouncil.org.uk/news-opinion/what-framework-innovation-design-councils-evolved-double-diamond

Dillon Dahleh, M., Thomson, W. T. (2002a). Vibration, Mechanical. In R. A. Meyers (Ed.), *Encyclopedia Of Physical Science And Technology, Third Edition* (Vol. 17, pp. 455). Academic Press

Dillon Dahleh, M., Thomson, W. T. (2002b). Vibration, Mechanical. In R. A. Meyers (Ed.), *Encyclopedia Of Physical Science And Technology, Third Edition* (Vol. 17, pp. 461). Academic Press

European Agency for Safety and Health at Work. (n.d.). *Directive 2002/44/EC - Vibration*. Safety and Health at Work EU-OSHA. Retrieved April 12, 2022, from https://osha.europa.eu/en/legislation/directives/19

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology, 47*(6), 381.

Gerhardsson, L., Ahlstrand, C., Ersson, P., & Gustafsson, E. (2020). Vibration-induced injuries in workers exposed to transient and high frequency vibrations. Journal of Occupational Medicine and Toxicology, 15(1), 1-9.

Grahn, R., & Jansson, P. Å. (2002). Mekanik.

Hanington, B., & Martin, B. (2012). 49 KJ Technique. In Universal methods of Design: 100 Ways to Research Complex Problems, Develop Innovative Ideas, and Design Effective Solutions (pp. 104-105). Rockport publishers.

Hanson, L., Sperling, L., Gard, G., Ipsen, S., & Vergara, C. O. (2009). Swedish anthropometrics for product and workplace design. *Applied ergonomics, 40*(4), 797-806.

Hunter, T. (2021). Dental handpieces: Maintenance, repair, and infection control, 3rd edition. Dental Economics, 111(2), 54.

Hutchings, I., & Shipway, P. (2017). *Tribology: friction and wear of engineering materials*. Butterworth-Heinemann.

Google. (n.d.-a). Crazy 8s. Design Sprint Kit. Retrieved April 14, 2022, from https://designsprintkit.withgoogle.com/methodology/phase3-sketch/crazy-8s

Google. (n.d.-b). *Empty States.* Material Design. Retrieved May 9, 2022, from https://material.io/design/communication/empty-states.html

Govindaraju, S. R., Curry, B. D., Bain, J. L., & Riley, D. A. (2008). Nerve damage occurs at a wide range of vibration frequencies. *International Journal of Industrial Ergonomics*, *38*(9-10), 687-692.

Interaction Design Foundation. (n.d.). *Fitts' Law*. The Interaction Design Foundation. Retrieved May 16, 2022, from https://www.interaction-design.org/literature/topics/fitts-law

International Ergonomics Association. (n.d.). *What Is Ergonomics?* Retrieved May 16, 2022, from https://iea.cc/what-is-ergonomics/

International Organization for Standardisation. (2001). *Mechanical vibration — Measurement and evaluation of human exposure to hand-transmitted vibration — Part 1: General requirements.* (ISO Standard No. 5349-1:2001). https://www.iso.org/standard/32355.html

Jordan, P. W. (1998). *An Introduction To Usability* (1st ed. pp 25-38). CRC Press.

Jänsch, J., & Birkhofer, H. (2006). The development of the guideline VDI 2221-the change of direction. In *DS 36: Proceedings DESIGN 2006, the 9th International Design Conference, Dubrovnik, Croatia.*

Johannesson, H., Persson J-G. & Pettersson D. (2004a). Brainstorming. *Produktutveckling - effektiva metoder för konstruktion och design.* (pp. 425-426). Liber.

Johannesson, H., Persson J-G. & Pettersson D. (2004b). 4.3.6 Prototyper. *Produktutveckling - effektiva metoder för konstruktion och design.* (pp. 99-100). Liber.

MacKenzie, I. S., Sellen, A., & Buxton, W. A. (1991). A comparison of input devices in element pointing and dragging tasks. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 161-166).

McAtamney, L., & Corlett, N. (2004). Rapid upper limb assessment (RULA). In *Handbook of human factors and ergonomics methods* (pp. 86-96). CRC Press.

Mojica, R. (2011). *Why is there no white anodized aluminum? (Anodized Aluminum 101)*. Blue Buddha Boutique. Retrieved May 18, 2022, from https://www.bluebuddhaboutique.com/blog/2011/09/no-white-anodized-aluminum/

Monö, R. (1997). *Design for Product Understanding:The aesthetics of design from a semiotic approach* (pp. 66-113). Liber.

National Heart, Lung, and Blood Institute. (n.d.). Vasculitis - What is vasculitis? NHLBI, NIH. Retrieved April 14, 2022, from https://www.nhlbi.nih.gov/health/vasculitis

Naturvårdsverket. (n.d.). *Konsumtionsbaserade växthusgasutsläpp per person och år*. Retrieved May 17, 2022, from https://www.naturvardsverket.se/data-och-statistik/konsumtion/vaxthusgaser-konsumtionsbaserade-utslapp-per-person

Nielsen, J. (1994a). *Usability Engineering*(pp 17). Elsevier Gezondheidszorg.

Nielsen, J. (1994b). *Usability Engineering*(p p 26-37). Elsevier Gezondheidszorg.

Occupational Safety and Health Administration. (n.d.). *Ergonomics - Solutions to Control Hazards*. U.S. DEPARTMENT OF LABOR. Retrieved May 16, 2022, from https://www.osha.gov/ergonomics/control-hazards

Pahl, G. & Beitz, W. (1995a). *Engineering Design: A Systematic Approach*(2nd ed., pp 61-70). Springer.

Pahl, G. & Beitz, W. (1995b). *Engineering Design: A Systematic Approach*(2nd ed., pp 64). Springer.

Research Institutes of Sweden. (2020, July 6). Vanligaste arbetssjukdomen kan förebyggas. RISE. https://www.ri.se/sv/berattelser/most-common-occupational-injury-preventable

Roozenburg, N. F. M., & Eekels, J. (1995). *Product Design: Fundamentals and Methods (Product Development: Planning, Design, Engineering)*(pp 87-93). Wiley.

Rytkönen, E., Sorainen, E., Leino-Arjas, P., & Solovieva, S. (2006). Hand-arm vibration exposure of dentists. International archives of occupational and environmental health, 79(6), 521–527. https://doi.org/10.1007/s00420-005-0079-y

Svenska institutet för standarder. (n.d.). *Standard - Vibration och stöt - Mätning och bedömning av vibrationer som överförs till handen - Del 1: Allmänna riktlinjer (ISO 5349-1:2001) SS-EN ISO 5349-1*. Svenska Institutet För Standarder, SIS. Retrieved April 12, 2022, from https://www.sis.se/produkter/miljo-och-halsoskydd-sakerhet/vibration-med-avseende-pa-manniskor/sseniso53491/

Teghammar, A. (2019). Hälso- och sjukvården påverkar klimatet. Läkartidningen. https://lakartidningen.se/klinik-och-vetenskap-1/artiklar-1/temaartikel/2019/02/halso-och-sjukvarden-paverkar-klimatet/

Ullman, D. G. (1997). *The Mechanical Design Process* (2nd ed., pp 60-68). Mcgraw-Hill College.

Unger, R., & Chandler, C. (2012). *A Project Guide to UX Design: For user experience designers in the field or in the making (Voices That Matter)* (2nd ed., pp 186-214). New Riders.

Vattenfall. (2020). *EPD ger förutsättning för klimatneutralitet*. Energy Plaza. Retrieved May 17, 2022, from https://energyplaza.vattenfall.se/blogg/epd-ger-forutsattning-for-klimatneutralitet

Wange, E. (2019). *Sjukvårdens påverkan på miljön och klimatet är stor*. Sjukhusläkaren. https://www.sjukhuslakaren.se/foreningsnyheter/sjukvardens-paverkan-pa-miljon-och-klimatet-ar-stor/

Wigley, F. M., & Flavahan, N. A. (2016). Raynaud's phenomenon. *New England Journal of Medicine*, *375*(6), 556-565.

Wikberg Nilsson, Å., Ericson, Å. & Törlind P. (2016a). Braindrawing. In *Design: Process och metod.* (pp. 128-129). Studentlitteratur.

Wikberg Nilsson, Å., Ericson, Å. & Törlind P. (2016b). Brainstorming. In *Design: Process och metod.* (pp. 124-125). Studentlitteratur.

Wikberg Nilsson, Å., Ericson, Å. & Törlind P. (2016c). Braindrawing. In *Design: Process och metod.* (pp. 128-129). Studentlitteratur.

Zimmerman, J. J., Bain, J. L., Wu, C., Lindell, H., Grétarsson, S. L., & Riley, D. A. (2020). Riveting hammer vibration damages mechanosensory nerve endings. *Journal of the Peripheral Nervous System*, *25*(3), 279-287.

Österlin, Ö. (2003a). Moodboards. In *Design i fokus för produktutveckling*. (pp.48). Liber Ekonomi

Österlin, Ö. (2003b). Kravspecifikation. In *Design i fokus för produktutveckling*. (pp.43). Liber Ekonomi.

Österlin, Ö. (2003c). Brainstormingmedtoder. In *Design i fokus för produktutveckling*. (pp.45-50). Liber Ekonomi

FIGURES

Chapter covers (in order of appearance):

Burns, C. (2017). *In the line of fire*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/8KfCR12oeUM

Brunner, B. (2021b). *Person using impact wrench*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/_kvdYDxvnCo

Smyth, D. (n.d.). *Vertical Steel Milling With Splashes*. Pexels. Retrieved May 30, 2022, from https://www.pexels.com/photo/vertical-steel-milling-with-splashes-8865188/

Beech, J. (2020). *Metal work*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/tXJhAFVOHVk

Högberg J. S., Edholm T. (2022). *Burrito*. Own Work.

Carsience, M. (2019). *Fireworks transformed through experimental techniques*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/txThZOwDrCs

Figure 2.2 - Cars:

Migl, A. (2021). *File:Volkswagen Golf VIII IMG 3829.jpg*. Wikimedia Commons. Retrieved May 30, 2022, from https://commons.wikimedia.org/wiki/File:Volkswagen_Golf_VIII_IMG_3829.jpg

Vauxford. (2018). *File:2018 Mini Countryman Cooper S 2.0 Front.jpg*. Wikimedia Commons. Retrieved May 30, 2022, from https://commons.wikimedia.org/wiki/File:2018_Mini_Countryman_Cooper_S_2.0_Front.jpg

Figure 3.2 - Moodboard industrial:

Suwandi, R. (2019). *yellow Dewalt hand drills on table*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/wDC-SOW6AcM

Pearce, S. (2018). *green Makita cordless drill near angle grinder*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/WRgKwttuP7A

Eliason, K. (2018). *selective focus photography of mechanics tool lot*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/60krlMMeWxU

Brunner, B. (2021a). *Person using impact wrench*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/K3cjUOMmMhc

Willquezada. (n.d.). *Electric instrument for electrical measurements in workshop*. Pexels. Retrieved May 30, 2022, from https://www.pexels.com/photo/electric-instrument-for-electrical-measurements-in-workshop-4398314/

Figure 3.2 - Moodboard technology:

Cottonbro. (n.d.). *Oscilloscope*. Pexels. Retrieved May 30, 2022, from https://www.pexels.com/photo/white-and-black-digital-device-7858288/

Kvistholt, K. (2017). *Rackmounted server*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/oZPwn40zCK4

Kwok, C. (2017). *Grey industrial equipment*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/mhUsz2ezlXQ

ThisisEngineering RAEng. (2020). *Female electronics engineer tests vehicle software with team*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/WjOWazUPAss

Testalize.me. (2020). *Samples processing in lab*. Transport to analyzer. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/9xHsWmh3m_4

Figure 3.2 - Moodboard medical:

Charlesdeluvio, C. (2019). *Doctor's office*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/2is2GQovngg

Andrews, S. (2021). *Heart rate monitor*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/7P1KdY9wZjA

Graphics, M. (2021). *Clean medical inhaler in hand on white background*. Unsplash. Retrieved May 30, 2022, from https://unsplash.com/photos/2WlwSXFw7Kk

Czerwinski, P. (2018). *Photo of a microscope*. Unsplash. https://unsplash.com/photos/JdtUKqGdqw8

Danilyuk, P. (n.d.). *Medical Equipment with Samples in Close Up View*. Pexels. Retrieved May 30, 2022, from https://www.pexels.com/photo/medical-equipment-with-samples-in-close-up-view-8442031/

APPENDIX 1 - INTERVIEW TEMPLATE

Hej,

Tack så mycket för att vi får intervjua dig om det här. Jag är XX, och det här är min kollega YY som kommer att anteckna intervjun. Vi gör vårt exjobb tillsammans med RISE, dom har utvecklat ett chip för att mäta ultrahögfrekventa transienta vibrationer och vi ska hjälpa dom med att utveckla det som användarna kommer i kontakt med, så hölje och digitalt gränssnitt. Vi har därför en del frågor om hur man jobbar med vibrationsmätningar.

Är det okej om vi spelar det här, vi kommer enbart använda det ifall vi missar att anteckna något?

1. Varför mäter du vibrationer i ditt jobb?

2. Vad gör att du bestämmer dig för att göra en vibrationsmätning?

3. Vad är din process för att göra en mätning (i dagsläget)?

4. Vilka faktorer väger du in när du gör en mätning? (tex tid, ergonomi, utfall, stressigt)

5. Hur lång tid mäter du på en dag? Hur lång batteritid har dina mätinstrument?

6. Har du någonsin känt att du haft behov av att mäta transienta vibrationer? (Alltså såna vibrationer som pågår i korta impulser. (t.ex. Som slagen i en muttersknackare)) Hur tolkar du resultat från sådana mätningar?

7. Har du någonsin känt att du haft behov av att mäta ultrahögfrekventa vibrationer (över 1250Hz från ISO5349) Har du gjort det & hur tolkar du resultat från sådana mätningar?

8. Var tittar du i nuläget på din mätdata? Använder du skärm på enheten, har du någon applikation på dator eller mobil? Vad avgör var du kollar på din data?

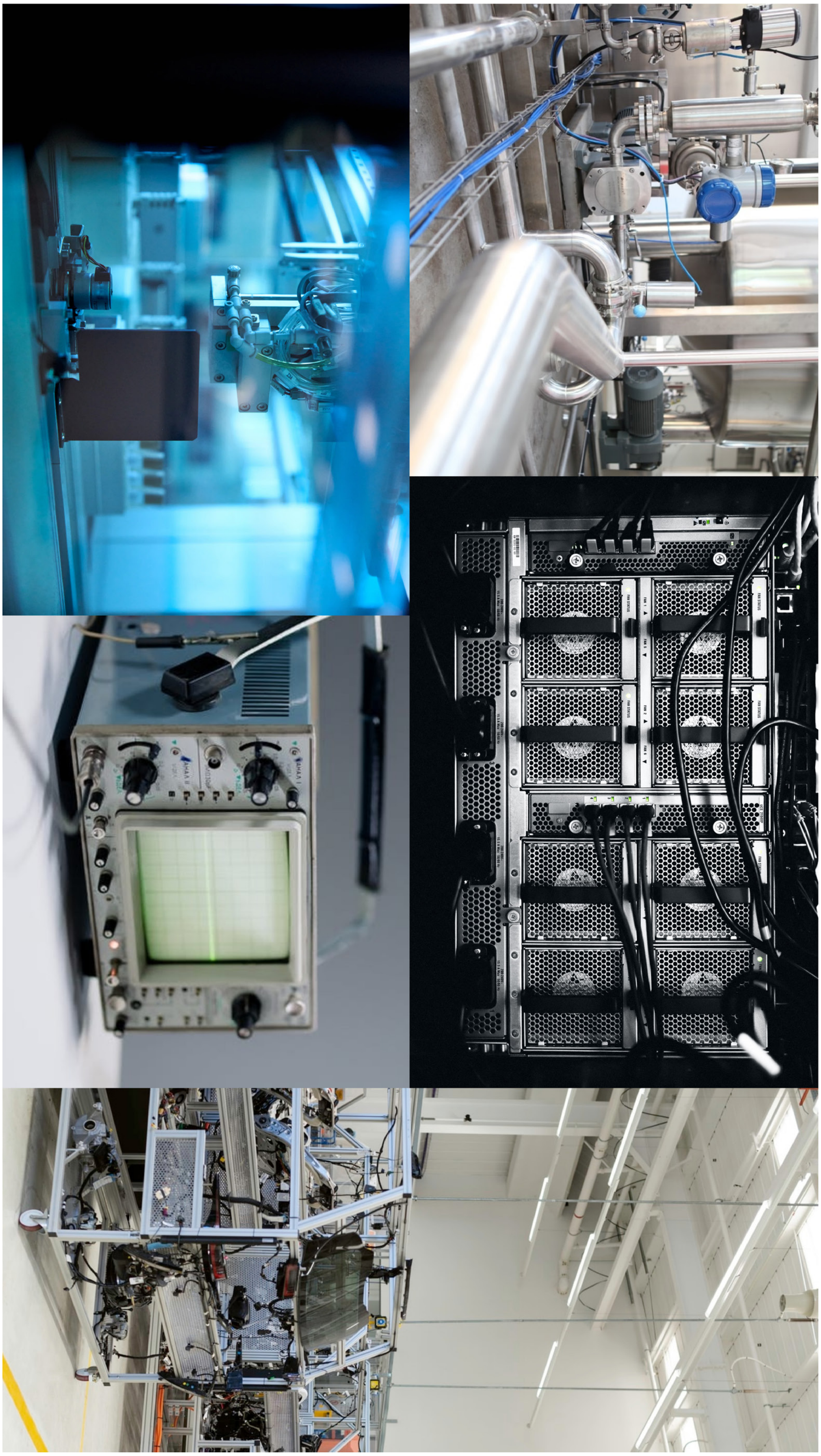
9. Hur analyserar du din mätdata? Går du bara på RMS-värden eller analyserar du också kurvor eller data på andra sätt? Använder du arbetsmiljöverkets poängsystem?

10. Vad tror du folk (lekmanna-mätare t.ex. vi två) gör fel på när de mäter vibrationer?

11. Moodboards: Vi ska ju designa ett nytt verktyg för vibrationsmätningar och funderar därför på vad du som arbetsmiljöingenjör tycker om rent visuellt. Vi kommer därför visa tre kollage som är tänkta att representera instrumentets framtoning. Det är då alltså inte mätinstrument på bilderna utan mer situationen och uttrycken från bilderna. Så vi vill veta vilka kollage du gillar och gärna varför och även vad du gillar i dem.

12. Är det något du tycker vi har missat?

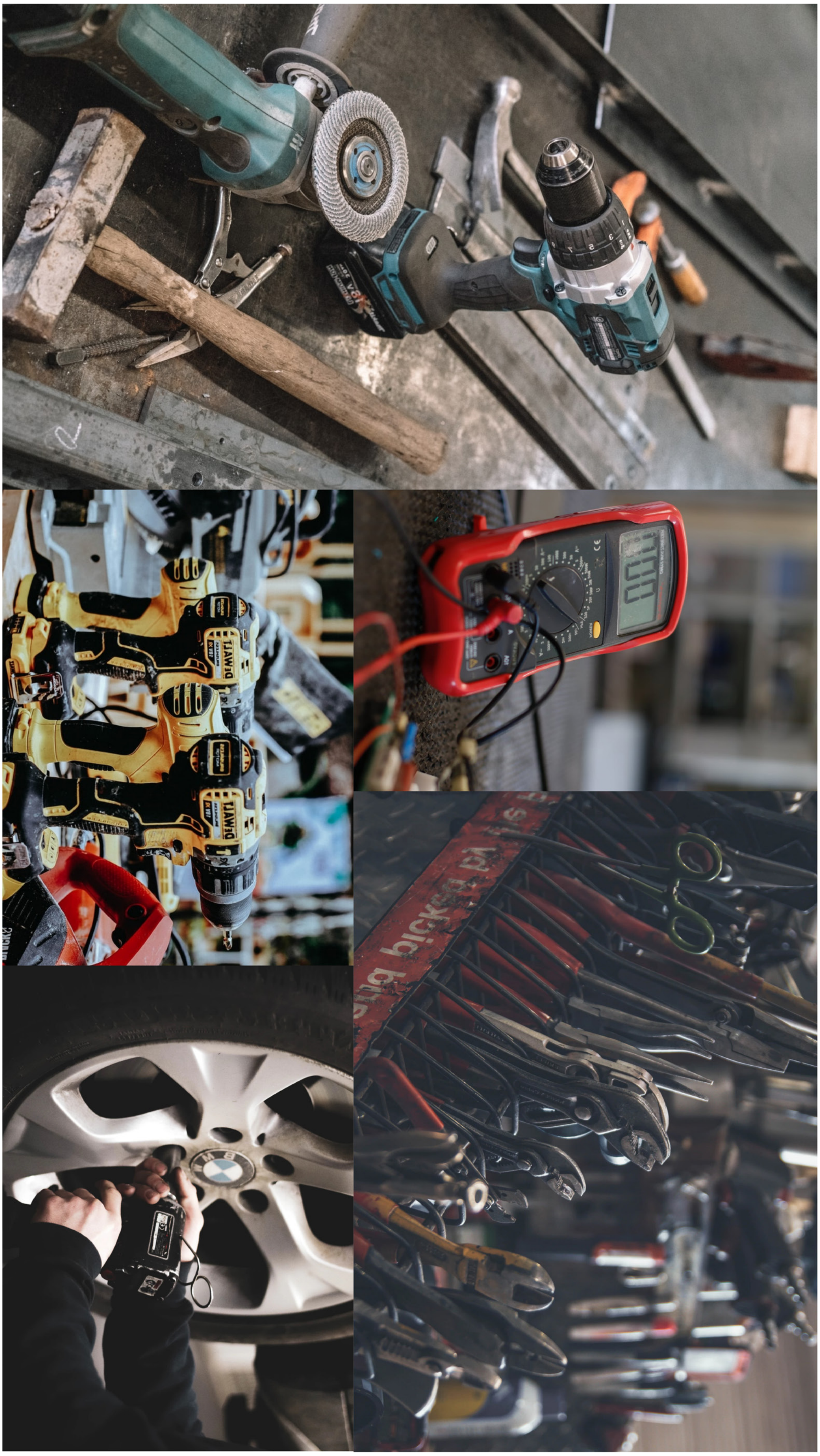
APPENDIX 2 - MOODBOARDS




Type something


Type something


139
10
78



APPENDIX 3 - TREE OF FUNCTIONS

APPENDIX 4 - DESIGN SPECIFICATION

RISE	Dokumenttyp	Designspecifikation
	Projekt	RVM10
Utfärdare: *T. Edholm, J. S. Högberg*		*Skapad:* 2022-02-22 *Modifierad:* 2022-02-25

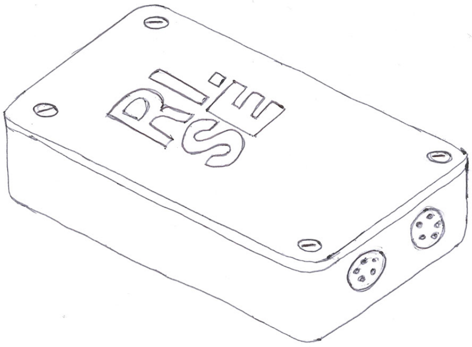
	Kriterier	*Målvärde*	*K/Ö*	*Vikt*	*Verifieringsmetod*	*Referens (kravställare)*
0.	**Funktion**					
0.1	Erbjuda registrering av vibrationer		K			
1.	**Prestanda**					
1.1	Mätfrekvens	> 50 kHz i en riktning	K		Specifikation & Test	RISE
	50 kHz fångar upp nästan alla högfrekventa vibrationer					
1.2	Mätfrekvens för ISO5349	I fleraxligt	Ö	3	Specifikation	RISE
1.3	Batteritid	> 12 h	Ö	4	Beräkning	Anvädarkrav
	Användare vill hinna göra så många mätningar som möjligt under en arbetsdag					
1.4	Använda extern strömkälla		Ö	1	Specifikation	Användarkrav
	Ifall man vill mäta extremt långa tider eller glömt att ladda batterierna och inte hinner					
1.5	Ha wifi		K		Specifikation	RISE
1.6	Ha bra wifi-räckvidd	> 25 m	Ö	3	Specifikation & test	Användarkrav
	Bra att den som mäter kan stå en bit ifrån och fånga upp datan					
1.7	Mäta kontinuerligt	1 min - 8 h	Ö	3	Specifikation	Användarkrav
1.8	Mäta vid två platser		Ö	2	Specifikation	Användarkrav
	Bra att kunna mäta på båda ställen där operatören håller					
2.	**Miljö**					
2.1	Gå att reparera	Se 4. Underhåll				
2.2	Gå att återvinna	Gå att plocka isär för återvinning	Ö	3	Specifikation & CAD	Miljö
2.3	Ha acceptabel livslängd	Se. 3. Livslängd				
3.	**Livslängd**					
3.1	Livslängd	10 år	Ö	3		SIS Standard XXX
3.2	Gå att reparera	Se 4. Underhåll				
3.3	Tåla normal användning	Se. 11. Material				
4.	**Underhåll**					
4.1	Öppningsbart hölje	≤ 5 min för att öppna hölje	K		CAD & Test	Produktplanering
4.2	Behållbar Hi-range sensor		Ö	2	CAD	RISE
	Att separera Hi-range accelerometer från restrerande elekronik på sensorkortet är önskvärt					
4.3	Utbytbar kabel	Se 22. Kabel				
5.	**Tillverkningskostnad**					
5.1	Rimlig kostnad	< 2500 kr / enhet för allt utöver elektronik	Ö	2	Simulering & CAD	RISE
	Elektroniken är det dyra, men bra om resten inte är orimligt dyrt heller					
6.	**Paketering**					
6.1	Förvarings- och fraktetui	Skydda systemet från slag under transport	Ö	3	CAD-modell	Användarkrav
6.2	Maxstorlek	BxDxH: 200 x 400 x 120 mm	Ö	1	CAD-modell	Användarkrav
7.	**Tillverkningsanläggning**					
7.1	Produktionsvolym	10-100 enheter/år	K		Simulering	RISE
	Ska gå att tillverka med processer som är rimliga för små serier, t.ex. kanske formsprutning inte passar					
8.	**Storlek**					
8.1	Maxstorlek	BxHxT 100 x 200 x 120 mm (bredd höjd tjocklek)	K		CAD-modell	Ergonomikrav
8.2	Önskad storlek	BxHxT 60 x 150 x 35 mm	Ö	4	CAD-modell	Ergonomikrav
9.	**Vikt**					
9.1	Maxvikt	< 500 g	K		Beräkning mha CAD-modell	Ergonomikrav
	Något mer än en medelstor inbunden bok (BeagleBone väger 40 g själv)					
9.2	Önskad vikt	< 250 g	Ö	3	Beräkning mha CAD-modell	Ergonomikrav
	Strax över vikten på en något större mobiltelefon					
9.3	Önskad minsta vikt	> 200 g (beroende på ytfriktion)	Ö	3	Beräkning mha CAD-modell	Användarkrav
	Viktigt att den inte glider med om det rycks i enheten					
10.	**Estetik och ytfinish**					
10.1	Ha slät form	Inte ha skrymslen < 5 mm (gå att rengöra med t.ex. tops)	K		CAD-modell	Användarkrav
	Vara lätt att rengöra för mätningar i ren miljö					
10.2	Uttrycka Klinisk precision		Ö	5	Semantisk ordskala	Användarkrav
10.3	Uttrycka Industriell tålighet		Ö	1	Semantisk ordskala	Användarkrav
10.4	Friktionsbelag		Ö	3	Materialdata	Användarkrav
	Viktigt att den inte glider med om det rycks i enheten					
11.	**Material**					
11.1	Tåla vanliga rengöringsmedel		K		Materialdata	Användarkrav
	Vara lätt att rengöra för mätningar i ren miljö; fotogen, laknafta & t-sprit					
11.2	Tåla vanliga kemikalier		Ö	4	Materialdata	Användarkrav
	I verkstadsmiljöer finns ofta oljor eller andra kemikalier					
11.3	Tåla stötar och slag	Se 14. Kvalitet och Tillförlitlighet				
11.4	Tåla gniststänk	Se 14. Kvalitet och tillförlitlighet				
11.5	Tåla UV-ljus	Tåla motsvarande 1 års exponering i soljus	Ö	4	Materialdata	Användarkrav
11.6	Tåla kyla och värme	Användningstemp. -20° < x < 40°			Materialdata	Användarkrav
12.	**Standarder och lagkav**					

12. Standarder och lagkav						
12.1	Mäta enligt ISO 5349		K		Specifikation & Test	ISO 5349:2
	Klara av att mäta enligt nuvarande standard för HAVs.					
12.2	Mäta enligt ISO/TS 5349-4		K		Specifikation & Test	Rise
	Klara av att mäta enligt utökad standard för HAVs (Planerad standard)					
12.3	Gå att fästa enligt ISO 5348		Ö	3	Test	ISO 5348
12.4	Klara ISO 8041		Ö	1	Specifikation & Test	ISO 8041
	Inte säker att triaxell komponent klarar detta					
13. Ergonomi						
13.1	Handhållenhet	Se 11. Storlek				
	Enheten ska gå att hålla med en hand					
13.2	Gå att lägga i ficka		Ö	5	CAD & Test	Användarkrav
	Rymmas i en ficka i ett par genomsnittliga arbetsbyxor					
13.3	Bältfästbar		Ö	4	CAD & Test	Användarkrav
	Gå att fästa i ett bälte					
13.4	Ergonomiskt grepp		Ö	4	RULA	Ergonomikrav
	Tillåta att hållas i handen utan att skada eller vara obekväm för användaren					
14. Kvalitet och tillförlitlighet						
14.1	Tåla stötar och slag	Tåla att tappas från 3m	K		Simulation	Användarkrav
	Produkten kommer att användas i verkstadsmiljöer där tålighet krävs					
14.2	Tåla gnistTänk	Gniststänk från 0.5m - längre	K		Materialdata	Användarkrav
	Ej antändas eller sättas ur funktion vid arbete i verkstadsmiljöer där gnistor eller svetsloppor förekommer					
14.3	Kännas välbyggd		Ö	4	Test	Användarkrav
	Det är viktigt att användarna har förtroende för att produkten är välbyggd och kommer hålla					
14.4	Tåla vattenstänk	motsvarande IP54 (stänk)	Ö	4	CAD & Test	Användarkrav
	Bra att den tål regn och liknande					
14.5	Tåla mycket vatten	motsvarande IP67 (kort nedsänkning)	Ö	2	CAD & Test	Användarkrav
	Optimalt att tåla stora mängder vatten för att säkerställa okänslighet					
15. Lagerlivslängd						
15.1	Batterier ska klara lagring	> 5 år utan användning	Ö	3	Specifikationer	
16. Tidsschema						
16.1	Underlag redo för överlämning till RISE	03-06-22	K		-	RISE
	Sista dagen på exjobbet					
16.3	Underlag redo för överlämning till RISE	06-05-22	Ö	4	-	RISE
	Sista dagen innan rapportskrivning och presentation måste vara fokus					
17. Säkerhet						
17.1	Inte ha vassa delar		K		CAD	
	Undvika skärskador på användarna					
17.2	Inte orsaka elektriska stötar		K		CAD	
17.3	Inte störa operatör	Se 21. Kabel & 22. Sensor				
17.4	Inte riskera att antändas		Ö	5	Materialdata	
17.5	Synas ordentligt		Ö	3	CAD & Test	tidigare 4
	På en arbetsplats kan det vara farligt att snubbla på utrusning, vilket kan undvikas av en synlig enhet					
17.6	Inte göra höga ljud		Ö	5	Specifikation	
	Ifall ljud används för att interagera med användaren är det viktigt att dessa inte är så höga att de blir skadliga.					
17.7	Inte avsöndra farliga ämnen		Ö	5	Materialdata	
	T.ex. vid nötning av hölje eller liknande					
18. Interna begränsningar						
18.1	Elektroniken måste få plats	BxDxH: 55 x 95 x 25	K		CAD-modell	RISE
	Beaglebone + hatt är ca 95x55x25					
19. Gränssnitt						
19.1	Visa och Analysera signalkurvor	Både rå signaldata och fft-graf	K		Gränssnittsmockup	Användarkrav
19.2	Visa och Analysera RMS	m/ss	K		Gränssnittsmockup	Användarkrav
19.3	Visa och Analysera peakvärden	m/ss	K		Gränssnittsmockup	Användarkrav
19.4	Visa och Analysera transienta	VSI, Vibration Shock Index	Ö	4	Gränssnittsmockup	Användarkrav
19.5	Visa och Analysera olika algoritmer		Ö			
	RISE utvecklar just nu många olika algorimter för dataprocessering, bra att kunna få ut många olika för att kunna se vilken som korrelerar bäst till skador					
19.6	Filtrera signalkurvor för ISO och High-range oberoende		Ö	4		
19.7	Spara och öppna data		K		Gränssnittsmockup	Användarkrav
	Spara data så att den går att öppna i gränssnittet					
19.8	Välj lagringsplats och namn för data		Ö	4	Gränssnittsmockup	Användarkrav
	För att kunna organisera output-data enklare					
19.9	Tillåta metadata	Gärna genom t.ex. fotografier	Ö	3	Gränssnittsmockup	Användarkrav
	Bra att kunna koda data med metadata för att lättare kunna analysera den sedan					
19.10	Tillåta val av sekvenser som ska sparas		Ö	4	Gränssnittsmockup	Användarkrav
	Man kan se så att datan är deterministisk samt ser rimlig ut med hjälp av en signalkurva i det spannet man väljer					
19.11	Exportera data		Ö	4		
	Exportera data så att den går att öppna och hantera i andra programvaror. t.ex. csv, ev. inställningar för detta					
19.12	Filtrera och analysera enligt standard	5349 (gärna vektorsumma) + eventuellt någon annan, afs2005-1	K		Gränssnittsmockup	Användarkrav
19.13	Indikera status		Ö	4	Gränssnittsmockup	Användarkrav
	Visa om enheten är redo att användas, har systemfel eller mätfel					
19.14	Indikera låg batterispänning		K		Grännsittsmockup & CAD	
	Mätningarna kan bli felaktiga om batterispänningen är för låg					
19.15	Indikera baterinivå & laddningsstatus		Ö	5	Gränssnittsmockup	Användarkrav
	Viktigt för att kunna avgöra hur länge man kan mäta utan att ladda					
19.16	Förhindra användning vid låg batterispänning		Ö	5	Gränssnittsmockup	Användarkrav
	Mätningarna kan bli felaktiga om batterispänningen är för låg					
19.17	Tydligt och enkeltydigt gränsnitt		Ö	5	Gränssnittsmockup	Användarkrav
	Förhindra feltolkningar av data utifrån att felavläsning av gränsnittet					
19.18	Gränssnitt kompatibelt med vanliga mentala modeller för vibrationssmätutrusning/digitala gränssnitt		Ö	3	Heuretisk Analys	Användarkrav
	För att användarna ska kunna byta från ett annat system utan för stora problem					
19.19	Byta mellan avancerad & enkel vy		Ö	2	Gränssnittsmockup	Användarkrav
	Forskarna behöver mycket mer info än t.ex. arbetsmiljöingenjörer					
19.20	Guida användarna		Ö	3	Gränssnittsmockup	Användarkrav
	T.ex. informera om vikten av driftförhållanden av maskinen eller hur man placerar sensorn korrekt					
19.21	Validera att datan är riktig på plats		Ö	4	Gränssnittsmockup	Användarkrav
	För att undvika att göra mätningar och sedan märka på kontoret att datan ej är användbar					
19.22	Erbjuda ett monitorläge		Ö	3	Gränssnittsmockup	Användarkrav
	För att kunna se datan live och göra bedömningar om mätkvalité					
19.23	Starta mätning snabbt	< 1 min	Ö	3	Gränssnittsmockup	Användarkrav

19.23	Starta mätning snabbt	< 1 min	Ö	3	Gränssnittsmockup	Användarkrav
19.24	Tillåta kalibrering av sensorkort enligt datablad		K		Gränssnittsmockup	Användarkrav
	Om sensorkortet behöver bytas är det viktigt att kunna kompensera för toleranserna i tillverkningen av korten					
19.25	Informera om wifi-lösenord		Ö	3	Gränssnittsmockup	Användarkrav
	För att slippa läsa i dokumentationen om man glömt lösenordet					
19.26	Förhindra oavsiklig input		Ö	4	Gränssnittsmockup	Användarkrav
19.27	Gå att använda med handskar		Ö	3	Gränssnittsmockup	Användarkrav
	Visa miljöer kräver att den som mäter bär handskar, därför är det bra om dom slipper ta av handskarna för att interagera med gränssnittet					
19.28	Gå att använda med enbart tangentbordet		Ö	3	Gränssnittsmockup	Användarkrav
	Inte alltid smidigt att använda mus eller trackpad					
20. Trigger						
20.1	Tillåta aktivering av mätning med båda händerna på maskinen som ska mätas		K		Specifikation	Användarkrav
20.2	Fungera utan USB-reciever		Ö	5	Specifikation	Användarkrav
20.3	Indikera när mätningen startar och stoppar		Ö	3	Specifikation & Heuretisk Analys	Användarkrav
21. Kabel						
21.1	Vara utbytbar		Ö	5	Specifikation	Användarkrav
	Kabeln är svagaste länken på produkten och måste därför kunna bytas ut om den bryts					
21.2	Ej gå av	Tåla dragkrafter upp till 50N	Ö	5	Specifikation & Test	Användarkrav
	Man ska kunna rycka i kabeln utan att den går av till en rimlig gräns					
21.3	Tillåta fästning på operatör		Ö	5	Såecifikation & Test	Användarkrav
21.4	Tillåta mätning på avstånd	5m avstånd	Ö	3	CAD & Specifikation	Användarkrav
	För att skydda den som mäter och instrumentet mot eventuella faror nära operatören, ger även den som mäter möjlighet att stå framför operatören och t.ex. vinka för att kommunicera					
21.5	Ändra längd på kabel	(5m) 2m - 0.5m	Ö	4	CAD	Användarkrav
	Bra att kunna ändra den så att den inte är ivägen, oberoende av var på kroppen den placerats.					
21.6	Enkelt att sätta in kabeln åt rätt håll		Ö	3	CAD & Test	Användarkrav
	T.ex. med en kabel som är vändbar eller med en märkning på kabel och kontakt					
21.7	Ej störa operatör		Ö	4	Test	Användarkrav
22. Sensor						
22.1	Gå att fästa fort	< 2min	Ö	4	Test	Användarkrav
22.2	Fästa stabilt med god kontakt		K		Test	Användarkrav

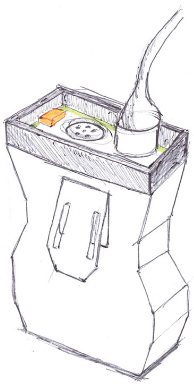
APPENDIX 5 - PUGH-MATRICES

Concept Ø

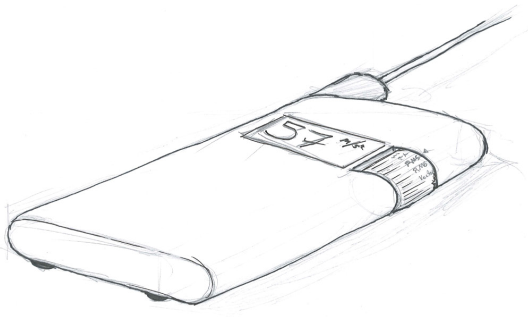


Concept A

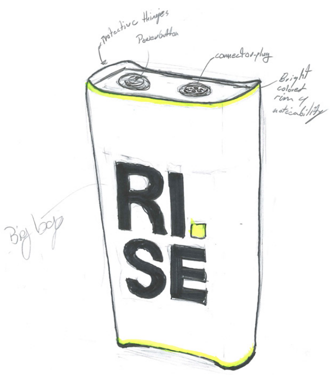
Concept B



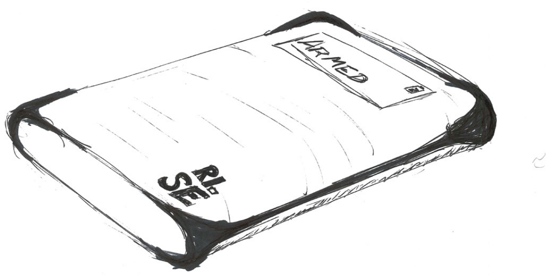
Concept C



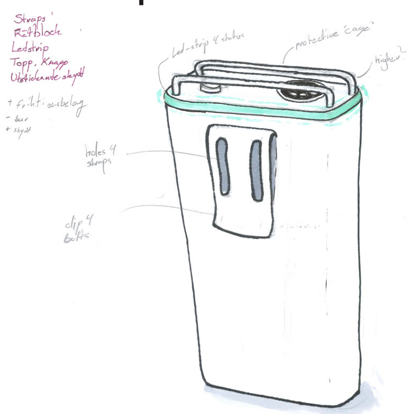
Concept D



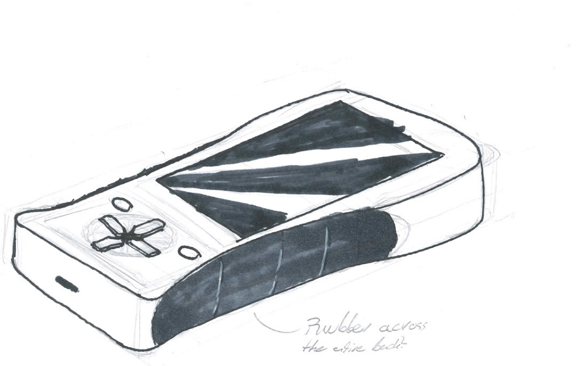
Concept E



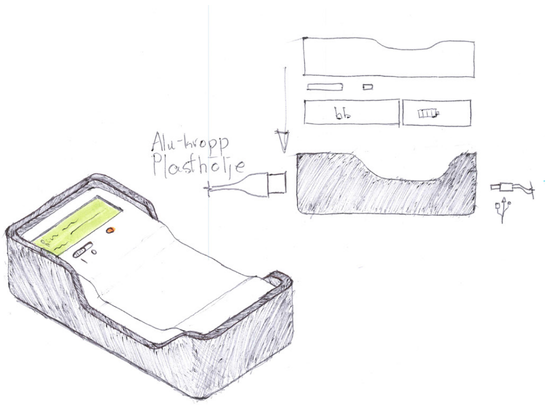
Concept F



Concept G



Concept H



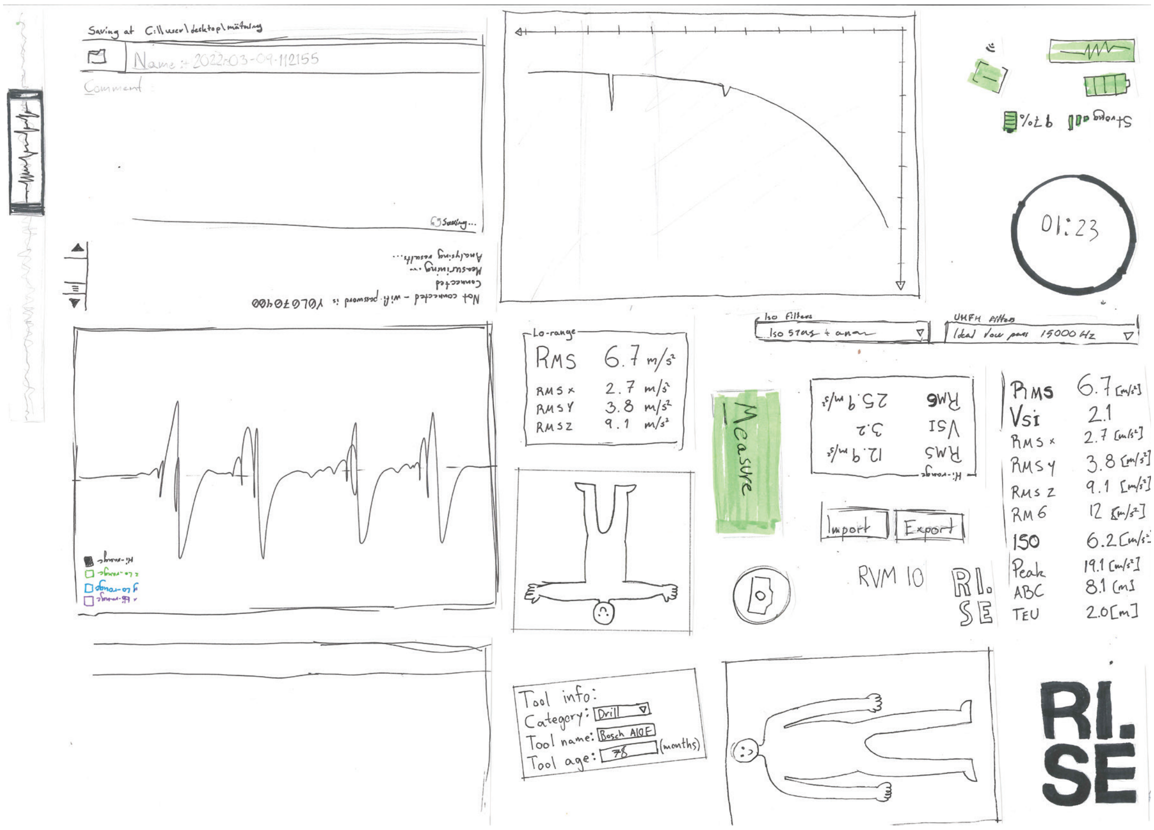
	Ska vara önskemål		Round 1 (ALLA)									
Verb	Funktioner		Concept 0	Concept A	Concept B	Concept C	Concept D	Concept E	Concept F	Concept G	Concept H	Sum
Medge	Grepp		0	1	1	1	1	1	1	1	1	8
Skydda	Elektronik		0	1	1	1	1	1	1	1	1	8
Medge	Analys (av data)		0	1	0	1	0	1	0	1	1	5
Medge	Jämförelse (av data)		0	0	0	0	0	0	0	1	0	1
Erbjuda	Kodning (av data)		0	0	0	0	0	0	0	1	0	1
Visa	Batteristatus		0	1	1	1	0	1	1	1	1	7
Visa	Systemstatus		0	1	1	1	0	1	1	1	1	7
Fungera	Med handskar		0	1	0	1	0	0	0	1	0	3
Medge	Validering av data på plats		0	1	0	1	0	1	0	1	1	5
Gå	Att rengöra		0	-1	-1	-1	1	0	1	-1	0	-2
Vara	Bärbar		0	1	1	1	1	1	1	1	1	8
Gå	Att sätta fast (i operatör)		0	1	1	0	0	0	1	0	0	3
Förhindra	Glid på yta		0	1	0	1	0	1	0	1	1	5
Förhindra	Snav		0	0	0	0	1	0	1	0	0	2
	SUMMA		0	9	5	8	5	8	8	10	8	59

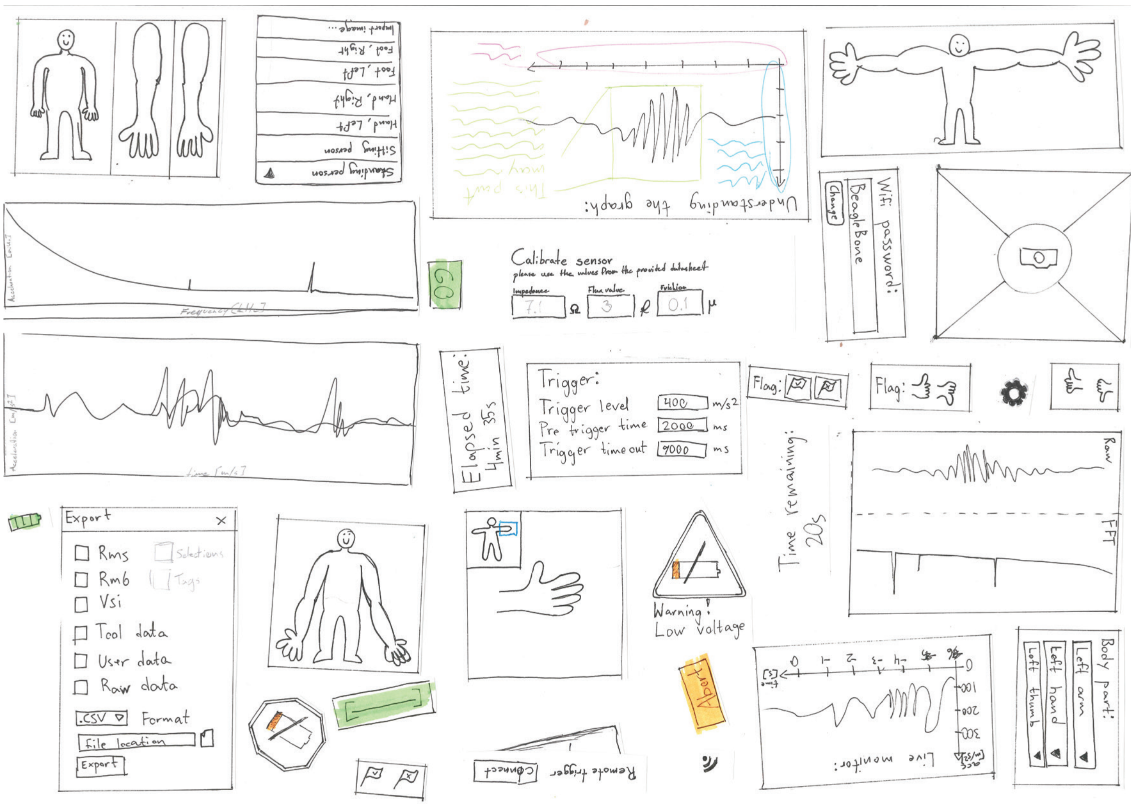
	Ska vara önskemål		Round 2 (ALLA)									
Verb	Funktioner		Concept A	Concept 0	Concept B	Concept C	Concept D	Concept E	Concept F	Concept G	Concept H	Sum
Medge	Grepp		0	-1	-1	-1	0	1	0	1	0	-1
Skydda	Elektronik		0	-1	1	1	1	1	1	1	1	6
Medge	Analys (av data)		0	-1	-1	0	0	0	-1	1	-1	-3
Medge	Jämförelse (av data)		0	-1	-1	-1	-1	-1	-1	1	-1	-6
Erbjuda	Kodning (av data)		0	0	0	0	0	0	-1	1	0	0
Visa	Batteristatus		0	-1	-1	0	-1	0	0	0	0	-3
Visa	Systemstatus		0	-1	-1	0	-1	0	0	0	0	-3
Fungera	Med handskar		0	-1	0	1	-1	0	-1	0	-1	-3
Medge	Validering av data på plats		0	-1	-1	0	-1	0	-1	1	0	-3
Gå	Att rengöra		0	1	-1	1	1	1	1	1	0	5
Vara	Bärbar		0	-1	0	0	0	0	0	0	0	-1
Gå	Att sätta fast (i operatör)		0	-1	0	-1	-1	-1	0	-1	-1	-6
Förhindra	Glid på yta		0	-1	-1	1	0	1	-1	1	1	1
Förhindra	Snav		0	0	0	0	0	0	0	-1	-1	-2
	SUMMA		0	-10	-7	1	-4	2	-4	6	-3	-17

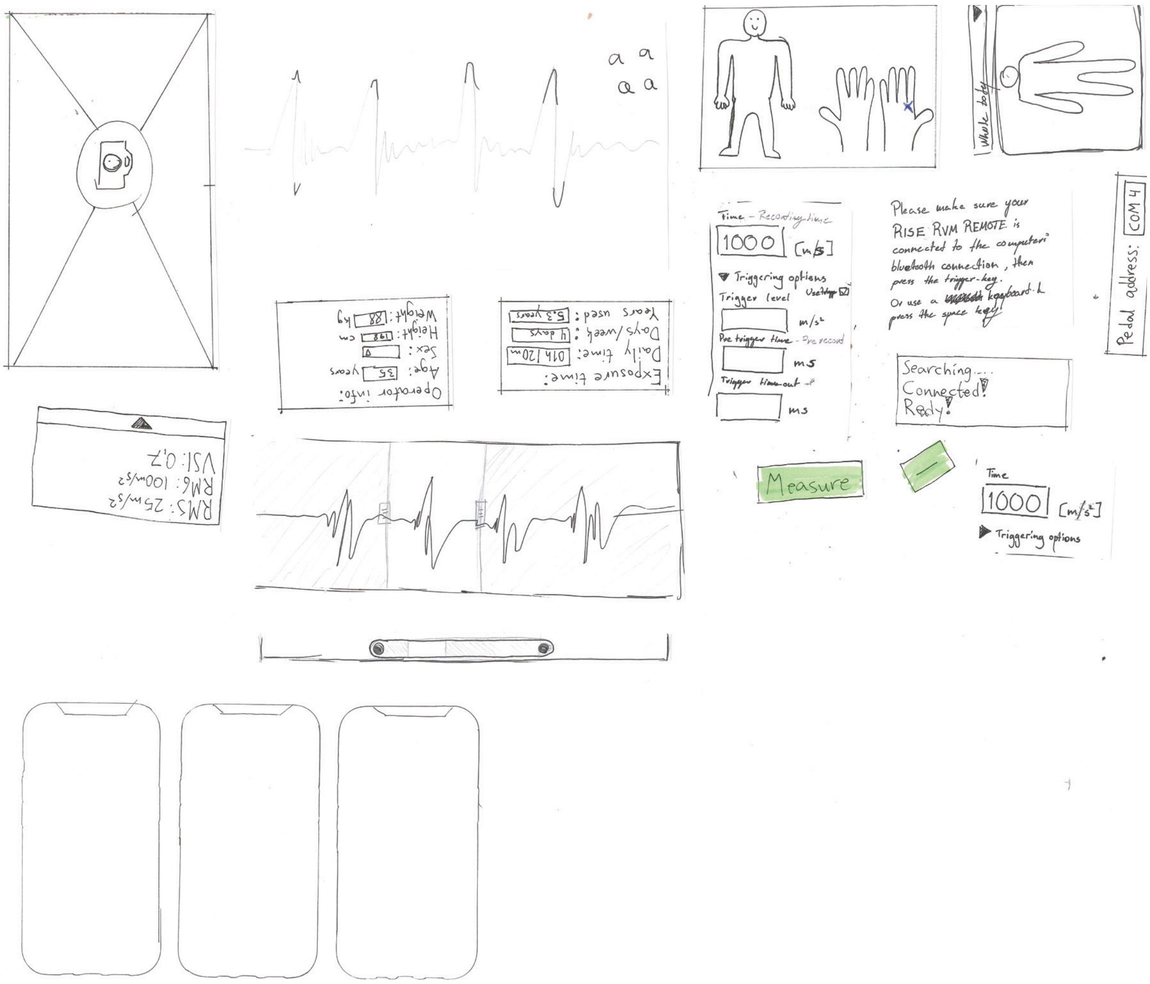
	Ska vara önskemål		ROUND 1 (UTAN SKÄRM)				
Verb	**Funktioner**		**Concept 0**	**Concept B**	**Concept D**	**Concept F**	**Sum**
Medge	Grepp		0	0	1	1	2
Skydda	Elektronik		0	1	1	1	3
Medge	Analys (av data)		0	0	0	0	0
Medge	Jämförelse (av data)		0	0	0	0	0
Erbjuda	Kodning (av data)		0	0	0	0	0
Visa	Batteristatus		0	1	0	1	2
Visa	Systemstatus		0	1	0	1	2
Fungera	Med handskar		0	0	0	0	0
Medge	Validering av data på plats		0	0	0	0	0
Gå	Att rengöra		0	-1	1	1	1
Vara	Bärbar		0	1	1	1	3
Gå	Att sätta fast (i operatör)		0	1	0	1	2
Förhindra	Glid på yta		0	0	0	0	0
Förhindra	Snav		0	0	1	1	2
	SUMMA		0	4	5	8	15

	Ska vara önskemål		ROUND 2 (UTAN SKÄRM)				
Verb	**Funktioner**		**Concept F**	**Concept 0**	**Concept B**	**Concept D**	**Sum**
Medge	Grepp		1	-1	0	0	-1
Skydda	Elektronik		1	-1	0	1	0
Medge	Analys (av data)		0	0	0	0	0
Medge	Jämförelse (av data)		0	0	0	0	0
Erbjuda	Kodning (av data)		0	0	0	0	0
Visa	Batteristatus		1	-1	-1	-1	-3
Visa	Systemstatus		1	-1	-1	-1	-3
Fungera	Med handskar		0	0	0	1	1
Medge	Validering av data på plats		0	0	0	0	0
Gå	Att rengöra		1	-1	-1	1	-1
Vara	Bärbar		1	-1	0	0	-1
Gå	Att sätta fast (i operatör)		1	-1	0	-1	-2
Förhindra	Glid på yta		0	0	0	0	0
Förhindra	Snav		1	-1	-1	0	-2
	SUMMA		8	-8	-4	0	-10

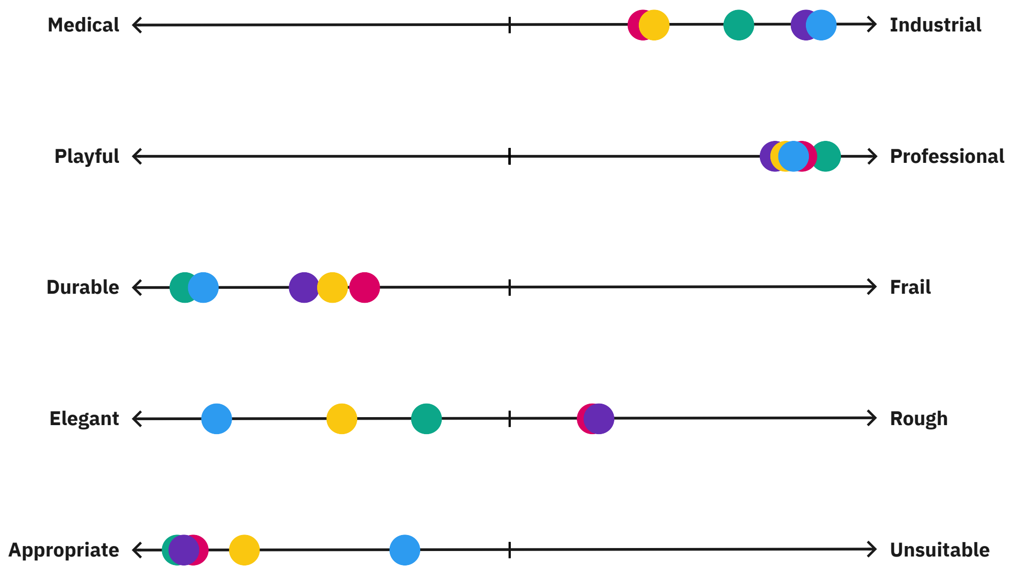
APPENDIX 6 - PAPER PROTOTYPE COMPONENTS



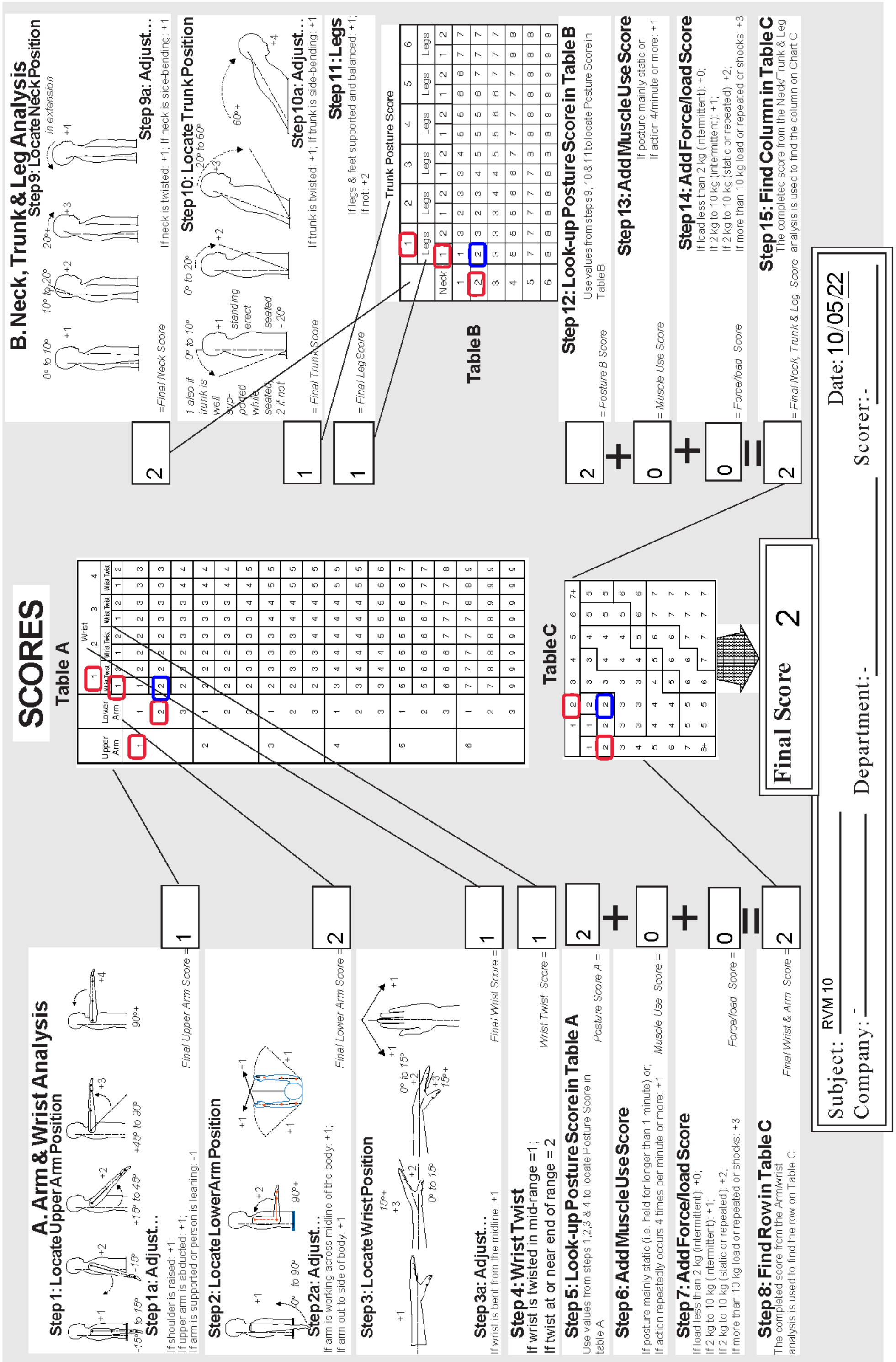



Time
1000
[m/s²]
Triggering options
Trigger level
m/s²
Pre trigger time
ms
Trigger time-out
ms
Please make sure your RISE RVM REMOTE is connected to the computer's bluetooth connection, then press the trigger-key.
Searching....
Connected!
Ready!
Measure
Pedal address:
COM4
Whole body
RMS: 25m/s²
RMG: 100m/s²
VSI: 0,7
Operator info:
Age: 35 years
Sex:
Height: 198 cm
Weight: 88 kg
Exposure time:
Daily time: 01h 20m
Days/week: 4 days
Years used: 5,3 years

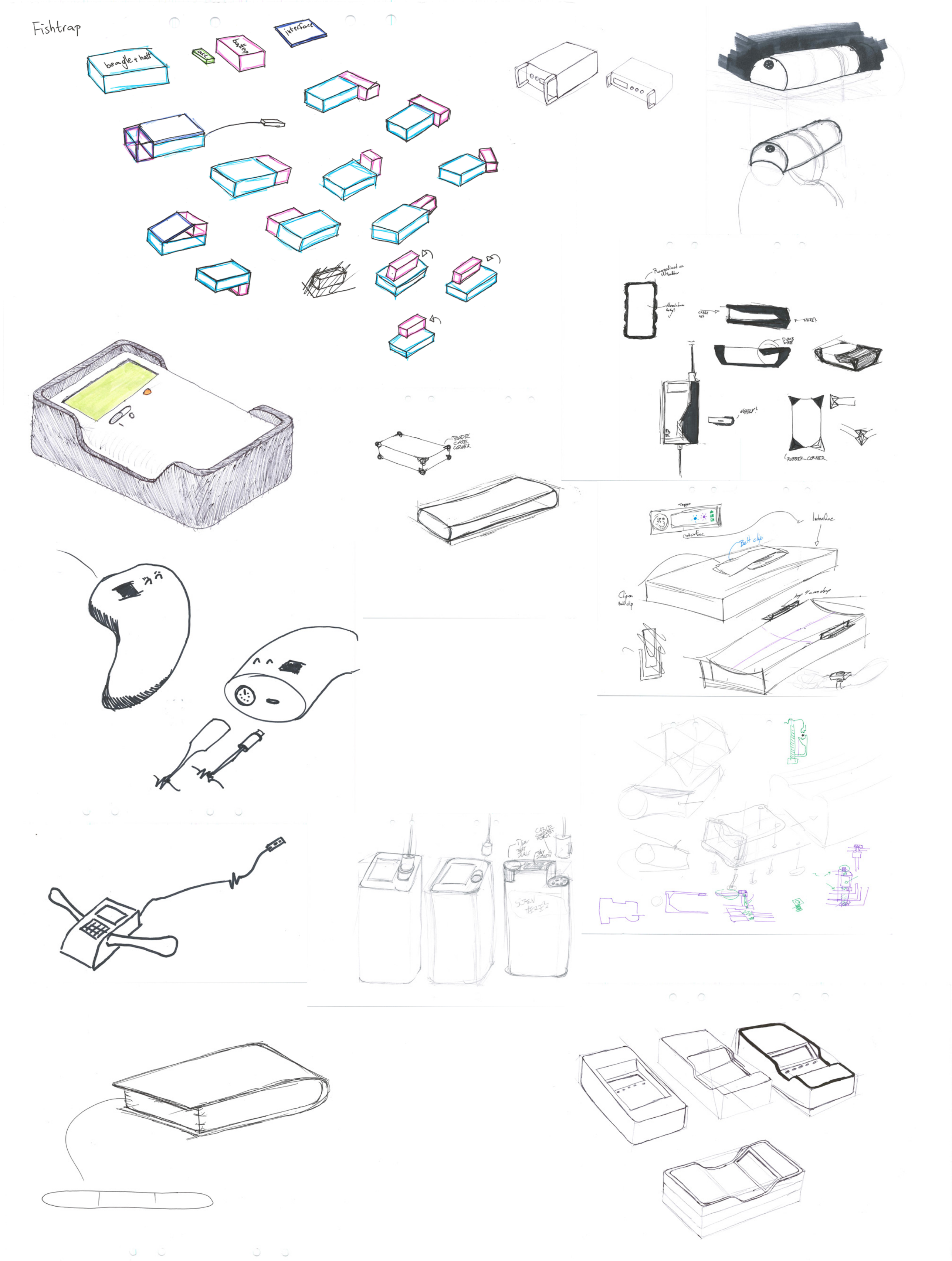
APPENDIX 7 - SEMANTIC DIFFERENTIAL



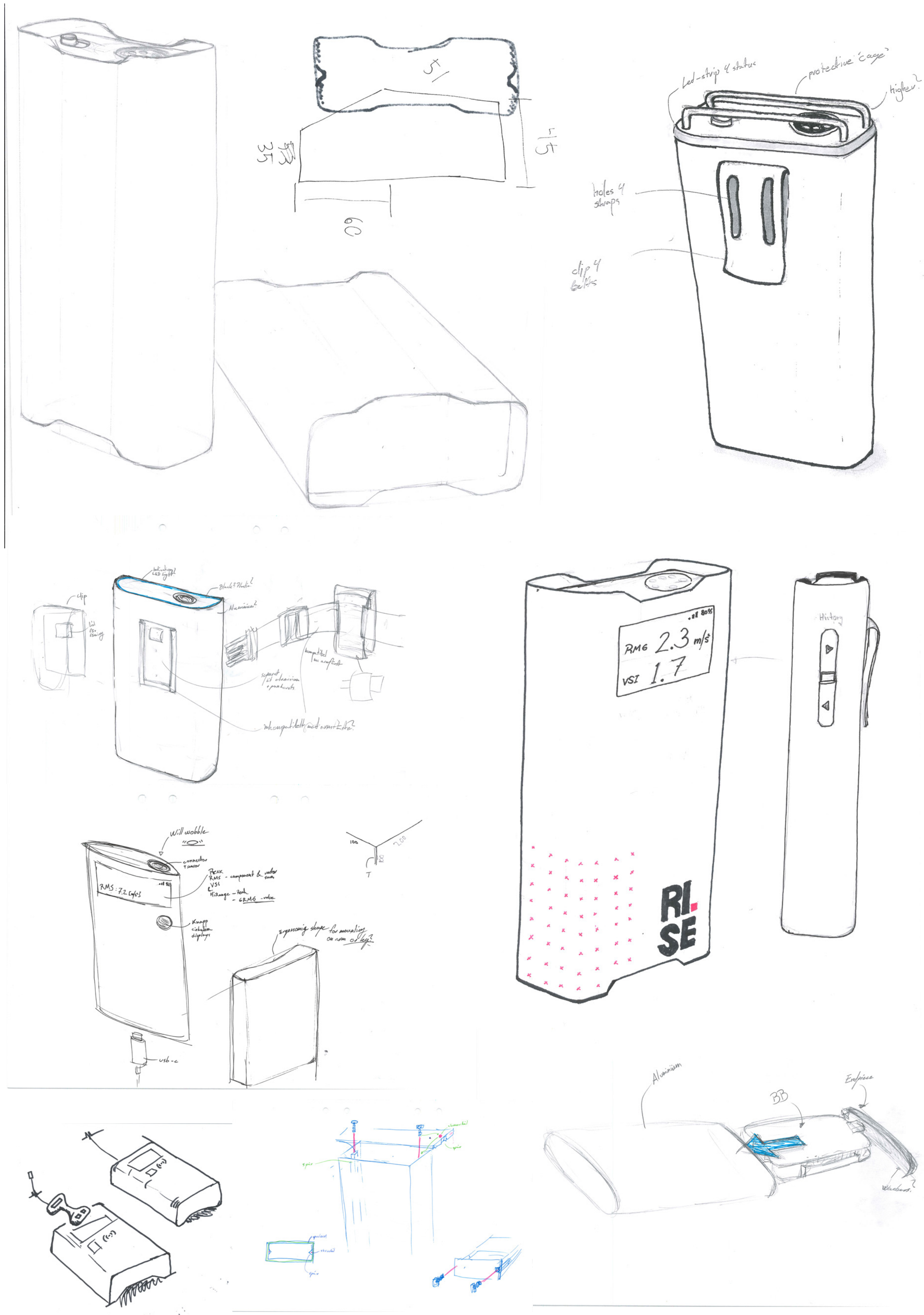
APPENDIX 8 - RULA



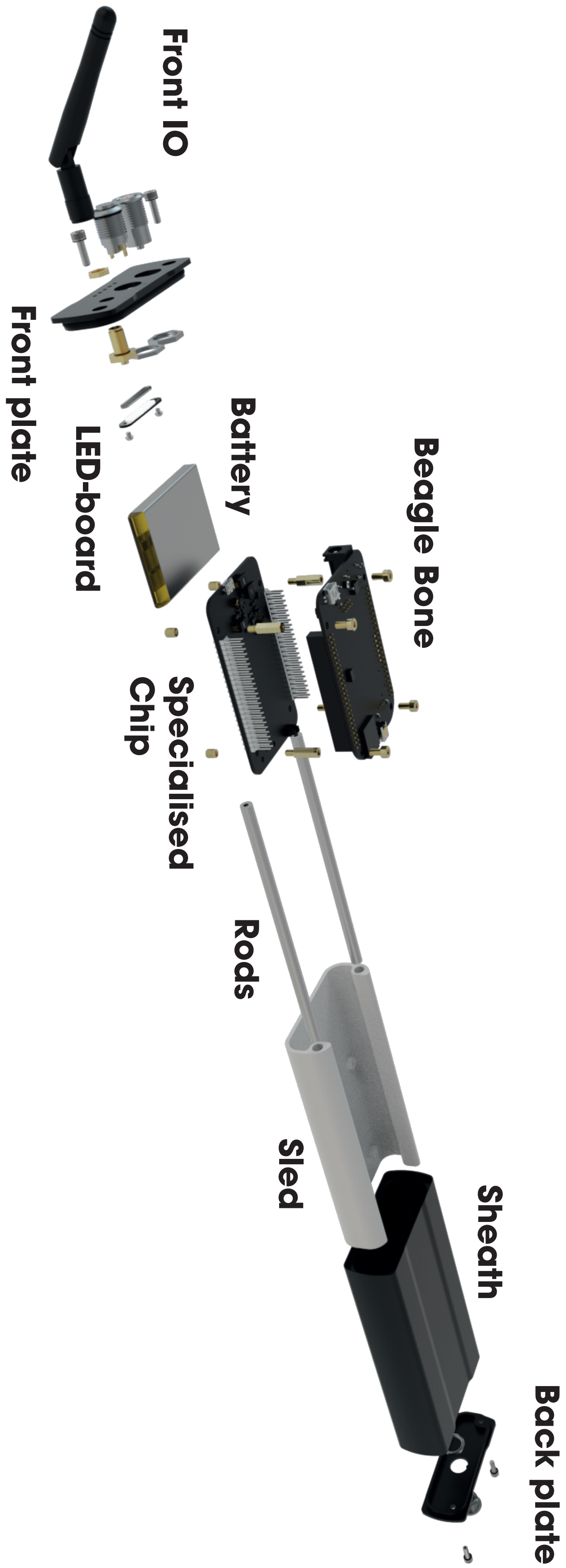
APPENDIX 9 - EARLY SKETCHES



APPENDIX 10 - REFINED SKETCHES



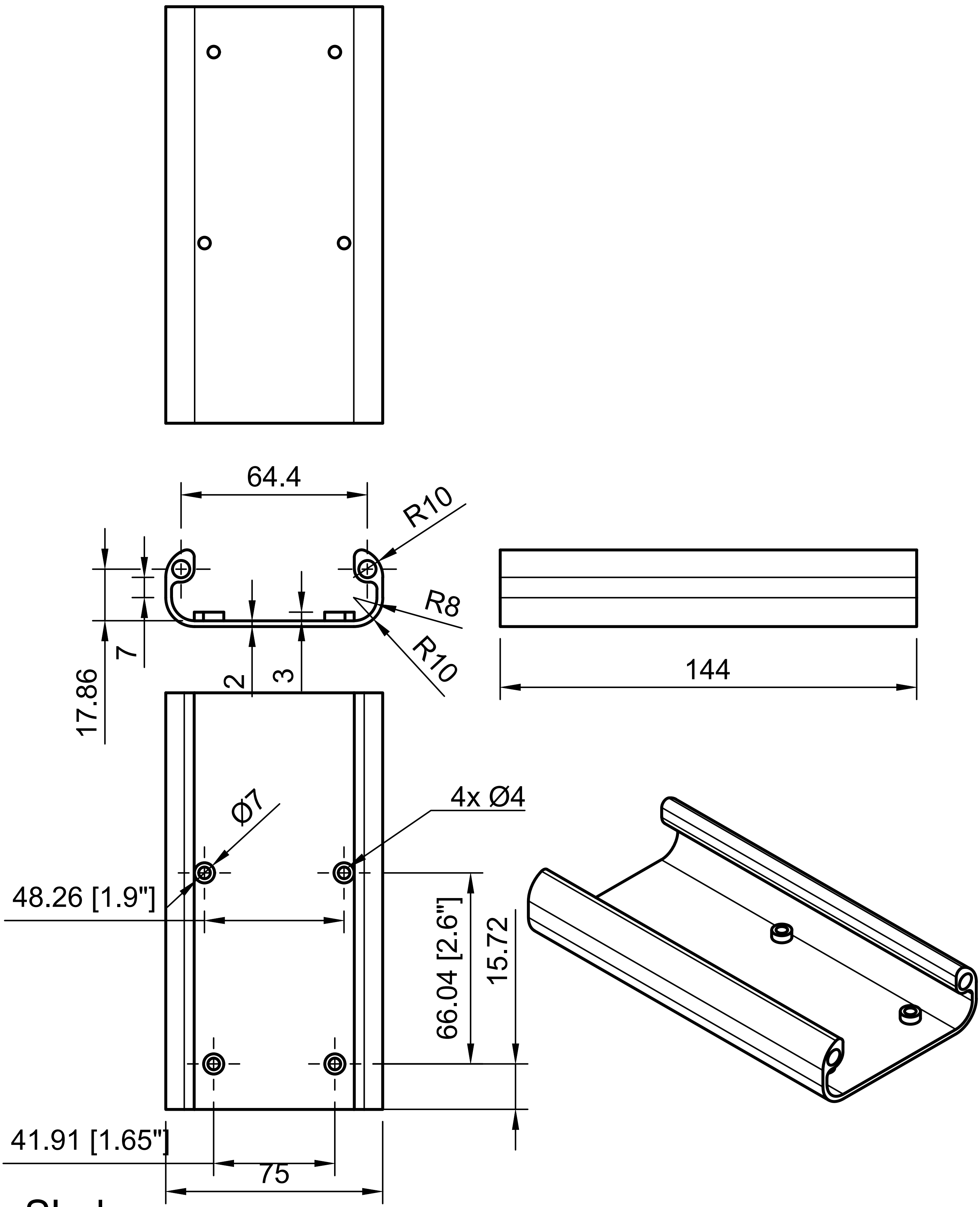
APPENDIX 11 - EXPLODED



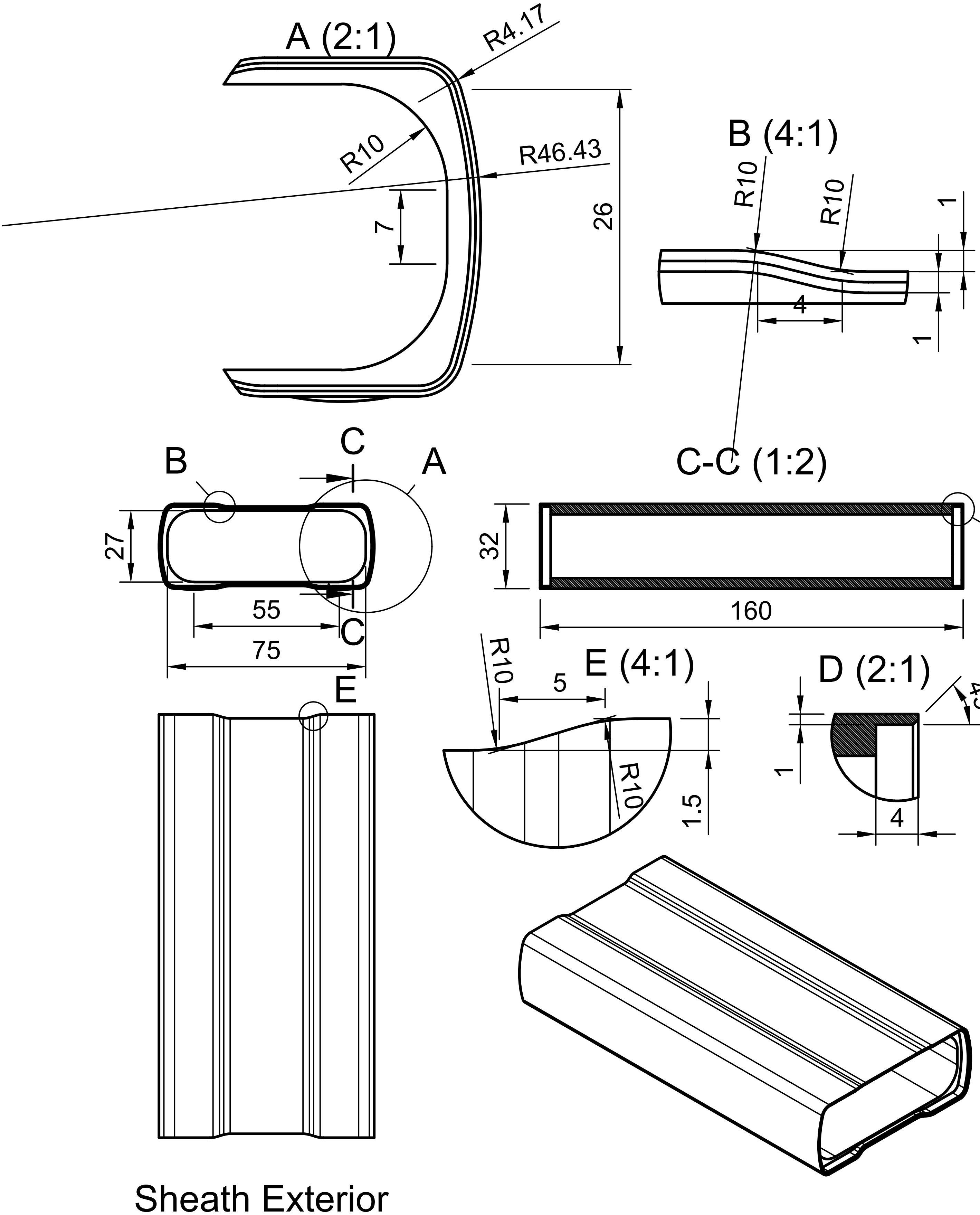
APPENDIX 12 - BILL OF MATERIALS

Product	Part number	Supplier		Unit Price	Sum
SMA-Female	32K601-271L5	Elfa	1	84.6	84.6
SMA-male (antenna)	GW.11.A153	Elfa	1	85.4	85.4
Button	MAV0120/3D	Elfa	1	145	145
Screw M3 10mm (bag of 50)	660-4636	RS	4	4.954	19.816
LEMO-connector	EGG.1B.307.CLL	Elfa	1	303	303
Battery	125-1266	RS	1	209	209
Charging Port	09 0408 00 03	Elfa	1	82	82
Threaded Inserts M3 (Bag of 100 för 181.5)	278-534	RS	4	1.815	7.26
Standoffs M3	176-8290	RS	4	5.833	23.332
Screw for standoffs M3 (Bag of 100)	528-738	RS	4	0.91	3.64
O-ring 180mm	196-4942	RS	2	12	24
Total price					987.048

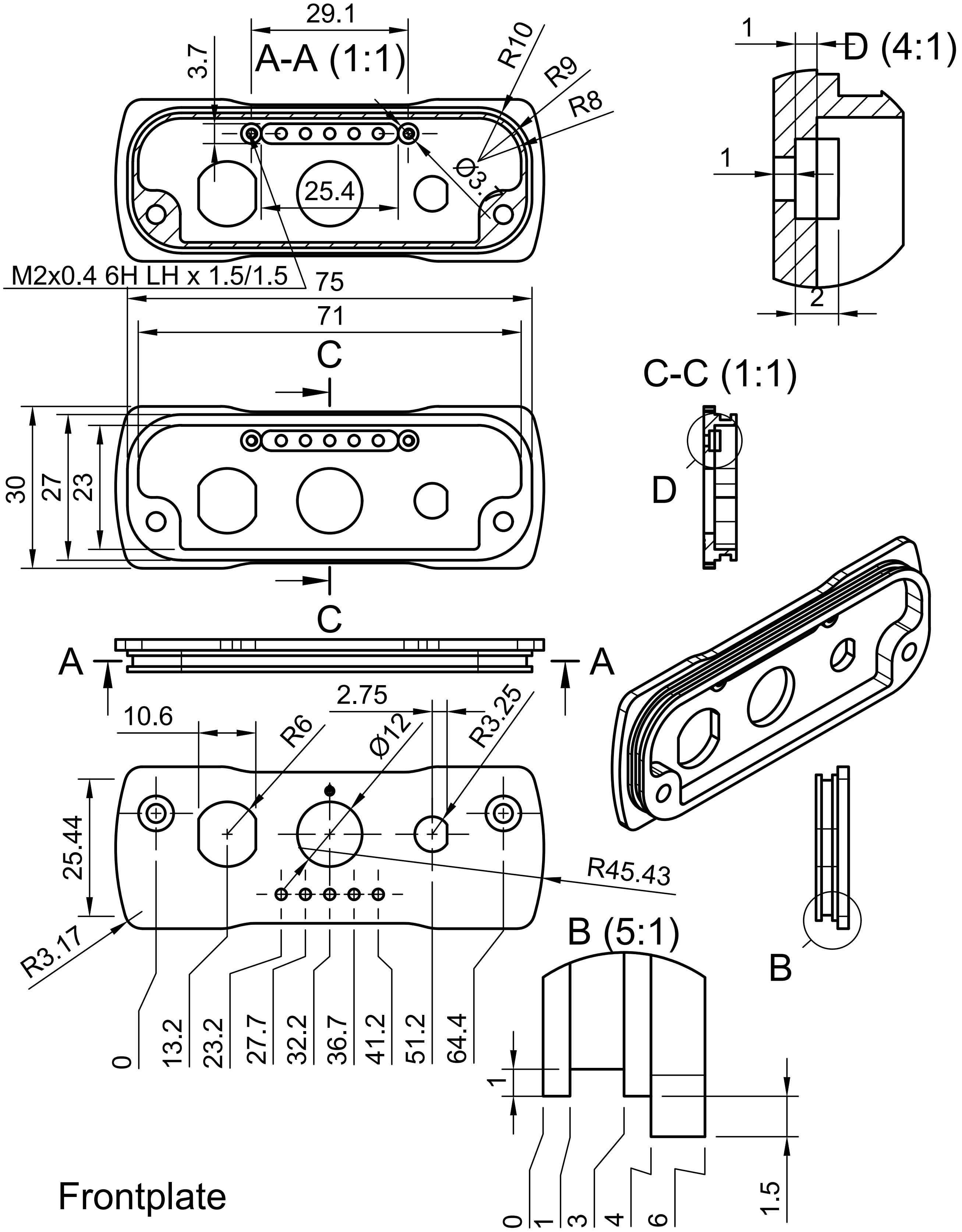
APPENDIX 13 - DRAWINGS



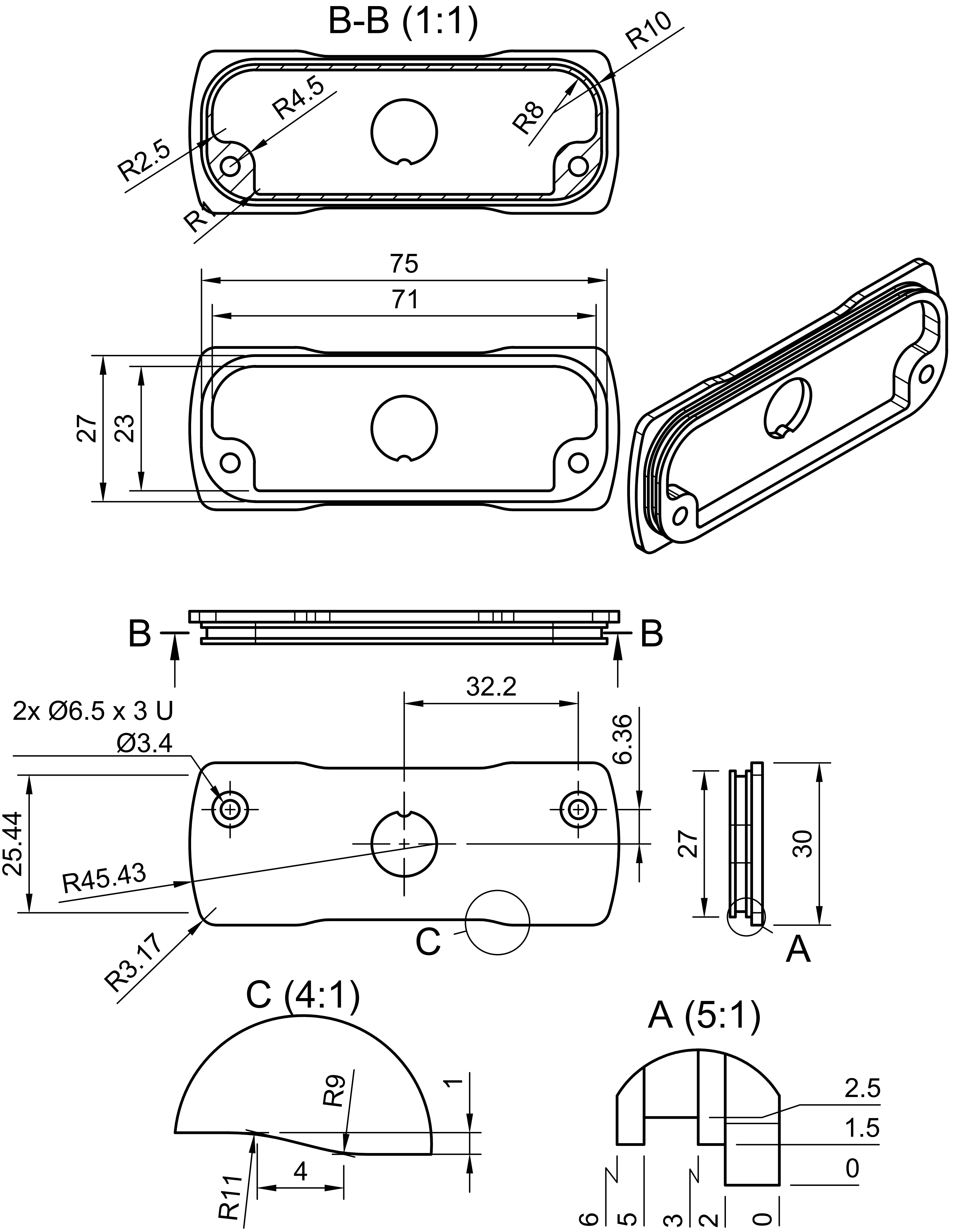
Sled



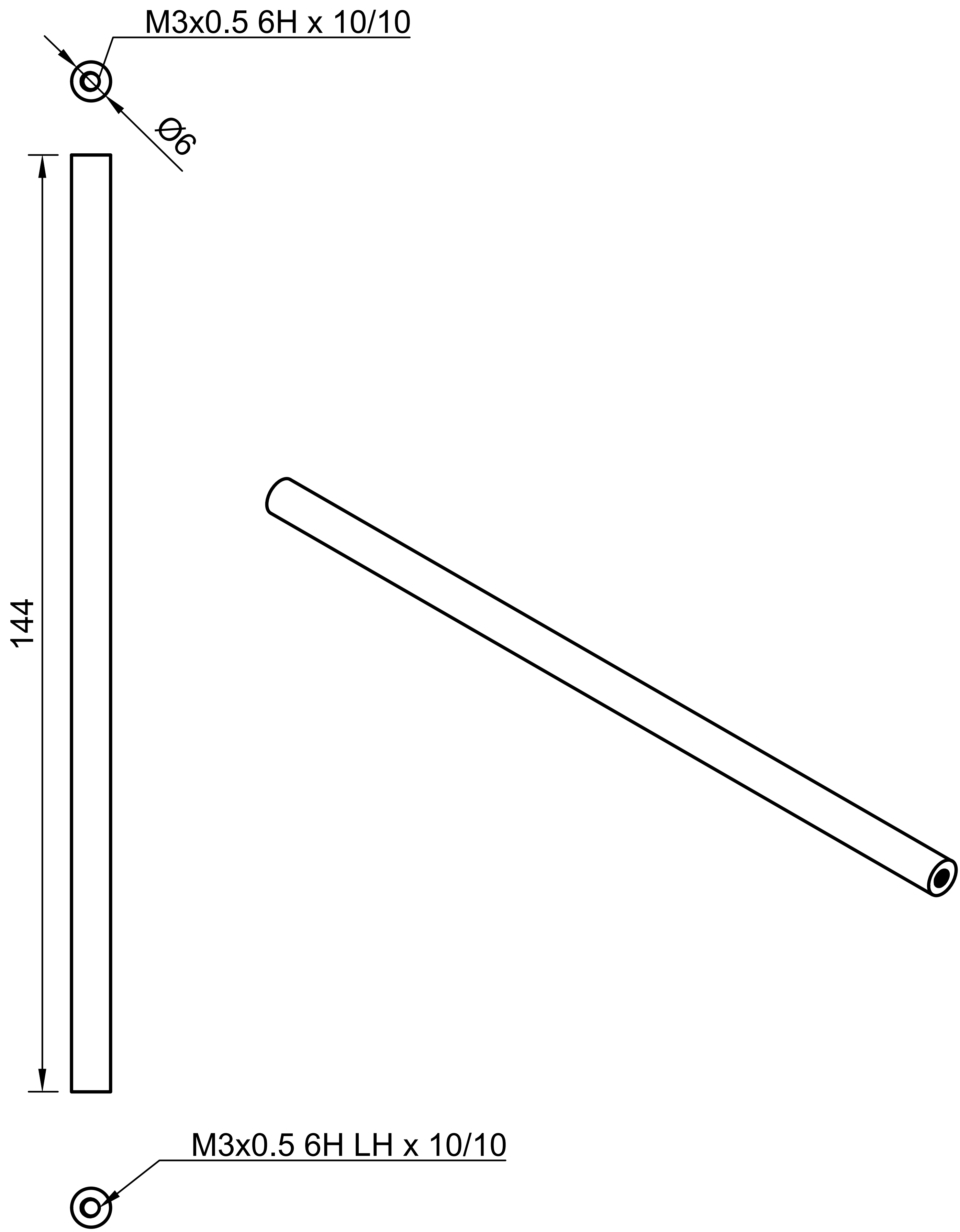
Sheath Exterior


A-A (1:1)
29.1
3.7
R10
R9
R8
Ø3
25.4
M2x0.4 6H LH x 1.5/1.5
75
71
C
30
27
23
C
D (4:1)
1
1
2
C-C (1:1)
D
A
A
10.6
2.75
R6
Ø12
R3.25
25.44
R45.43
R3.17
0
13.2
23.2
27.7
32.2
36.7
41.2
51.2
64.4
B (5:1)
B
1
1.5
0
1
3
4
6

Frontplate


B-B (1:1)
R10
R4.5
R8
R2.5
R1
75
71
27
23
B
B
32.2
2x Ø6.5 x 3 U
Ø3.4
6.36
25.44
R45.43
R3.17
C
27
30
A
C (4:1)
1
R9
4
R11
A (5:1)
2.5
1.5
0
6
5
3
2
0

Backplate



Rod

APPENDIX 14 - INTERFACE