Bachelor thesis – Interaction Design

HERTZIAN EXPERIENCE

The secret world of electromagnetic waves

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HERTZIAN EXPERIENCE

Abstract

Every day we are surrounded by a great variety of electromagnetic waves. Whereas some of them are perceptible by us, most of them remain hidden, since we lack the the necessary senses. In our project, we created body extensions that unlock this hidden world. These extensions let you explore fragments of a world you never perceived before. You may discover the electromagnetic space by feeling, seeing and hearing.

This documentation describes the process from ideation to the realisation of functional prototypes that allow you to explore the Hertzian space.

Index

Introduction

No matter where you are, and no matter what you hear, feel or see, you only perceive a small fraction of your environment. This is because our senses are specialized on very specific things: sight, hearing, touch, smell and taste. Besides this perceptible world, open to us thanks to our five senses, there is a hidden world that escapes our senses.

This hidden world has always been here. Natural sources of energy like the sun emit invisible waves and generate imperceptible energy for human beings. But in the last century humans became active designers of this world. Radio, cellphone, WiFi, TV remote control, radar, GPS: all these technologies have one thing in common, they communicate with electromagnetic waves - waves humans can not perceive. Thereby we create something without perceiving what is formed. Yet like the perceptible world interesting constructs, landscapes and dynamics emerge in this space.

The focus of our project is the part of the radiation that is made by humans. Since this part of the spectrum is still large we decided to narrow it down to FM/AM radio, microwave technology and alternating current.
This space is called “Hertzian Space”. The term was first described by Anthony Dunne and Fiona Raby (Dunne, 2005). It describes the space that is formed by human and electronic machine interactions. Everything that works with electricity emits electromagnetic fields. Those fields extend beyond the boundaries of the actual things we perceive. Interactions between those two spaces create a hybrid landscape of reflections and hot points.

Ideation

During the phase of ideation we wrote down everything to our topic of Hertzian Space. We created a collage on a window with these main terms: sources, receivers, perceptions, translations, consciousness, experiences, criticism and object as a physical outcome. We selected this sub terms as relevant for our main topic.

We started to collect images, facts, terms and ideas to the different main terms. During the first phase of ideation we tried to find as many ideas as possible no matter feasible or not. After this phase of generating ideas we started to arrange them on the term map, by looking for connections and similarities. Out of this process a lot of new ideas and some rough concepts for the project emerged. By creating "What if ..." scenarios which we pitched each other we developed those ideas and concepts further.

During this time the exchange of ideas and opinions with our mentors were very important. It often happened that we got lost in a detail or we narrowed down the topic too rapidly and too much. The conversations helped us to find new directions, inspiration and perspectives. After this process of ideation, we focused on several selected projects. Based on those we wanted to carry out the first experiments to test the experience. By doing that we hoped to have a fast feedback cycle of experimenting, experiencing and evaluating.

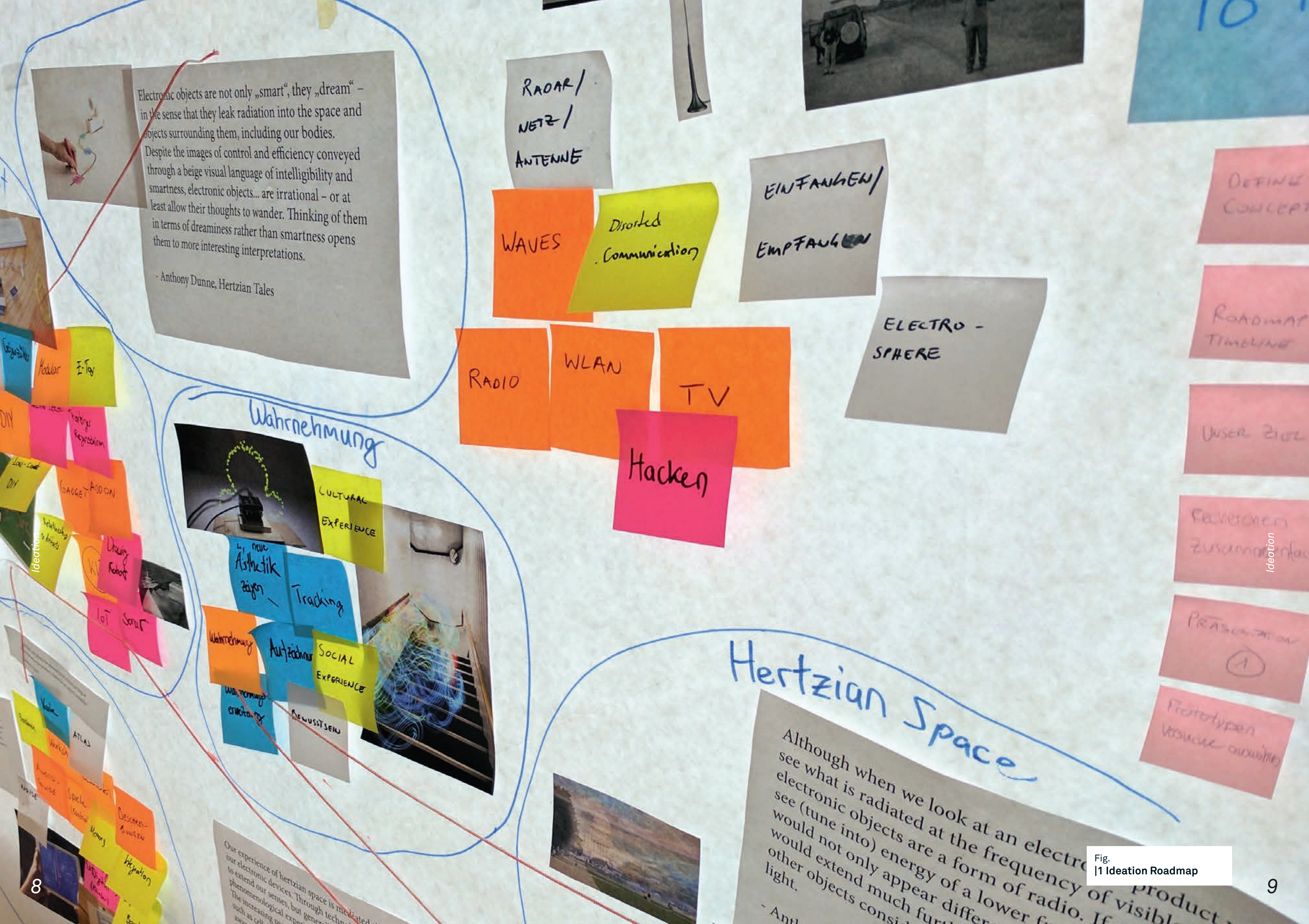


Fig.
|1 Ideation Roadmap

Ideation

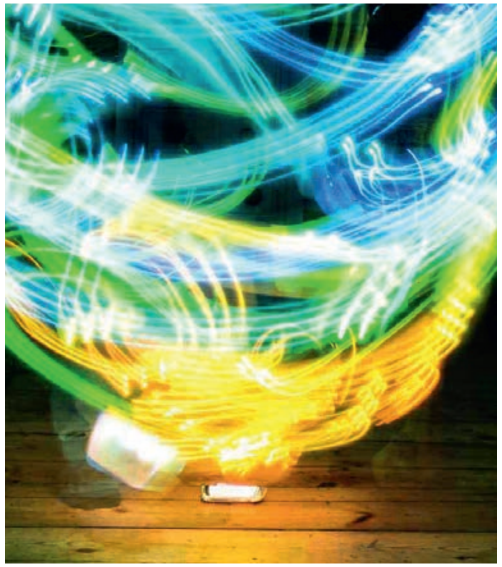
Related work – Inspiration

After the first ideation phase, we started to look for existing projects and persons related to Hertzian space. We tried to find out how other designers and scientists tackled the problem of making this space perceptible. Our search was guided by some of the main terms from our ideation map: Hertzian space, experience, perception, do it yourself, modularity.
The existing projects were a great inspiration and they also gave us a good overview of what was already done.

In addition to the desktop research we visited the Technorama in Winterthur to see how they present and explain these complex scientific phenomenon to the wider public.

The following selected works inspired us a lot. Most of these projects try to create an experience with Hertzian space. We replicated some of them in order to start our experimentation phase. Exploring these experiments ourselves allowed us to get a feeling of what we wanted to create and how we could communicate the project at the final exhibition.

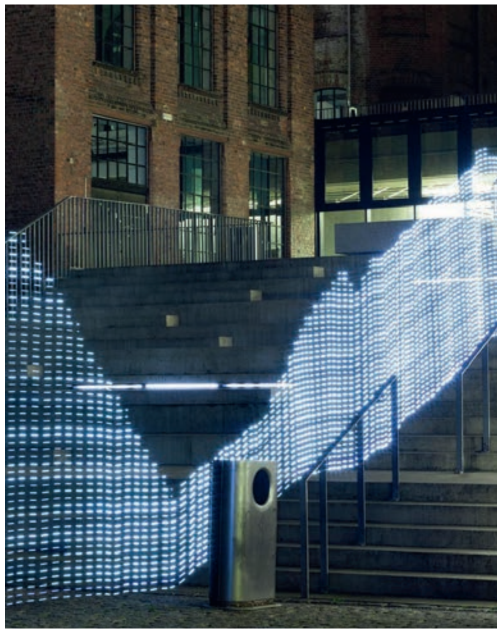
Projects



DIGITAL ETHEREAL

This project of Luis Hernan tackles the invisible structures and landscapes of our information technology. It is a creative exploration of wireless specters [Hernan, 2014].

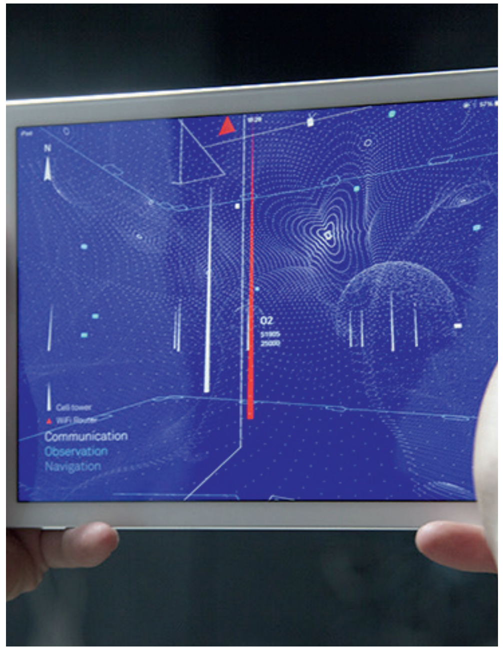
Fig.
|2 Digital Ethereal



Immaterials: Light painting WiFi

This project explores the invisible terrain of WiFi networks in urban spaces. By taking long exposure photos of light paintings of the WiFi networks signal strength it creates interesting new elements in urban space [Arnall, 2013].

Fig.
|3 Light painting WiFi



The Architecture of Radio

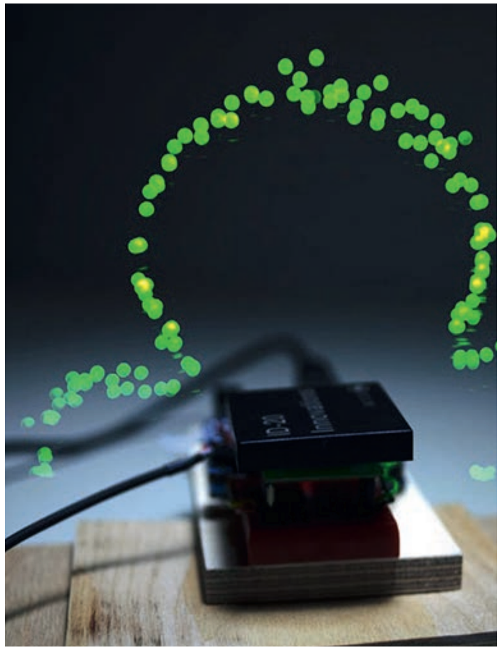
The app is an attempt to visualize the invisible world of electromagnetic radiation. With the resulting augmented reality, it is interesting to see all the radiation sources around you. The app does not
detect radiation. It is aware of the positions of WiFi hotspots, GSM antennas and satellites and yourself [Vijgen, n.d.].

Fig.
|4 Architecture of Radio

Magnetic Movie

The short movie by Ruth Jarman and Joe Gerhardt shows tires to visualize the invisible magnetic fields around the NASA Space Science Laboratories, UC Berkeley. It is a very beautiful and and interesting interpretation of this hidden world [Jarman, & Gerhardt, 2007].

Fig.
|5 Magnetic Movie



Making Visible

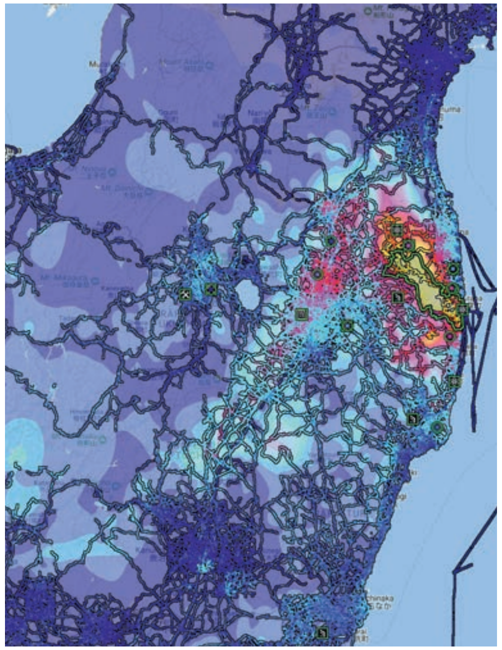
The PhD thesis of Timo Arnall reflects upon the design material exploration from the two earlier projects Yourban and Touch. In his thesis, he addresses the issue of invisibility and seamlessness in today's interfaces [Arnall, 2014].

Fig.
|6 Making Visible

Safecast

The project Safecast was developed in the aftermath of the horrible nuclear accident in Fukushima. To get live data of the current radiation levels in the contaminated region Sean Bonner and his team developed cheap and easy to build sensors that keep the map updated [Bonner, n.d.].

Fig.
|8 Safecast



Hidden landscapes

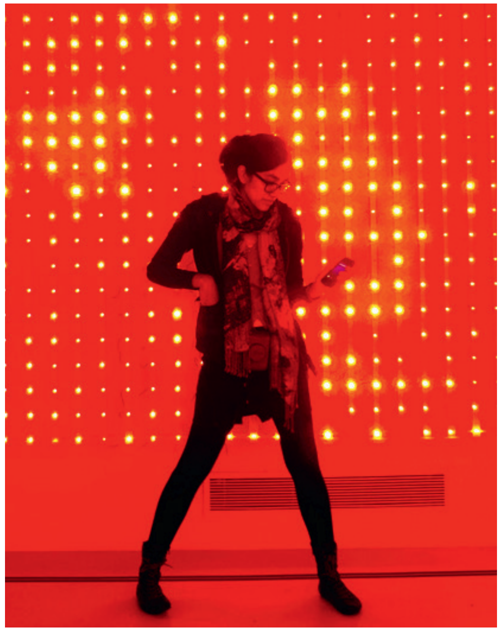
This is a blog collecting all kinds of projects that reveal hidden layers of space. Besides EMF visualization there are also projects about invisible health problems [Dear, 2012].

Fig.
|7 Hidden landscapes

Cell Phone Disco

The Cell Phone Disco installation by Ursula Lavrenčič and Auke Touwslager is an interactive visualization of the GSM signals of cell phones. Sensors placed on a surface pick up the signals strength and display it with LEDs [Lavrenčič, & Touwslager, 2006].

Fig.
|9 Cell Phone Disco



Related work – Inspritation

Skyear

Sky Ear is a one-night event in which a glowing "Cloud" of helium balloons filled with electromagnetic sensors and LEDs rises to the sky. As a result the detected radiation creates colorful patterns in the sky [Haque, 2004].

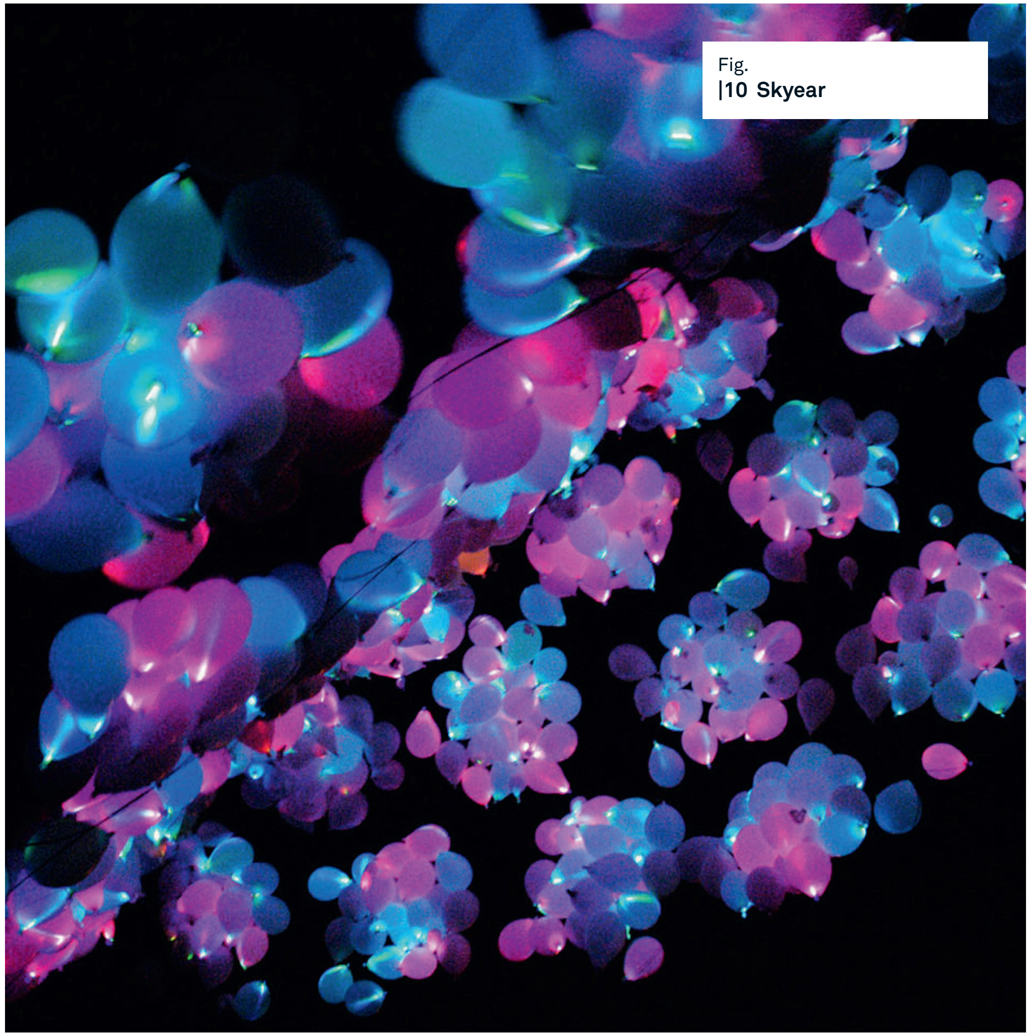


Fig.
|10 Skyear

Fig.
|11 Compass Table

Compass Table

There are a number of compasses that are embedded in the surface of a table. By placing electromagnetic devices on the table, you change the magnetic field and see the compasses change direction [Dunne, & Raby, 2011].

Field

Fig.
|12 Field

The project Field by Richard Box is an impressive demonstration of the electric fields surrounding overhead power-lines. 1301 fluorescent tubes are powered only by the energy that surrounds this fields [Sample, 2004].

Electrical walk

Fig.
|13 Electrical walk

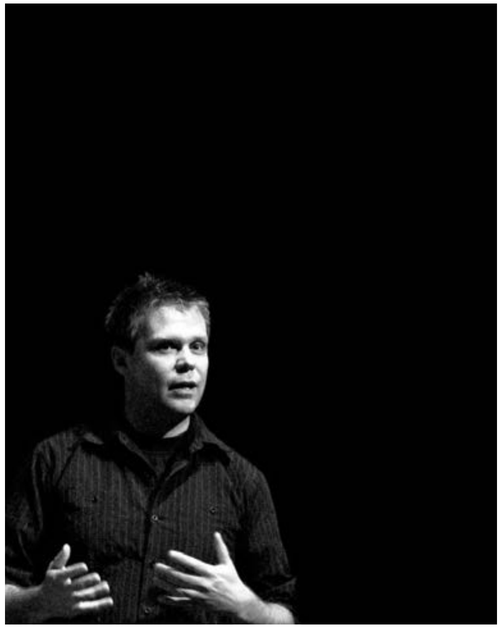
Electrical Walk is a public walk created by Christina Kubisch. It is a walk with special sensitive wireless headphones that amplify surrounding electromagnetic fields and make them audible [Kubisch, 2004].

Personas and Studios

Yuri Suzuki

Yuri Suzuki is sound artist and designer. By creating electronic music instruments, he explores the relationship between sound and people. By not hiding the electronics of his designs he often creates a very interesting aesthetics [Suzuki, n.d.].

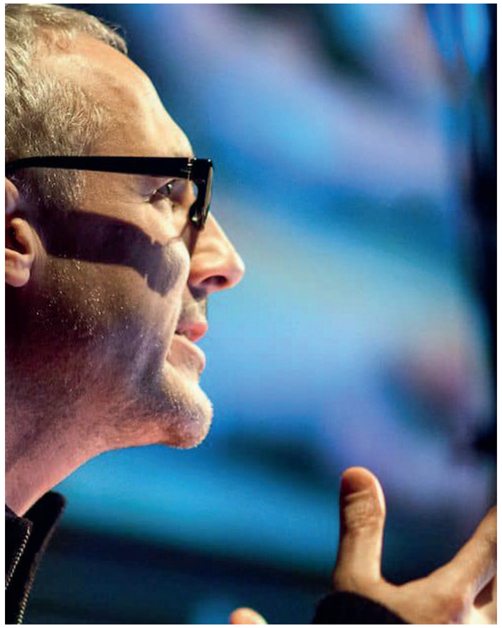
Fig.
|14 Yuri Suzuki



Timo Arnall

Timo Arnall led the research of the project Touch and participated in the Yourban project. His PhD thesis “Making Visible” investigated the question how Interaction Design influences the shaping of emerging interface technologies [Arnall, n.d.].

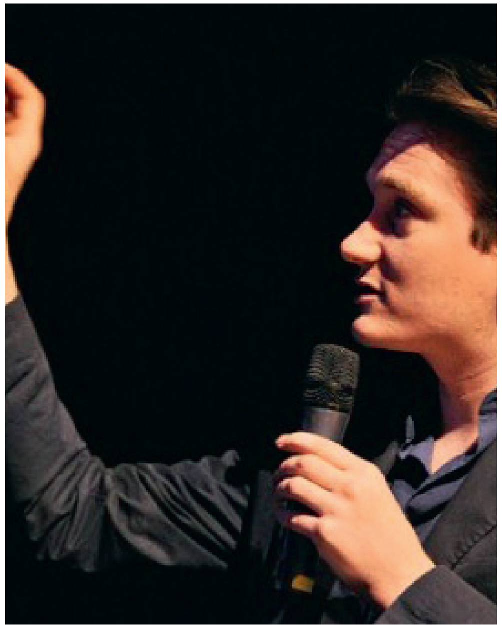
Fig.
|15 Timo Arnall



Anthony Dunne

Anthony Dunne is the author of Hertzian Tales: Electronic Products, Aesthetic Experience, and Critical Design. From 2005 to 2015 he was Head of the Design Interactions department at the Royal College of Art. Then he moved to New York to take up professorships at the New School [Dunne, n.d.].

Fig.
|16 Anthony Dunne



Richard Vijgens

Richard Vijgens is the creator of the app “The Architecture of Radio”. He is specialized in creating interactive data visualizations and installations from abstract concepts like the space of electromagnetic radiation [Vijgens, n.d.].

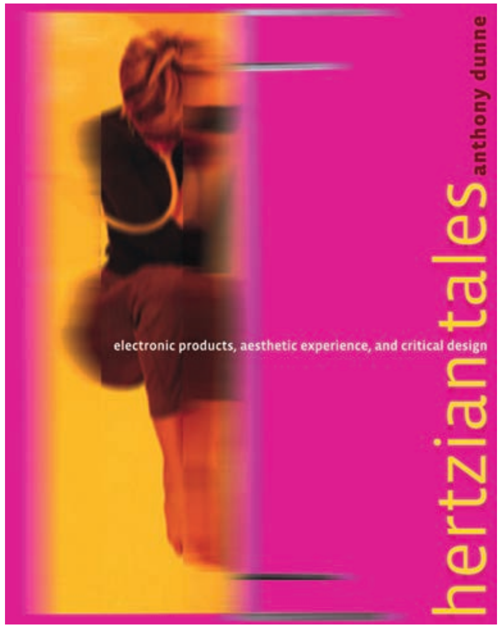
Fig.
|17 Riachard Vijgens

Related work – Inspritation

"Although when we look at an electronic product we only see what is radiated at the frequency of visible light, all electronic objects are a form of radio. If our eyes could see (tune into) energy of a lower frequency these objects would not only appear different but their boundaries would extend much further into space, interpenetrating other objects considered discrete at the frequency of light."

- Dunne, 1999

Literature and Video



Hertzian tales

In this book, Anthony Dunne defines the term "Hertzian Space" and describes the world of electromagnetic waves that emerge when machines and humans interact. For the most parts it is a philosophical discussion of the topic [Dunne, 1999].

Fig.
|18 Hertzian tales

Shock and Awe

Shock and Awe is a BBC tv show about the discovery of electricity and the history of wireless transmission. By reenacting experiments of some pioneers like Volta, Hertz and Tesla it shows how the electronics of today came into existenz [McCarthy, 2011].

Fig.
|19 Shock and Awe

Technorama

The Technorama is the perfect place to find scientific phenomena that are communicated through experience. By trying the experiments out, you start to understand the phenomenon. Because all these experiments are hands-on experiences it feels more like exploring science than learning science.
This thought of understanding and learning through exploring was very inspiring.

Besides visiting the exhibition, we also had the opportunity to meet Dr. Marco Miranda, Head of the Physics Lab and Research Associate.
We asked a lot of questions conserning the concept of the exhibition and learned a lot about how to prepare, present and test experiments. We learned about the importance of presenting one scientific phenomenon per experiment. Combining multiple phenomena in one experiment only confuses the visitors and makes it difficult to understand anything.
We also pitched our ideas for experiments and prototypes to Marco and got some valuable feedback concerning the process and its documentation. Especially interesting was the fact that even at the Technorama a lot of exhibits originated from extensive trial and error or small accidents. With every failed experiment, new findings were gained.
Since the process of trial and error is a great way to immerse into a topic we wanted to keep it in mind for our own design process.

To successfully pursue this method and to present it a comprehensible way crucial to create a good documentation of all the results. Therefore, we planned to create a blog with all the process steps.

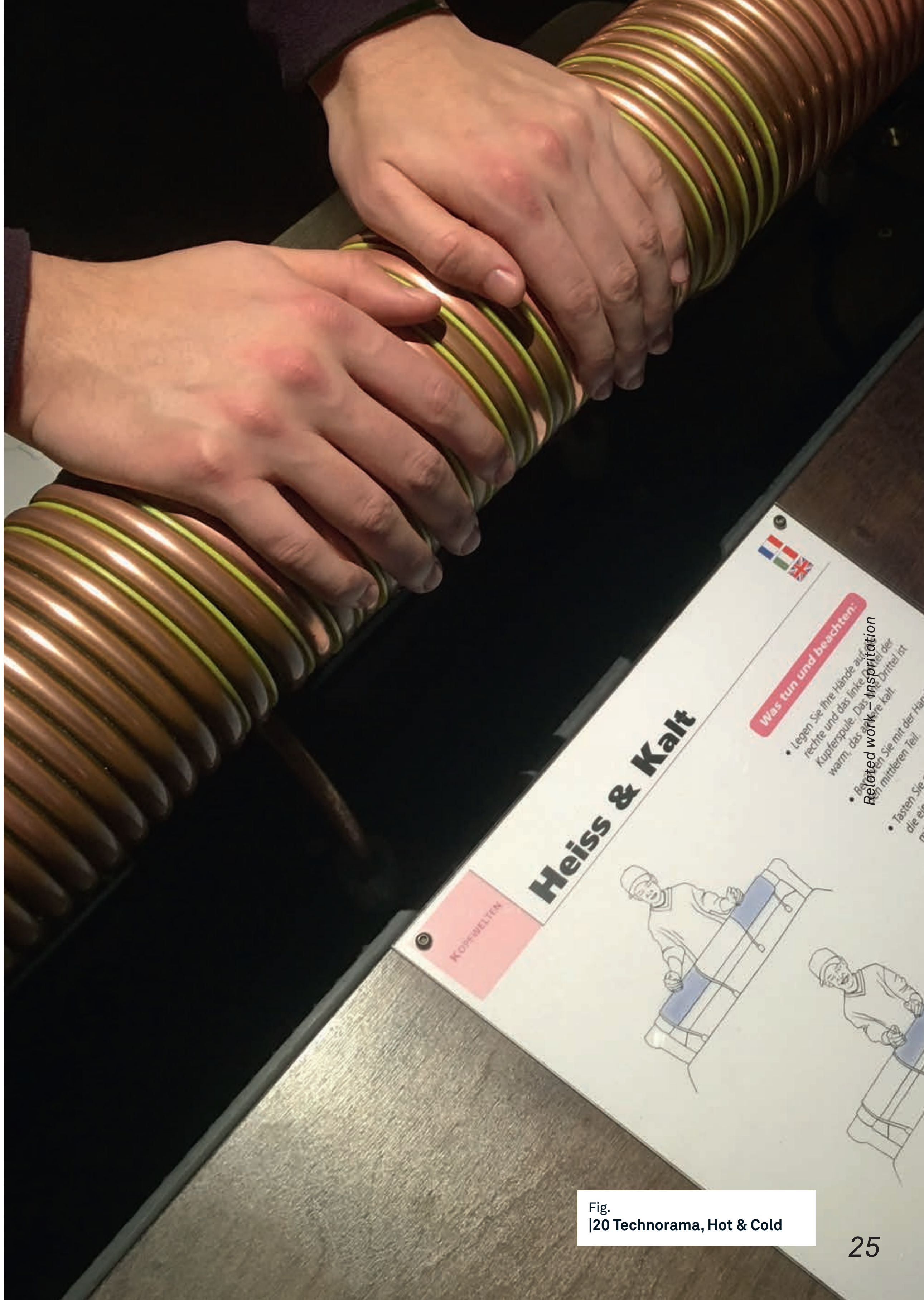


Fig.
|20 Technorama, Hot & Cold

Related work – Inspiration

Research

To understand the instructions of some experiments that we wanted to conduct we did some research about the technical aspects of electromagnetic waves, electronics and itshistory. Besides enhancing our understanding of the topic, the research opened our perspective and inspired us about experiments and ideas for the final concept. We god a lot of information from Wikipedia articles [“History of Radio”, n.d.]. But also, the BBC TV show “Shock and awe” [McCarthy, 2011] was very helpful. The journey back to the beginnings of electronics and wireless transmission allowed us to see and understand technology on a very basic level.
The more time we invested in learning about the technical aspects the more complex it became. By documenting most of what we learned on our blog, we could better memorize the material.

During our first interim presentation, we realized that there was the need to explain the very basics of the electromagnetic space. Without that information, the audience would always be slightly confused.

Overview of the spectrum

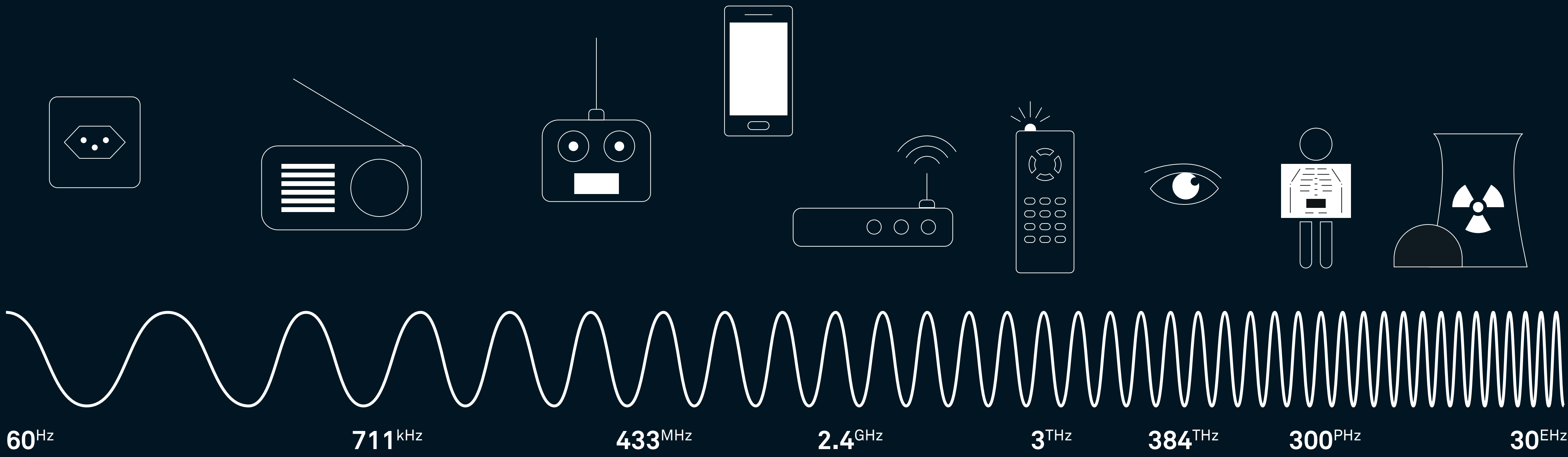


Fig.
|21 Graph overview of the spectrum

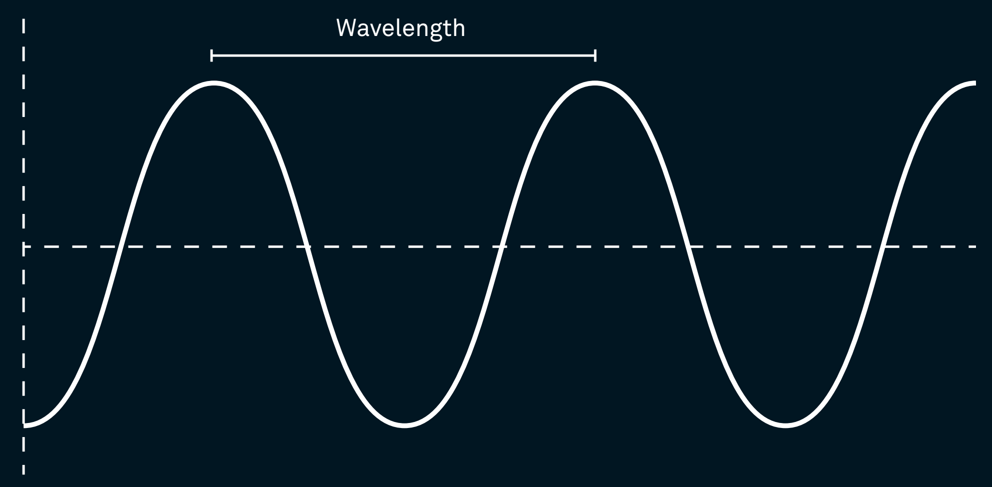


Fig.
|22 Graph, wavelength

The spectrum of electromagnetic waves

The first thing to understand is that Hertz (Hz), the unit of the frequency, represent the cycles per second. For example, if a wave oscillates 20 times in a second it has a frequency of 20 Hz. The frequency is a very important factor if you want to do anything. The lower the frequency of a wave the lower is its energy and the less information you can encode in it. Therefore, most of our information technology operates in the high range of MHz and GHz.
The frequency is also crucial for the penetration of matter. Some electromagnetic waves can penetrate walls in a house others cannot. This also depends a lot on the composition of the matter.

Our experiments began at 50-60 Hz. These low frequencies are not used to transmit information. They are emitted as a by-product of our ac power grid. By changing the direction of the current flow every 50-60 times a second it generates electromagnetic waves.

The next higher experiment started at 711KHz where we tried to receive amplitude modulated radio signals with our own crystal radio and transistor radio. Although the technology is almost ancient there are still radio stations all over the world broadcasting on these frequencies.

A lot of experiments took place in the micro wave spectrum. Between 433MHz and 5GHz we conducted different experiments to receive, transmit and block different information technologies. Almost all consumer technology of today operate in this frequency range.
Around 384THz the electromagnetic waves become visible for our eyes and we receive them as colors.

At about 300PHz the waves are very energetic. The radiation called x-rays is at a large dosage harmful to the body but correct utilized also very important for medicine.

Radiation above 30EHz is called gamma-ray. We utilize this radiation in power plants, science and war [“Electromagnetic Radiation”, n.d.].

To calculate the wavelength and energy for our prototypes we used the following formulas:

Wavelength

$$\frac{v}{f} = \Lambda$$

v = velocity of the wave in m/s
f = frequency in Hz
Λ = wavelength in m

Energy

$$h \times f = E$$

h = planck‘s constant
f = frequency in Hz
E = energy in J

Method

After the desktop research, we started to conduct the first experiments. Since we had not much experience with the topic of electromagnetic waves it was important for us to start with the experiments as soon as possible. By approaching it a more practical way we hoped to find a faster access to this complex subject.
During this process, we documented all the steps and experiences in our blog so that we always could reflect on the completed work. The time consumption and complexity of the experiments varied heavily. But in the end, we were glad for conducting them all since they led us to useful findings. While experimenting we also got many new ideas how we could make the hidden space explorable.

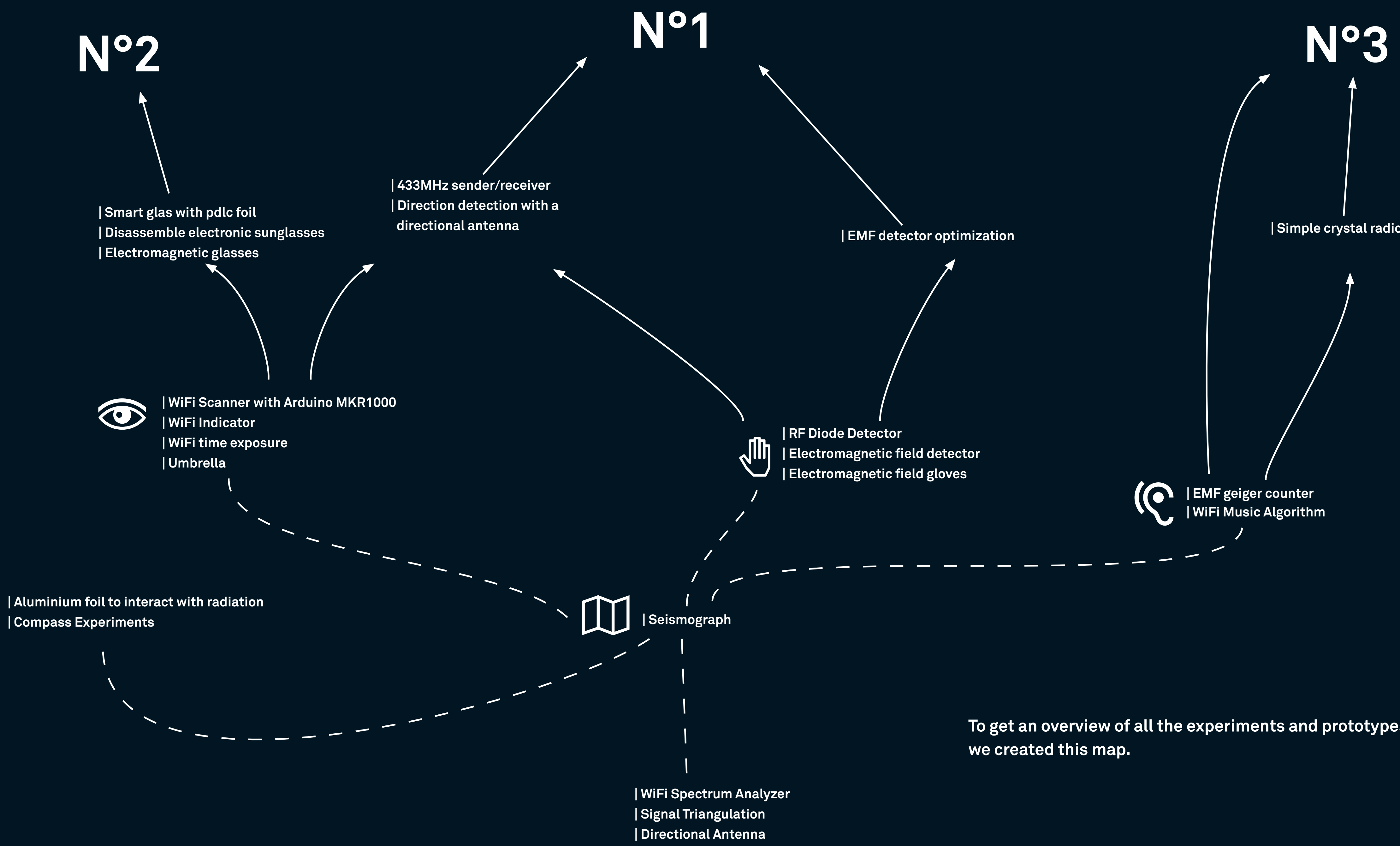
Rapid prototyping

"For human-centered designers, Rapid Prototyping is an incredibly effective way to make ideas tangible, to learn through making, and to quickly get key feedback from the people you're designing for. Because prototypes are meant only to convey an idea-not to be perfect-you can quickly move through a variety of iterations, building on what you've learned from the people you're designing for. Rapid Prototyping makes sure that you're building only enough to test your idea, and that you're right back in there making it better once you've gotten the feedback you need."
["Design Kit", n.d.]

Our methodology

We selected this method to quickly learn more about the topic and to stay agile during the whole project. The method was perfect for this tinkering process and it allowed us to work on different experiments at the same time, to share the learnings and to generate new ideas. The quick feedback from other people and ourselves enabled us to select suitable ideas from this wide range of experiments and prototypes.

Experiments and prototypes



To get an overview of all the experiments and prototypes we created this map.

Fig.
|23 Overview prototypes and experiments

WiFi Scanner with Arduino MKR1000

To start experimenting with WiFi signals, we got an Arduino MKR1000 and tried to program a WiFi Scanner. Based on the example code of the WiFi shield library we wrote a code printing out the number of networks around, the average signal strength and maximal signal strength.

WiFi Indicator

Based on the WiFi Scanner experiment we created a mobile WiFi signal indicator. The led glows red if the signal is weak, green if it is strong, and blue if it is very strong.

While preparing the rgb led we realized that it needed a resistor to control the voltage ["LED Resistor Calculator", n.d.]. We calculated the necessary resistor value with the following formula:

$$\frac{V_S - V_{LED}}{I_{LED}} = R$$

V_S = source voltage in V
V_{LED} = led voltage in V
I_{LED} = led current in A
R = resistance in Ω

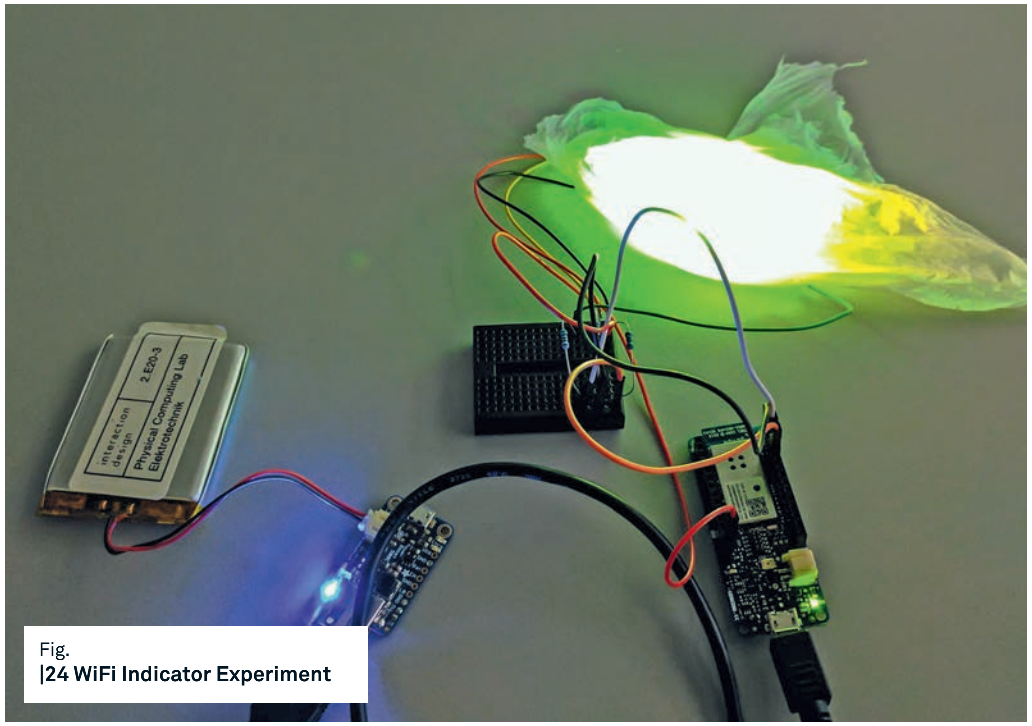


Fig.
|24 WiFi Indicator Experiment

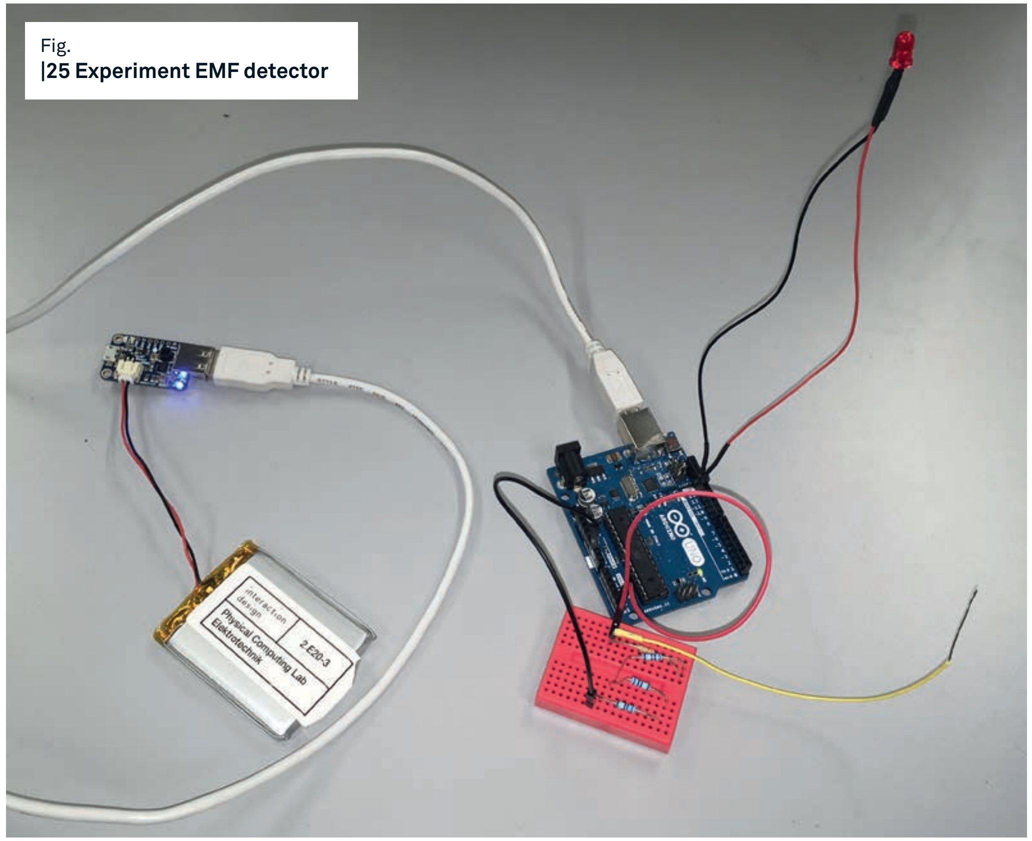


Fig.
|25 Experiment EMF detector

Electromagnetic field detector

The goal of the experiment was to measure electromagnetic fields with a simple circuit and a wire antenna. The detector consists of an Arduino Uno, jump-wires, resistors and a red led [computergeek, 2009]. To test it we held the antenna near the following devices:

- Lenovo laptop charger
- MacBook charger
- Microwave
- Handy
- Handy (with Hotspot)
- Fridge

There was no visible difference between these objects. Only the Lenovo laptop charger made the led shine brighter. Also, the light changed its brightness always in a waveform. For further experiments, we will change the antenna, vary the resistors and review the code.

Overview of experiments and prototypes

Fig.
|26 Experiment WiFi time exposure

<u>WiFi time exposure</u>

Inspired by Luis Hernans work we tried to visualize the WiFi by taking time exposure photographs of our WiFi indicator prototype [Hernan, 2017].

Because WiFi radiation has a far larger wavelength then visible light you would need also a huge camera to capture these waves (like a radio telescope). Therefore, we used time to move the sensor and generate the higher resolution.

To create these pictures, we first had to prepare the room. The room needed to be very dark and all WiFi access points except for one had to be turned off. Then we set the capture time of the camera between 30 seconds and 1 minute and carried the sensor slowly through the room.

The aesthetic of the photos was astonishing. Also, it is possible to find the WiFi access point on the picture by looking.

The experiment allowed us to visualize the strength of the WiFi and therefore search and find the radiation sources. Unfortunately, the led still needed one second to update its color. That resulted in hard color transitions and inaccurate values during fast movements.

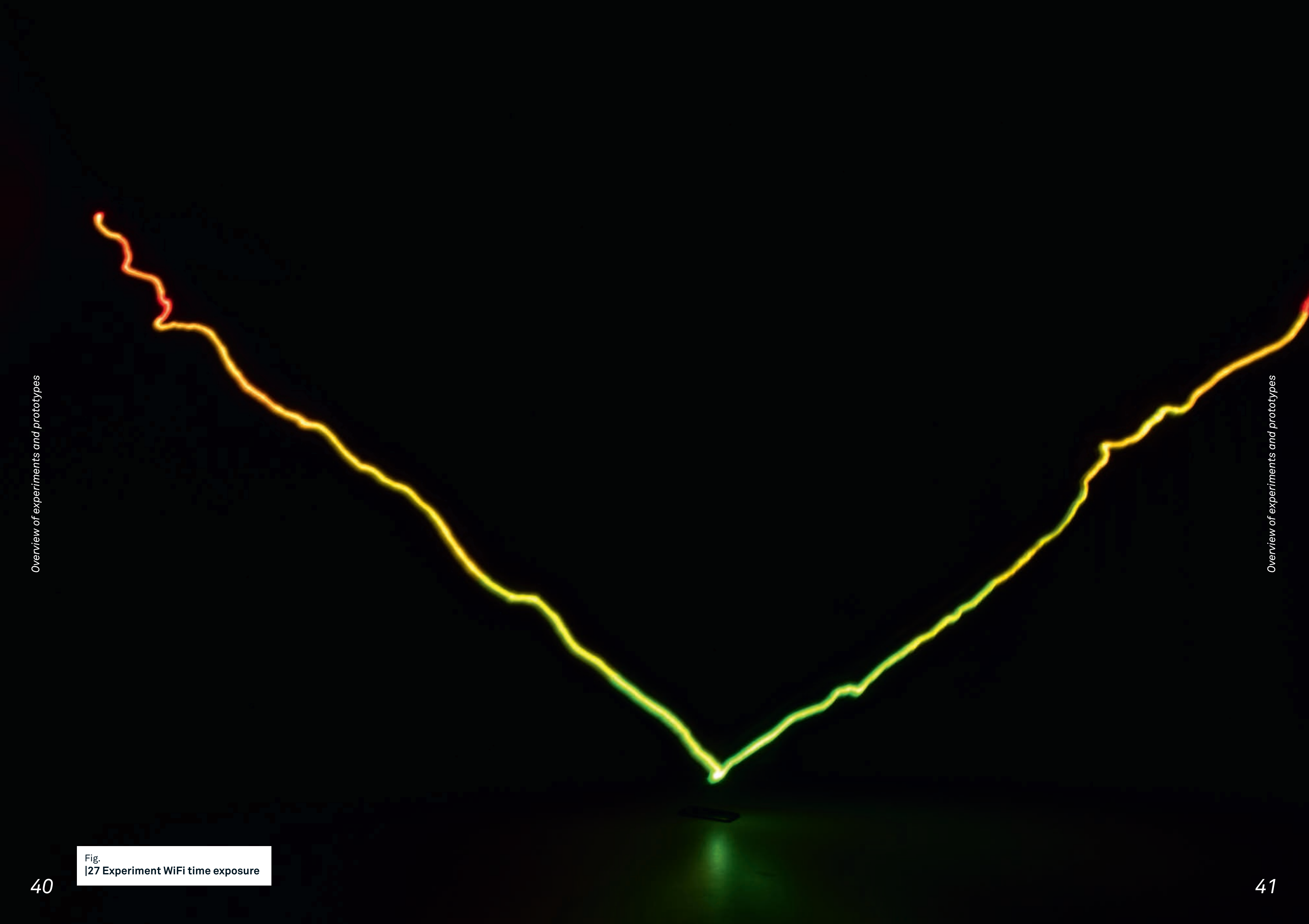


Fig.
|27 Experiment WiFi time exposure

Overview of experiments and prototypes

<u>Aluminum foil to interact with radiation</u>

To find out if we could somehow interact with electromagnetic radiation we tried to block of the WiFi frequency and the cellular frequency.
With three layers of aluminum foil we could absorb the cell phone radiation. But only a small hole in the shell was enough and the radiation was no longer blocked.

Afterwards we tried to build a radiation blocking case for the smartphone. However even the smallest gaps were enough and the radiation was no longer blocked.
In the end this experiment was not relevant since we decided to not work with the topic of absorption and blocking. Nevertheless, it was very interesting and insightful.

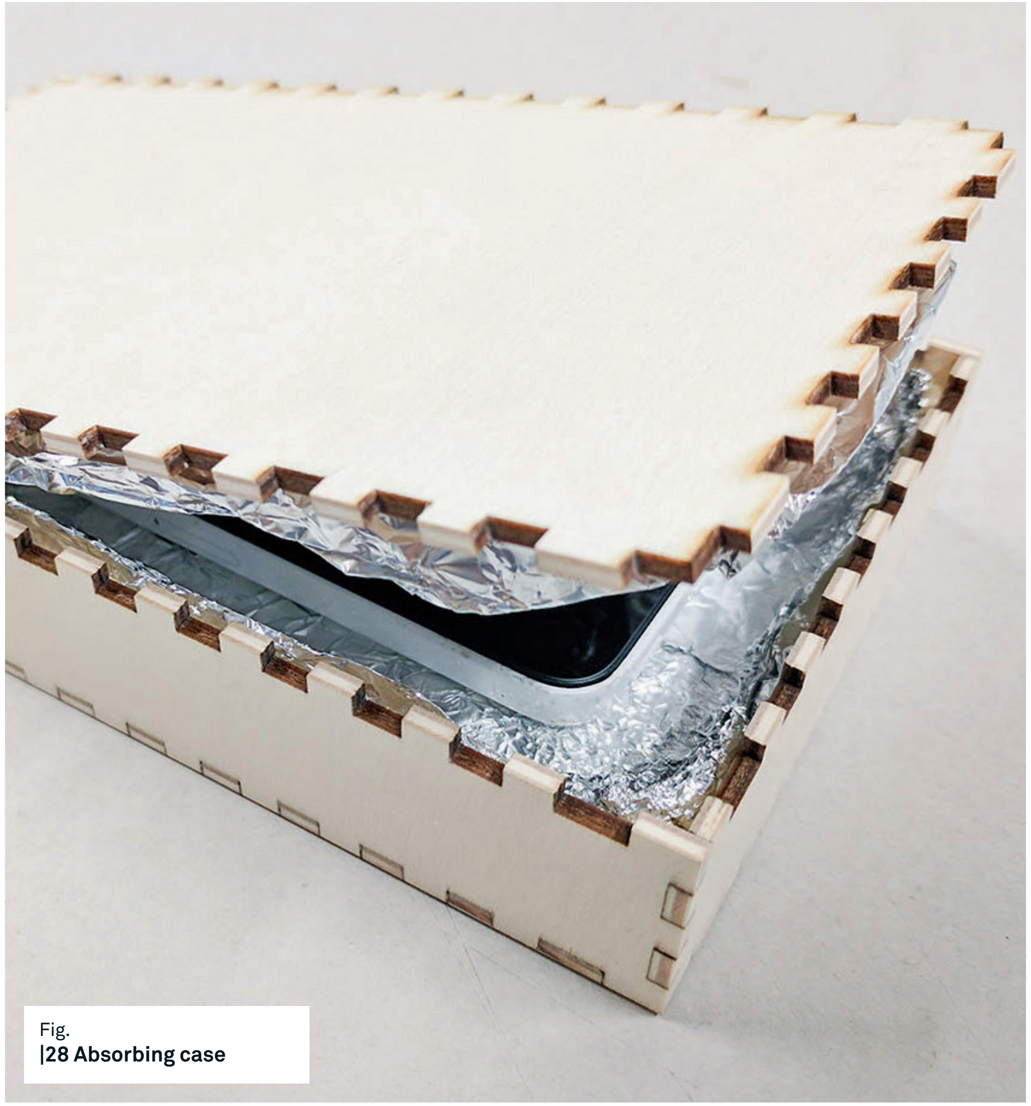


Fig.
|28 Absorbing case

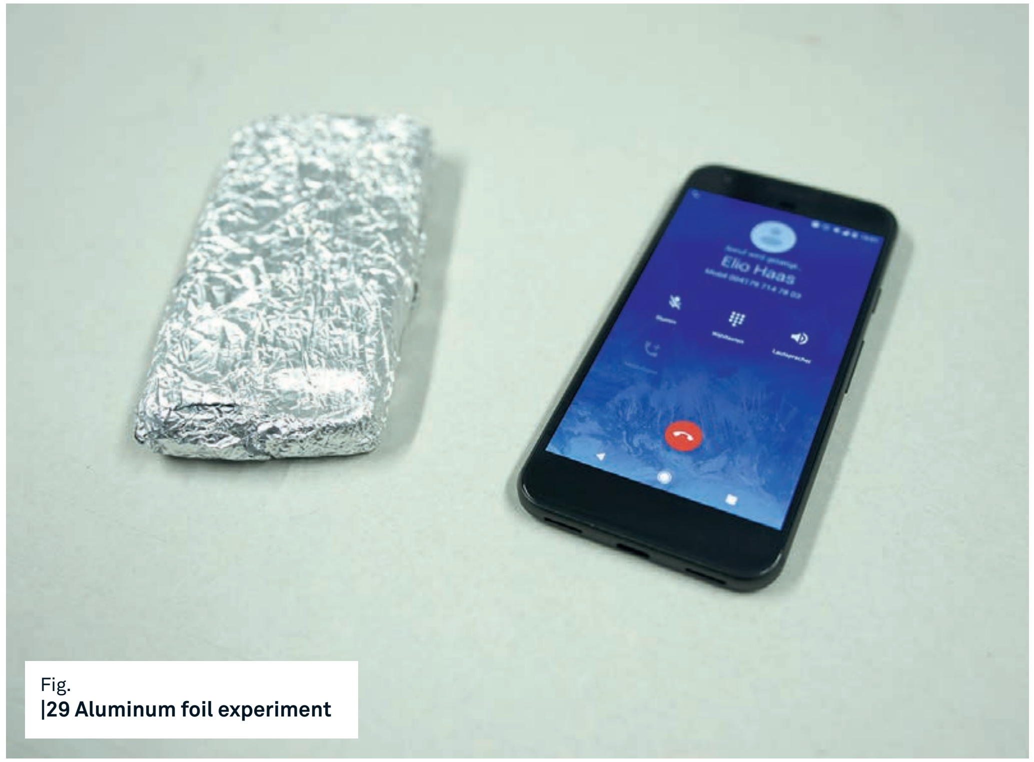


Fig.
|29 Aluminum foil experiment

Fig.
|30 Hole in aluminum foil

<u>Compass Experiments</u>

Inspired by the compass table of Anthony Dunne and Fiona Raby we wanted to build a compass from everyday materials and check if we could detect electromagnetic fields.

Made from cork, a ferromagnetic wire and bowl of water we started the first compass experiment. With a magnet, we magnetize the wire and pierced it through the cork. We then placed it on the water and waited for it to adjust to the magnetic field. Even though the wire did not point north it pointed always in the same direction. We believe that other magnetic fields in the house influenced the compass.
We tried to optimize the compass with a thicker wire and a bottle cap as float. The compass still pointed in the same direction as before.

Like the previous EMF detector prototype our compass reacted to magnetic fields. But in contrast to the last experiment it is completely made without electronics. This makes is much easier to understand and offers good entry into the topic. Unfortunately, the compass only reacts to rather strong magnetic fields. Therefore, we could not make the weak electromagnetic fields from WiFi, Smartphones, etc. visible.

The second test with the compass board was frustrating. It did not work at all. Either it was because of the cheap compasses which did not work very well or the fields are much to weak.

Still the compass is a very interesting object to visualize strong magnetic and electromagnetic fields.

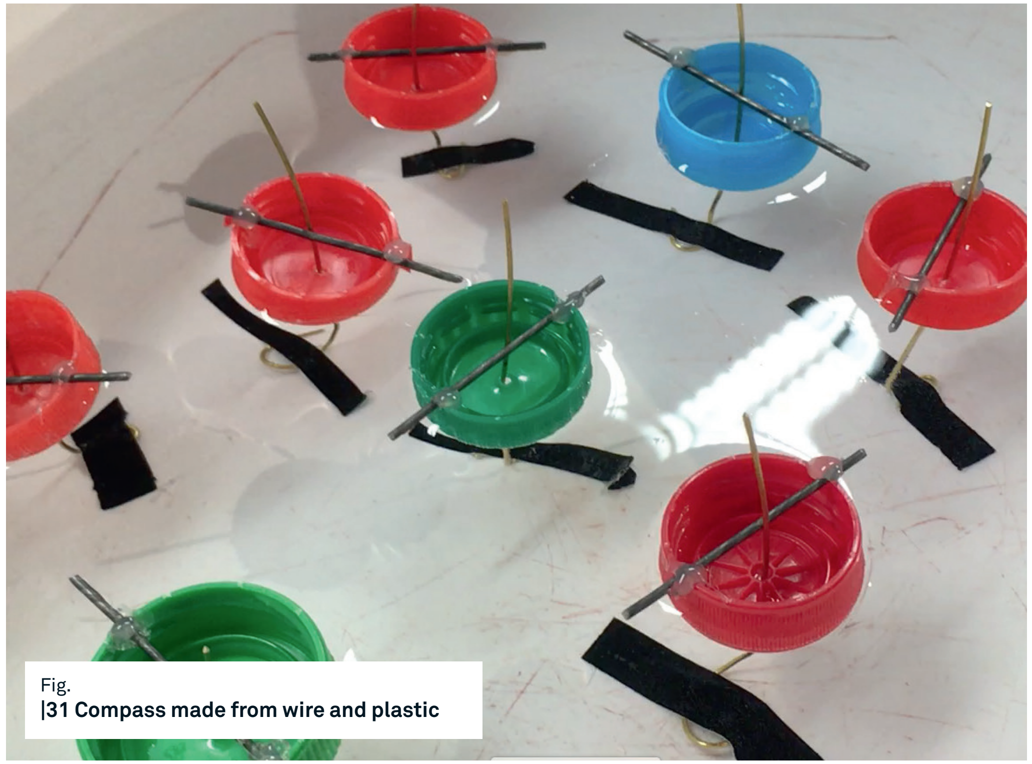


Fig.
|31 Compass made from wire and plastic

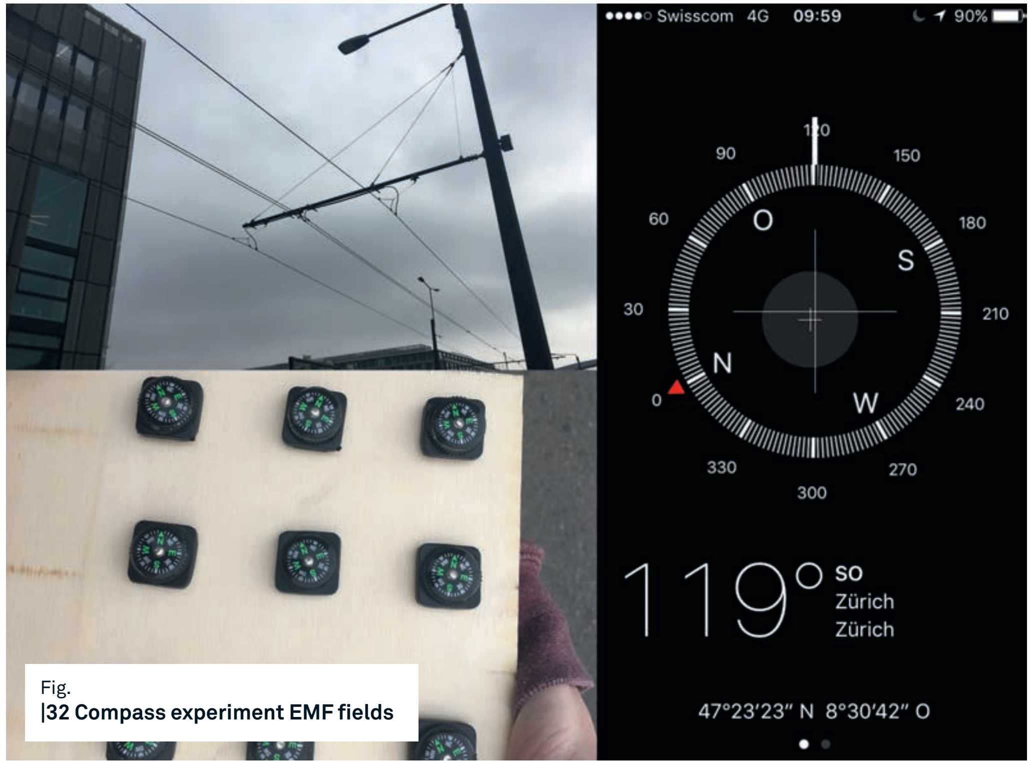


Fig.
|32 Compass experiment EMF fields

Overview of experiments and prototypes

RF Diode detector

Based on a few instructions from the internet ["DIY RF Meter using detector diodes", n.d.] we tried to build a RF detector that lights a led with just the energy the germanium diodes pick up from the surrounding radiation.

The prototype did not work. Even with the multimeter we did not get any noteworthy voltage results. While double checking on the internet we realized, that the schematics came all from the same RF protection equipment company. It is possible to pick up radiation change with germanium diodes but not to power a led with it.

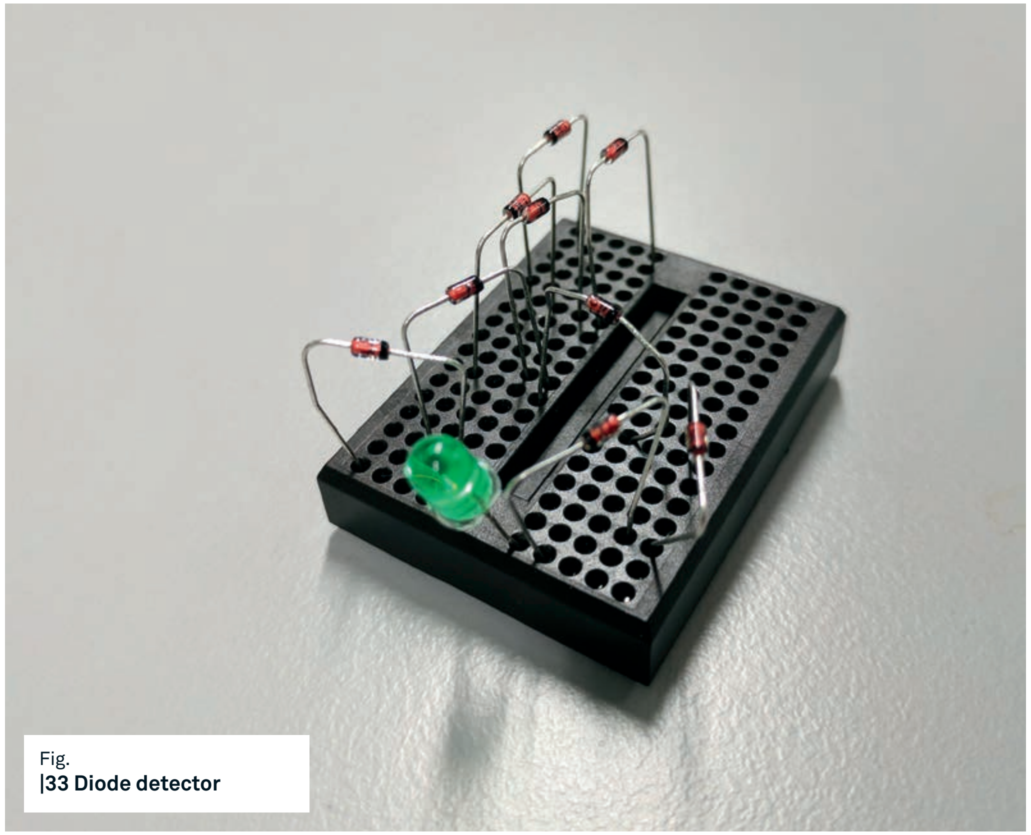


Fig.
|33 Diode detector

EMF Geiger counter

By removing the led from the Electromagnetic field detector and adding a speaker we tried to create a device with the same acoustic output as a geiger counter.

By accident we discovered that if you set the tone() frequency to 10Hz and the duration to 50ms the speaker generates a sound very similar to the geiger counter. This was surprising because the Arduino only supports frequencies to 31Hz.

The RF detector still works great and with the acoustic output of a geiger counter it attaches an unpleasant and dangerous aura to the prototype.

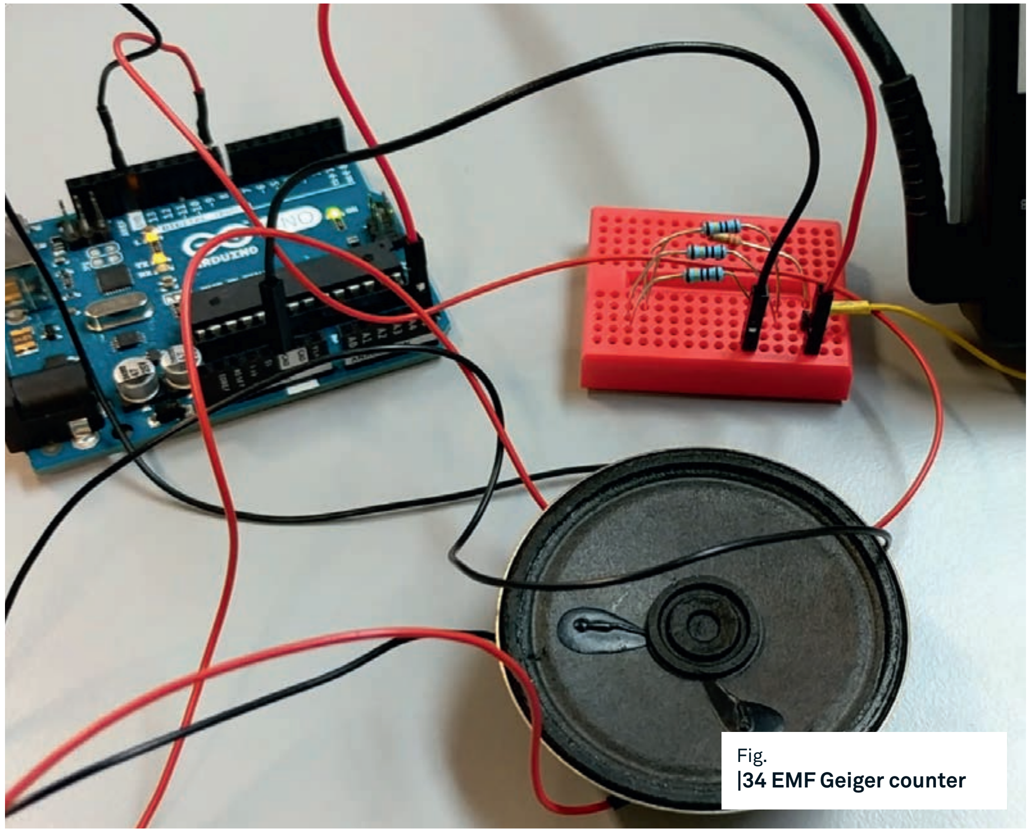


Fig.
|34 EMF Geiger counter

433MHz sender/receiver

By looking through the spectrum of electromagnetic waves we found the ISM bands. ISM stands for industrial, scientific and medical radio bands. The ISM bands are standardized frequency ranges used by a lot of different applications in our everyday life (car keys, remote controlled toys, baby phones, WiFi, Bluetooth, etc.). One of this bands works on the frequency 433MHz. To test this frequency, we bought a sender/receiver kit and started experimenting.

First, we started to build a communication device where we could write a sentence, send it over the 433MHz band and receive it with the other Arduino. While testing the communication device we realized that the length of the sender antenna is important for a successful transmission. The first attempts failed because we just used the included antenna. By mistake we touched the antenna with a finger and it started working.

As a result, we tried some other materials as antenna and ended up with a steel table leg.

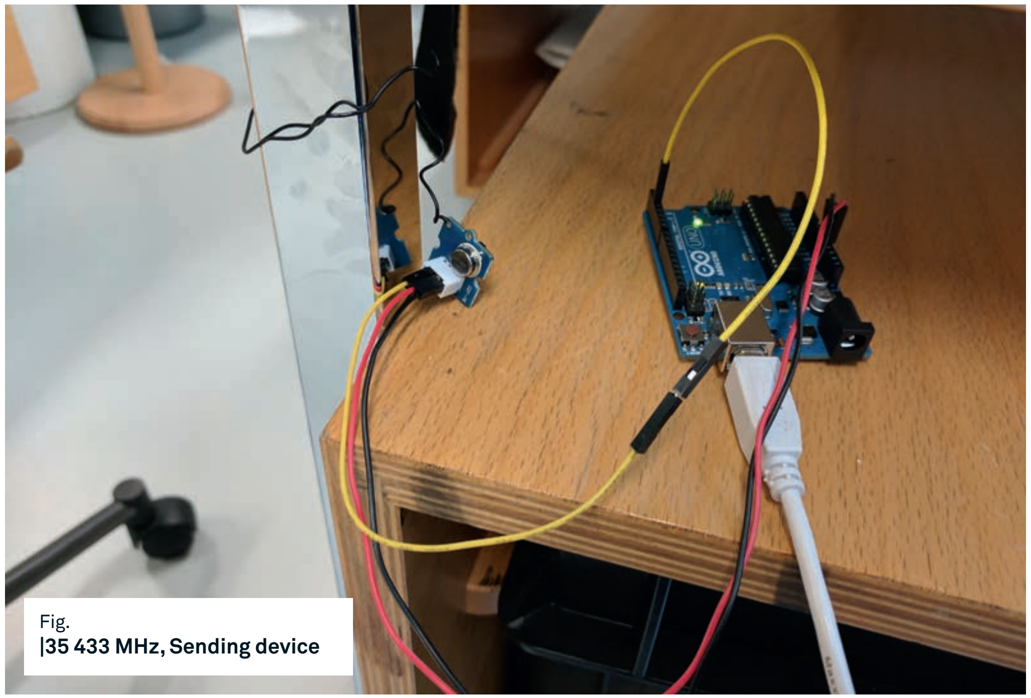


Fig.
|35 433 MHz, Sending device

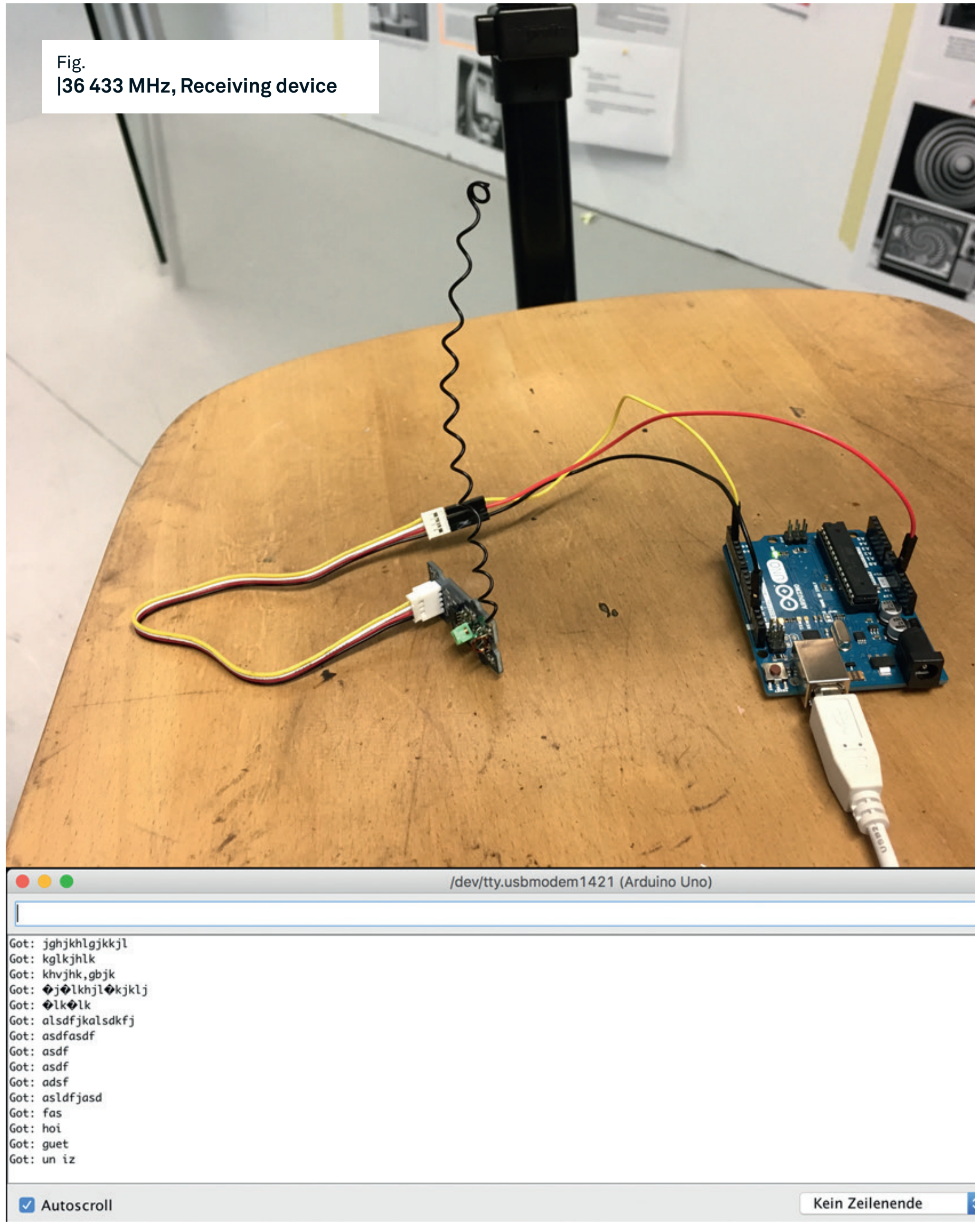


Fig.
|36 433 MHz, Receiving device

WiFi Seismograph

Our idea was to create a machine based on the mechanical properties of a seismograph. The machine was supposed to detect and display electromagnetic waves. With the merge of this old analog technology and the electromagnetic waves detector we wanted to create an interesting aesthetics.

To find out how to rebuild the mechanics of a seismograph we did some desktop research and looked at some existing do-it-yourself tutorials. Based on this research we created our first own sketches to build the prototype.

While building the prototype we ran into difficulties with the mechanics a lot. A rotating paper roll sounded easy in theory but to create a mechanism that runs smoothly was quite difficult.

To quickly get started we used the embedded WiFi module on the Arduino MKR1000 as WiFi indicator. It detects the strongest WiFi network around and passes the RSSI value on to the servo. The servo then draws it on the paper.

During the experiment, we had to rebuild several parts to optimize the construction. Especially the paper roll was quite difficult. To be prepared for some inaccuracy we also build the parts with the possibility to make small adjustments.

The drawing mechanism constructed of a pen holder and a spring makes it possible to insert different pens and adjust the its pressure on the paper.

Like the WiFi indicator this prototype made electromagnetic waves visible. But instead of light we used something analog to display and record it. Like the seismograph captures the tectonic movements the WiFi seismograph captures the WiFi signal strength. The prototype consisted of wood, metal screws, a pen, a paper roll, a dc motor and a servo.

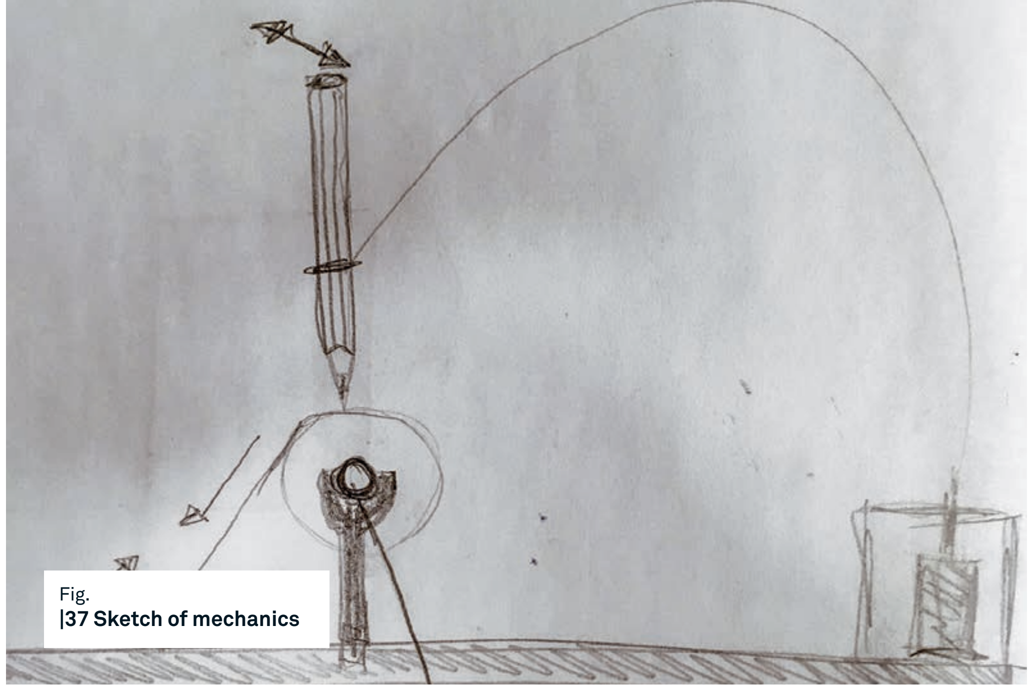


Fig.
|37 Sketch of mechanics

Fig.
|38 Pen mount

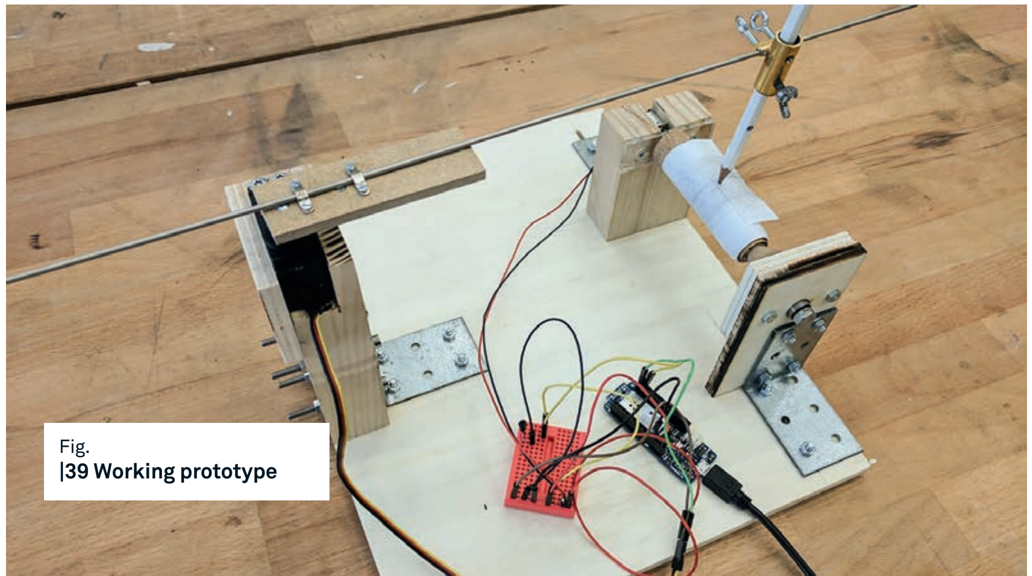


Fig.
|39 Working prototype

Electromagnetic field gloves

With these gloves, we wanted to create an object that gives you a haptic feedback. Based on our research and the experiments with EMF detector we decided to build a glove that detects magnetic fields and translates them into a haptic feedback. The prototype should give the wearer the feeling of touching something invisible.

By testing different options, we want to find the best fitting solution.

- Air pillow
- Electric Current
- Warmth
- Piezo
- Haptuator

The best haptic feedback was clearly the haptuator. But because of its large size we decided to go with the button vibration motor. To get a first experience of our intended prototype we hooked up the EMF detector to a vibration motor.

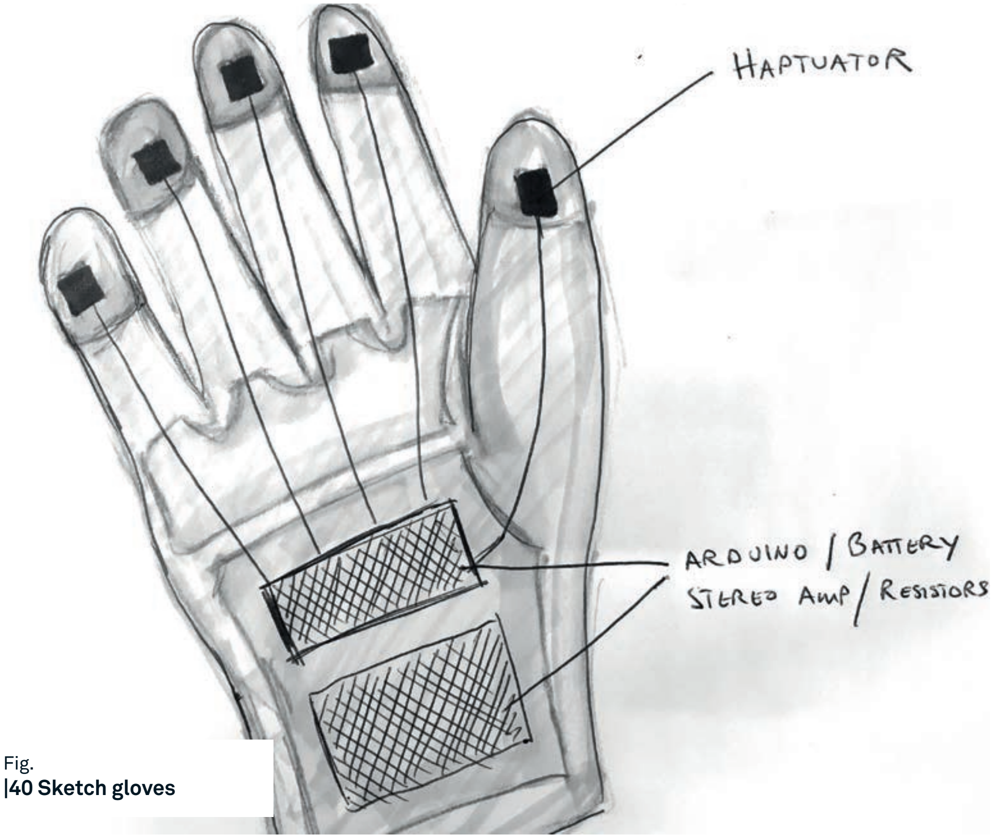


Fig.
|40 Sketch gloves

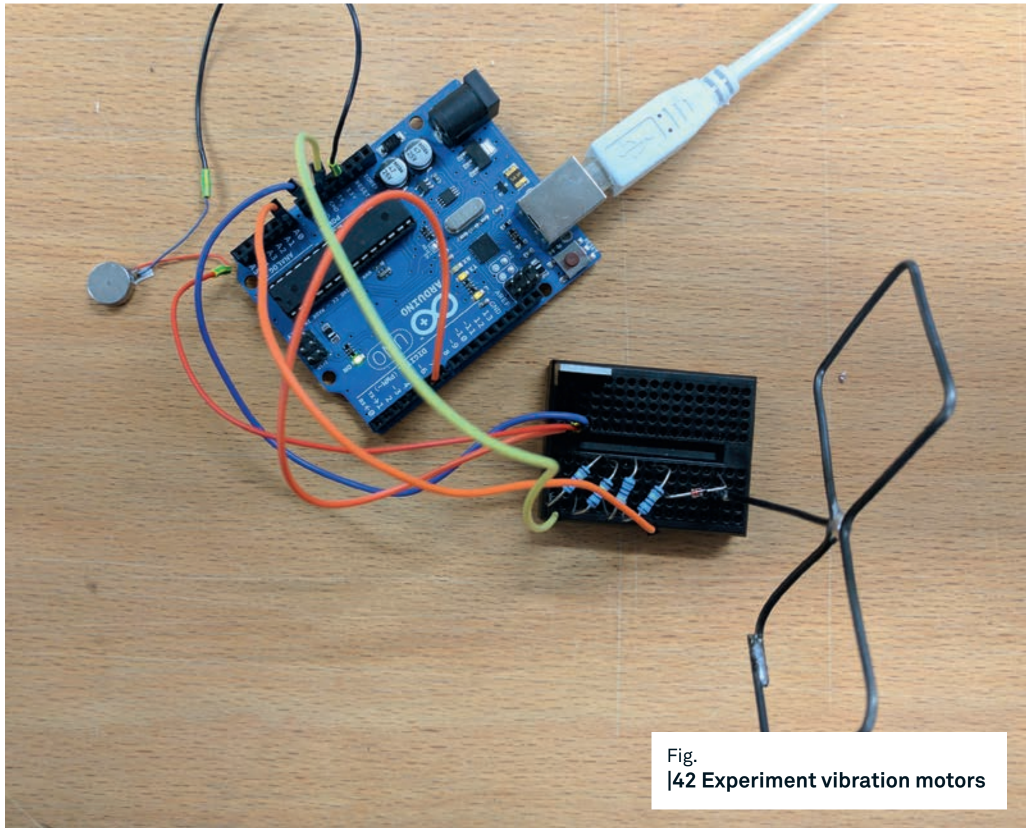


Fig.
|42 Experiment vibration motors

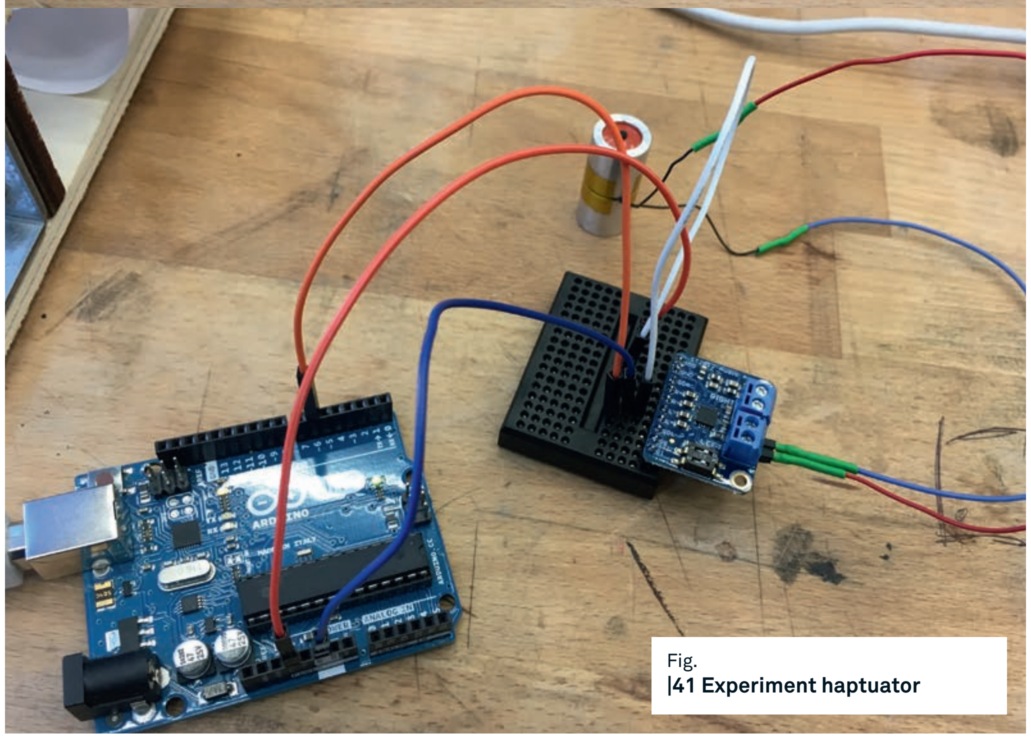


Fig.
|41 Experiment haptuator

WiFi Music Algorithm

With this experiment, we wanted to create music by inserting detected radiation sources into a music algorithm. The generate music would vary when changing location. Depending on what WiFi networks, Bluetooth devices, satellites and mobile networks are around the music would adjust.
To create a music algorithm, we looked for some simple examples. By altering these examples, we could code a very simple random music generator. The code randomly selected a note and played a corresponding arpeggio. By inserting information from the detected WiFi networks instead of random notes we create a very simple WiFi music algorithm.
Since we wanted to integrate the experiment into an object we tried to make it smaller than the currently used laptop. We bought a Raspberry Pi Wireless and tried to transfer the JavaScript program onto it. After several failed tries to the code and the sound working we moved on to the next experiments.
The WiFi music algorithm was a very interesting approach to make the hidden space audible. Since this idea could easily be a project on its own and because we struggled with many technical issues we decided to cast it aside.

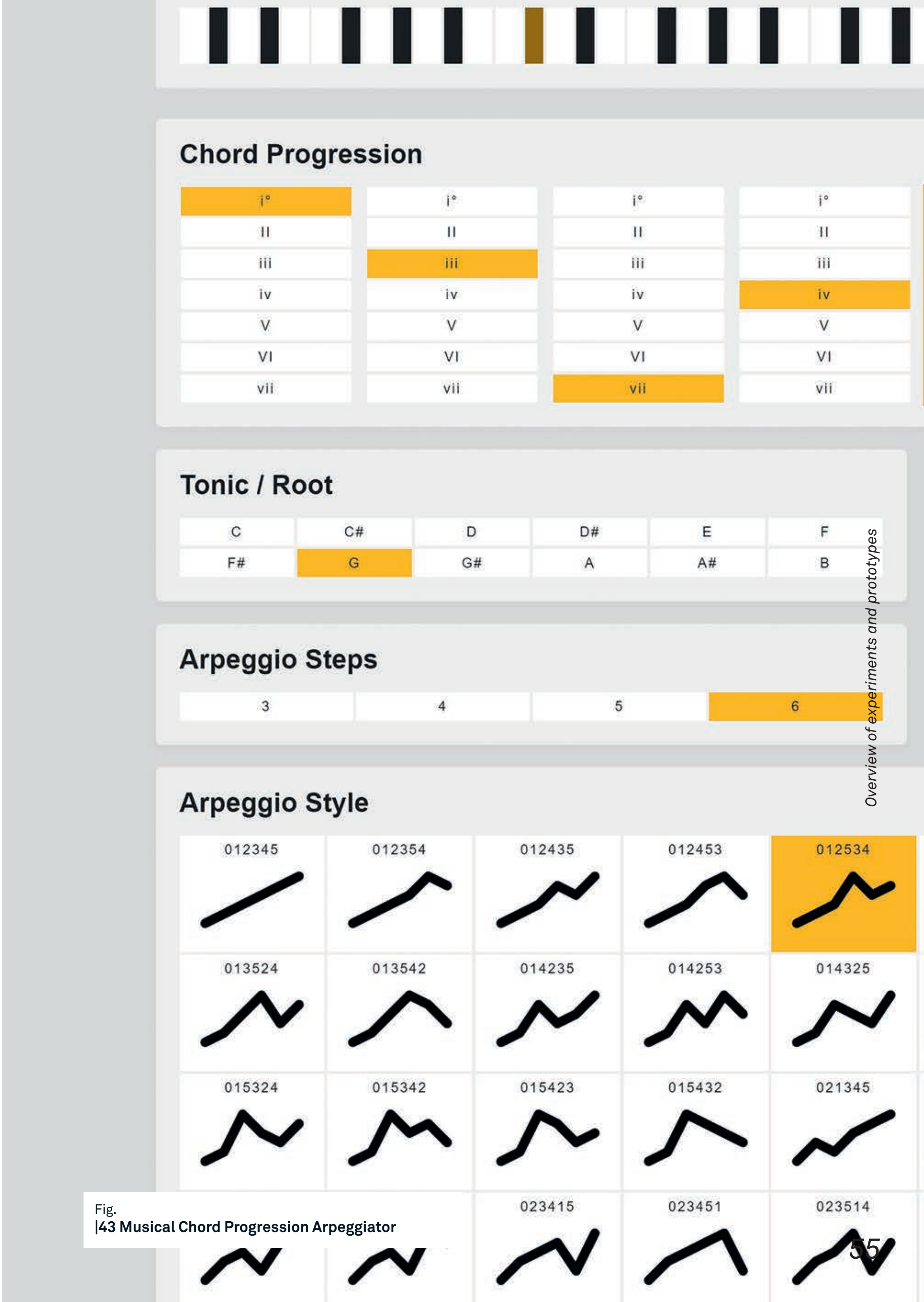


Fig.
|43 Musical Chord Progression Arpeggiator

Overview of experiments and prototypes

Direction detection

To get the direction of a radiation source we tried to build a directional antenna. When you turn a directional antenna 360 degree and take every few degree a RF power measurement you end up with a good overview where the radiation is coming from.

Based on some instruction about a can antenna we tried to build directional antenna for the WiFi spectrum. We bought a can with a diameter of 100 mm and installed a 33mm long copper wire.

Based on different instructions we build a yagi antenna for 2.45GHz. Like the can antenna the yagi antenna is a directional antenna that amplifies the signals from the direction you are pointing it at. Depending on how precise you worked and how many copper elements you embedded the antenna gets more directed.

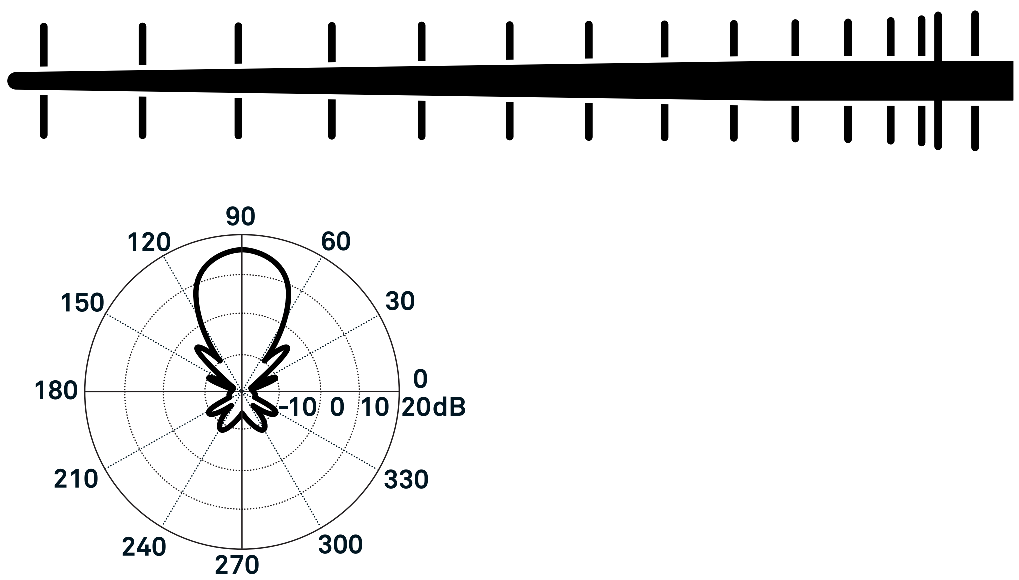


Fig.
|44 Yagi antenna with directional graph

Fig.
|45 Can antenna for WiFi

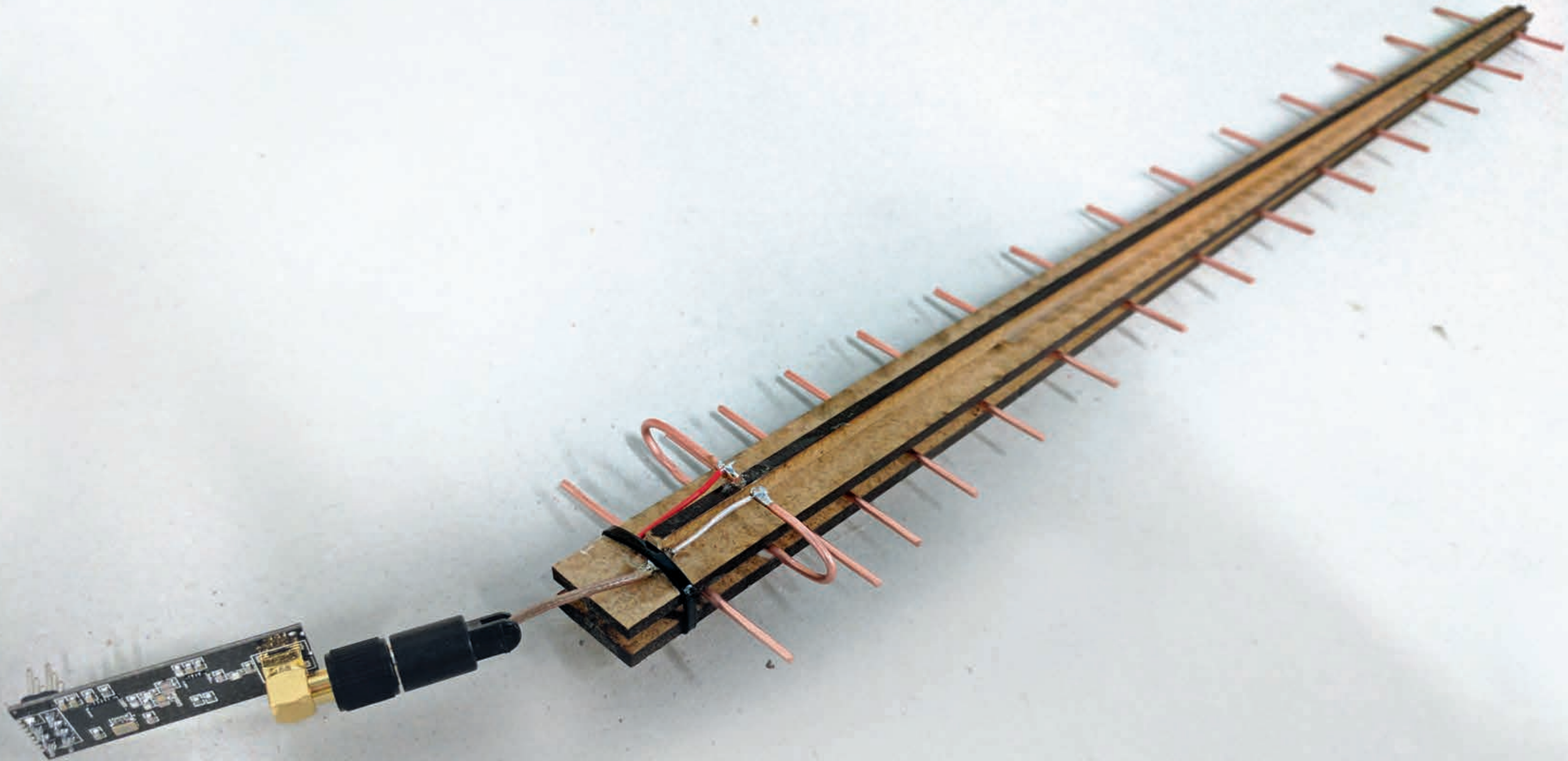


Fig.
|46 Yagi antenna for WiFi

Overview of experiments and prototypes

Fig.
|47 Construction for the video

Electromagnetic glasses

With this experiment, we wanted to find out how we could interfere with the sensory perception of sight.

As a first step, we tried to create glasses with a build-in light effect. We used a laser cut frame and a led that blinded the eye. As a next step, we sandblasted the glasses to change reflection properties. Creating a variety of different glasses allowed us to find a suitable model for further development. To optimize the effect, we wanted to work with a foil which reacts to electricity. With this foil, we wanted to create a more impressive effect and a better controlled prototype.

To get a glimpse on the effect and to present it at the interim presentation we decided to create a video. We captured the glasses in the first person view and simulated the effect with After Effects.

To get this effect in a real functional prototype we did a desktop research to the topic of PDLC foil/films. This material can change the opacity from clear to opaque by applying a voltage. We decided to test the material and see if we could achieve the desired effect.

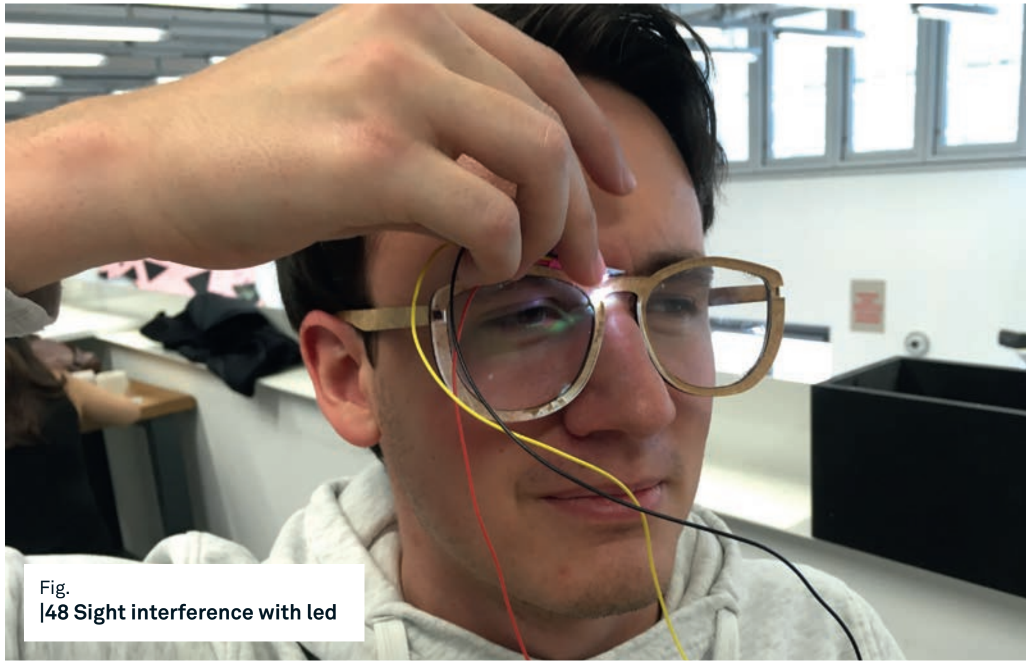


Fig.
|48 Sight interference with led

Smart glass / PDLC foil

To build the glasses we were looking further into PDLC foil. A material that could be controlled to switch between transparent and opaque.
The goal of this experiment was to figure out how the PDLC foil works and if it would fit our requirements.

Our first test with this material totally failed. The transformer started fuming, smelled bad and was destroyed. We knew it would be a risky attempt to connect the US 110V transformer to our 230V EU power outlet. But since we did not have and 230V -> 110V adapter we tried it anyway.

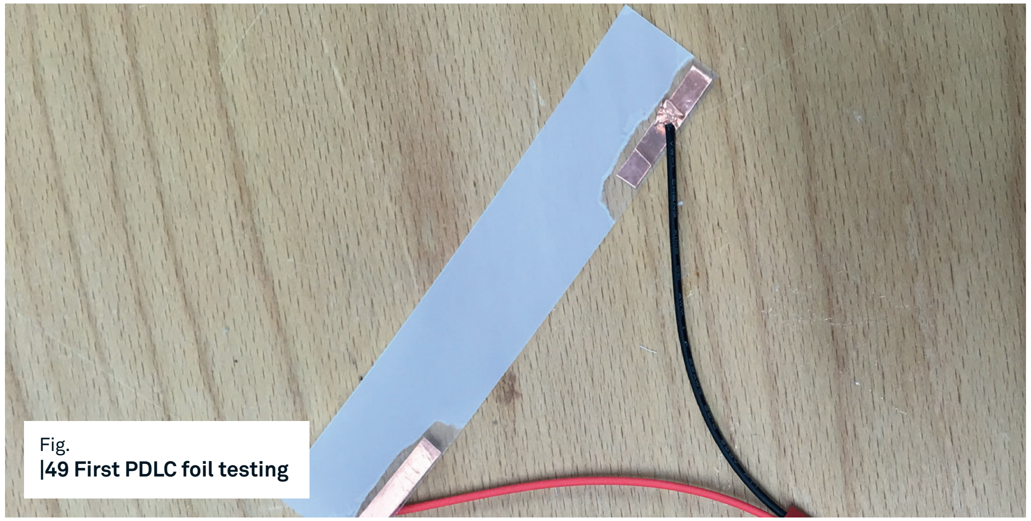


Fig.
|49 First PDLC foil testing

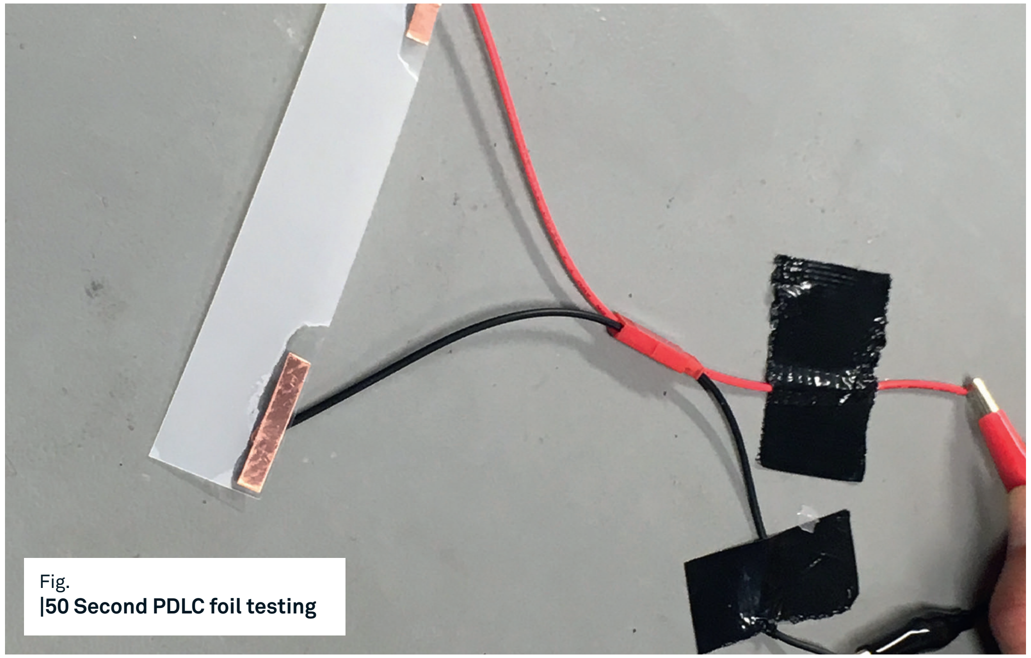


Fig.
|50 Second PDLC foil testing

Therefore, we bought a new transformer that generates the 60V AC we need. The new transformer was working as desired. But the foil was still blurred. After several more tests and frustrating hours we decided to abort the experiment. It was a hard decision because we really liked the concept with the blurry foil but we had already wasted too much time with it. Also, we had already a different experiment planned to create the effect with disassembled electrical sunglasses.

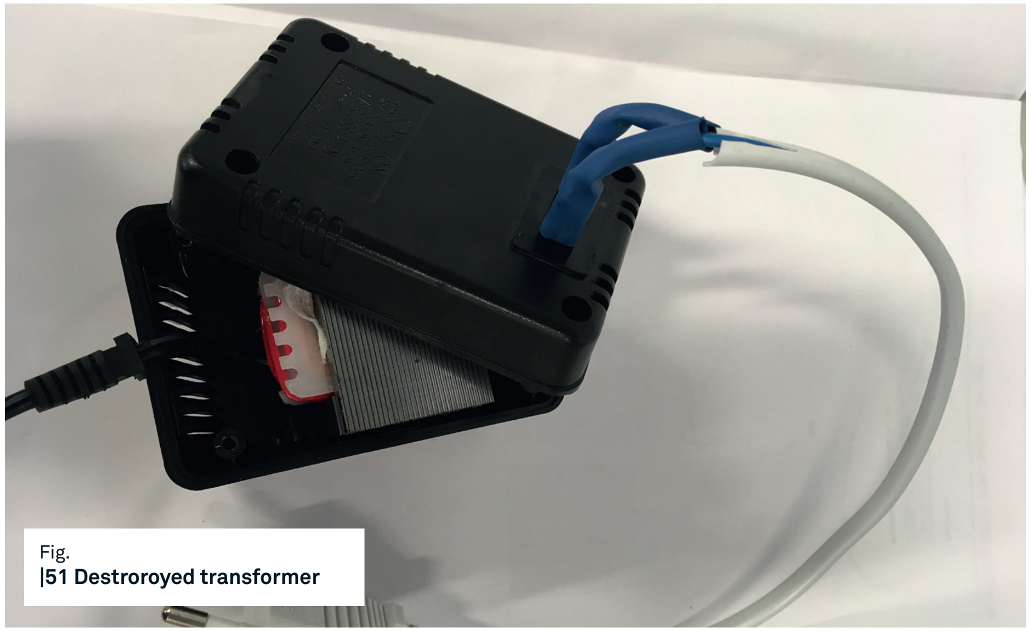


Fig.
|51 Destroroyed transformer

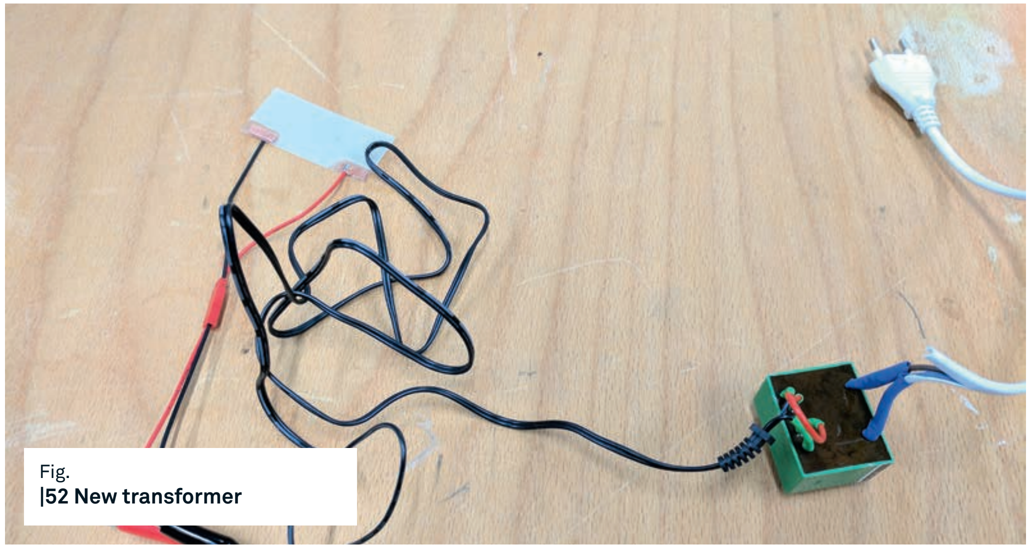


Fig.
|52 New transformer

Disassemble electronic sunglasses

Since we found glasses that can change the dimming we bought one and had a look on the technology behind it. By taking the glasses apart we hoped to find something we could use for our own glasses.

The glasses we bought had a surprisingly good quality. Everything was fixed with screws and no glue. The electronics of it was simple. To power the glasses, they used a 3.15 V button battery. A small PCB then converted the direct current to an alternating current of 2.5 Vm. By changing the duty cycle of the square wave, they controlled the dimming of the glasses.
Since it is quite complicated to create a real alternating current with an Arduino we tried to control the glasses just with a PWM signal and a voltage divider to limit the maximal voltage to 2.5 V. Luckily this worked great.

Fig.
|53 Disassembled sunglasses

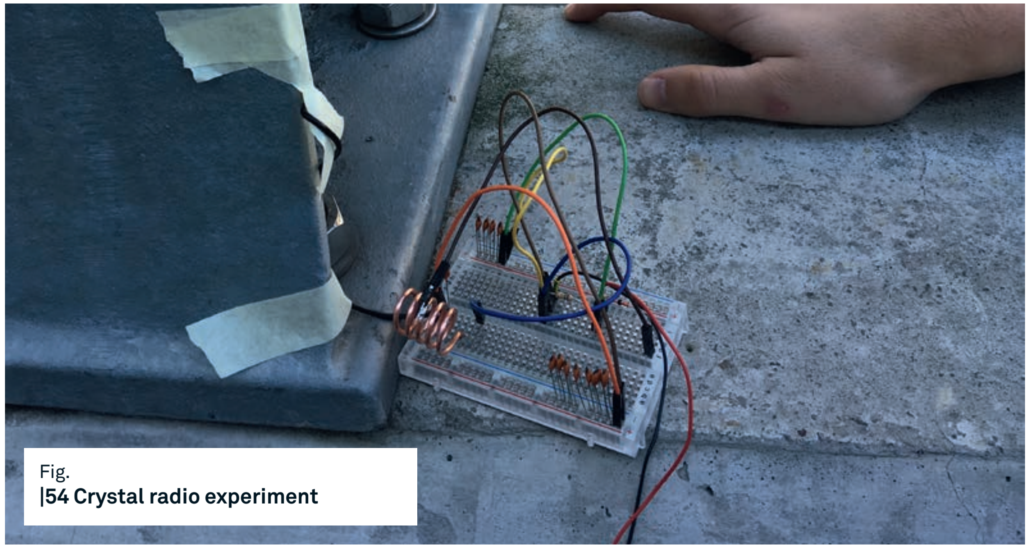


Fig.
|54 Crystal radio experiment

FM crystal radio.

Based on different instructions from the internet we tried to build a very simple low quality FM crystal radio.
FM radio is a method to transmit information (sound) by modulating the frequency of the signal. Luckily the electronics to receive FM signals are very simple. To build this circuit we only needed a 5 turns copper coil, an antenna, 2 standard capacitors, an 1N34 diode, a resistor and a variable capacitor. ["Capacitor", n.d.]

Since we did not find a suitable variable capacitor for our experiment we did some research how to build one. Every capacitor consists of two conductive materials separated by a nonconductive material. The capacity of the capacitor depends on the conductive material, its surface and the thickness of the nonconductive material. You can calculate the capacity with the following formula:

C = capacity (F)
ε0 = vacuum permittivity (F/m)
εr = relative permittivity of conductive material (F/m)
A = surface of conductive material (m2)
d = thickness of nonconductive material (m)

Based on this formula we started to build our own variable capacitor. Therefore, we cut two circles out of thin plastic foil and one slightly smaller circle out of aluminum foil. Then we cut the aluminum foil in half and glued each half on one plastic circle. Afterwards we only had to stack the two layers on each other. With the calculation, we estimated a maximal capacity of approximately 200 pF.
After testing the capacitor, we realized that some inaccuracies had a huge impact on the capacitor. The capacitor did not deliver as much capacity as we hoped for.

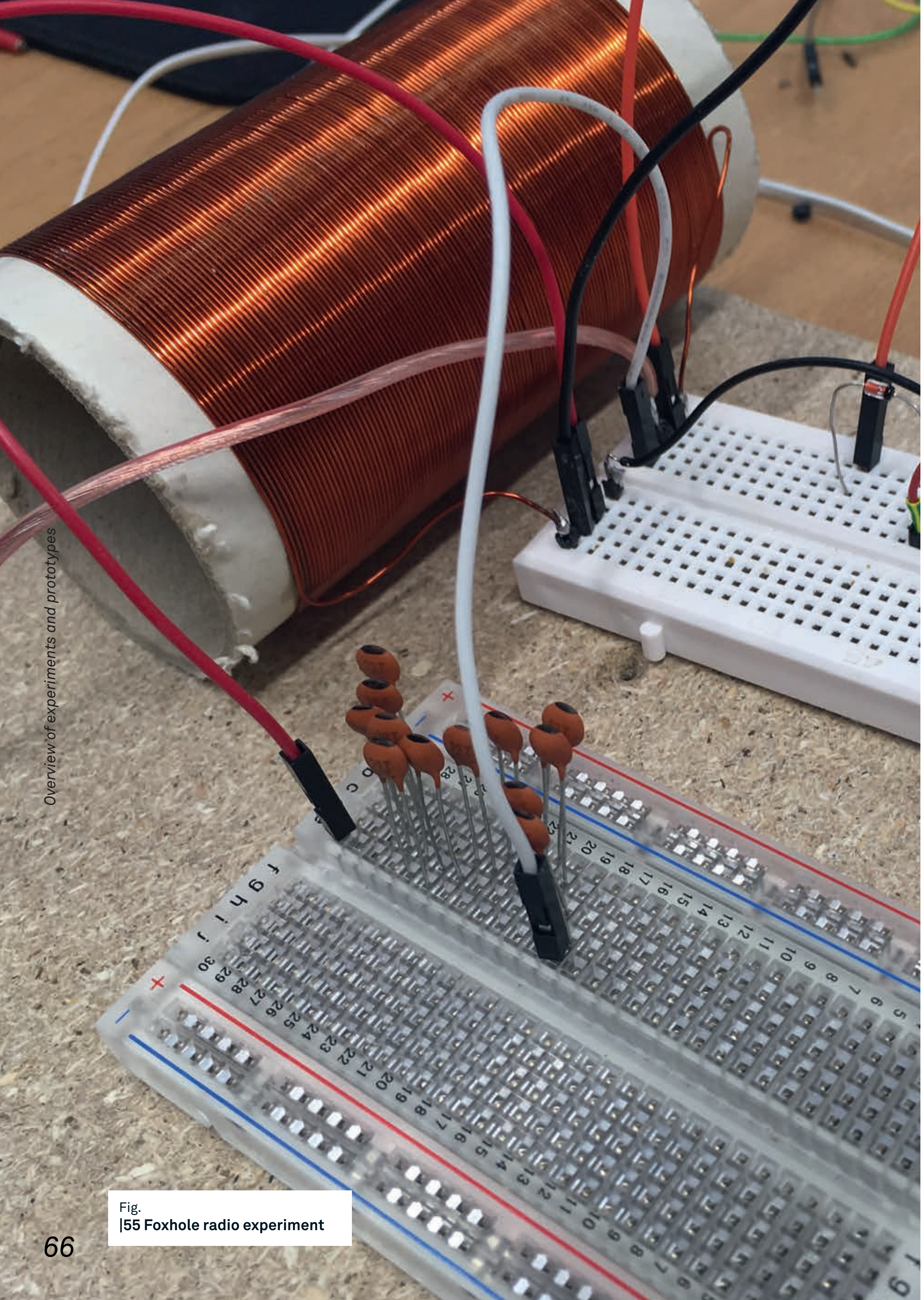


Fig.
|55 Foxhole radio experiment

To get a functional FM Radio we did a research of existing DIY FM Radios. With these instructions [Makezine, 2017], we started building our own radio. The first step was to create the copper coil that would induct the FM signal. Using a drill machine made this a lot easier.
After building the copper coil we started with the simplest instructions of foxhole radio. It consists only of a diode, an antenna, a coil and headphones.
We did everything as instructed but in the end, it did not work. We tried different coils, antenna lengths and diodes but nothing was working. It was frustrating because all the guides wrote about how easy it is.
We did not give up yet and started a new attempt. This time we decided to build a transistor radio. We went to an electrical store and bought all the required capacitors, transistors and inductors. We also made a copper coil with a new copper wire. We placed all the components on an empty breadboard and went outside to test it. Now we could hear a noise but still no music or radio shows. Because we slowly ran out of time we decided to talk with our mentors. After discussing the problem with them we decided to use another older experiment as base for the last prototype.

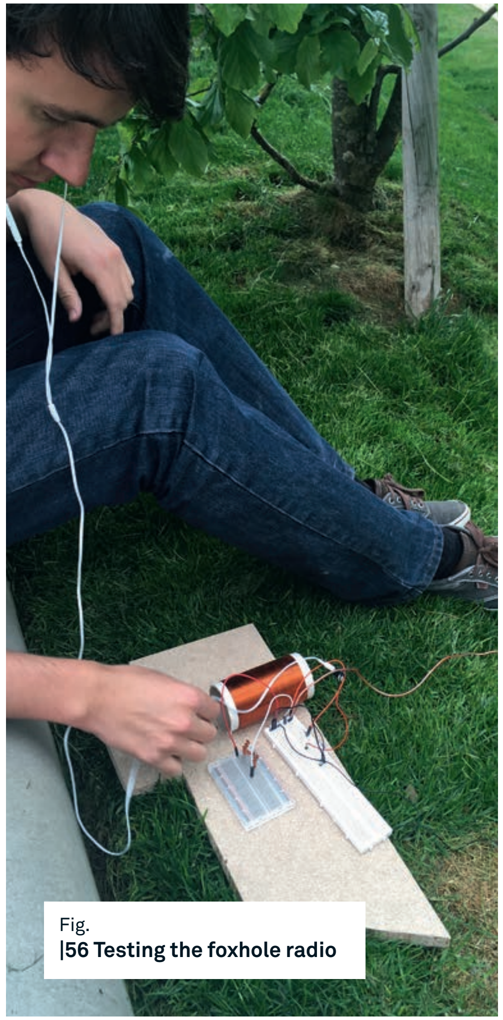


Fig.
|56 Testing the foxhole radio

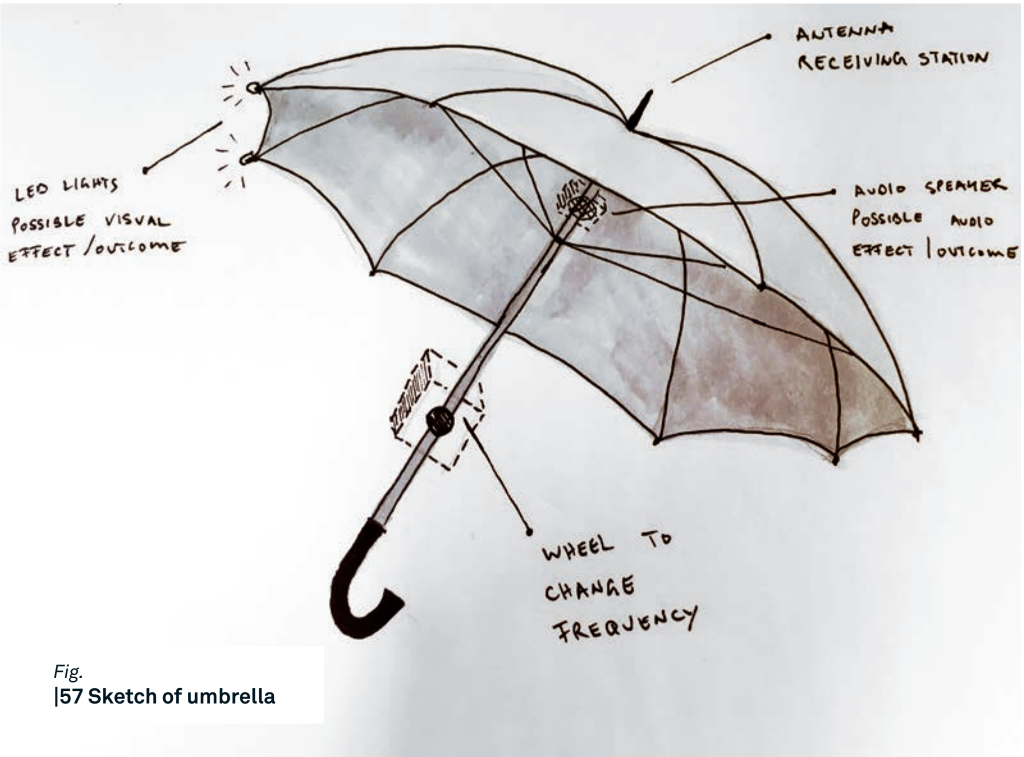


Fig.
|57 Sketch of umbrella

Radiation Umbrella

With this experiment, we wanted to find a way to visualize the radiation level through a colorful umbrella.
The sketch shows some first ideas. To change the frequency range we imagined a wheel or a speaker that sounds like a geiger counter.
The shape and function of an umbrella was very inspiring. On the one hand, it has the function to protect us. But if you turn it around you get something looking like a satellite dish. This contrast makes the umbrella to a very interesting object. The umbrellas shade is with its size perfect for light projection to visualize detected radiation. In addition, the umbrella is very mobile objects which makes it perfect to take everywhere and explore the Hertzian space.
As a first step, we created a construction consisting of 16 RGB LEDs. This umbrella screen should later be used to indicate the radiation detected by the antenna.
While testing the prototype we realized that the dark grey of our umbrellas shade did not work very well as reflector for the RGB LEDs. Hence replaced it with a white umbrella. And after some adjustments to the position of the LEDs we achieved the effect we were looking for. The light was now spreading on the whole umbrella and not just a spot in the center.

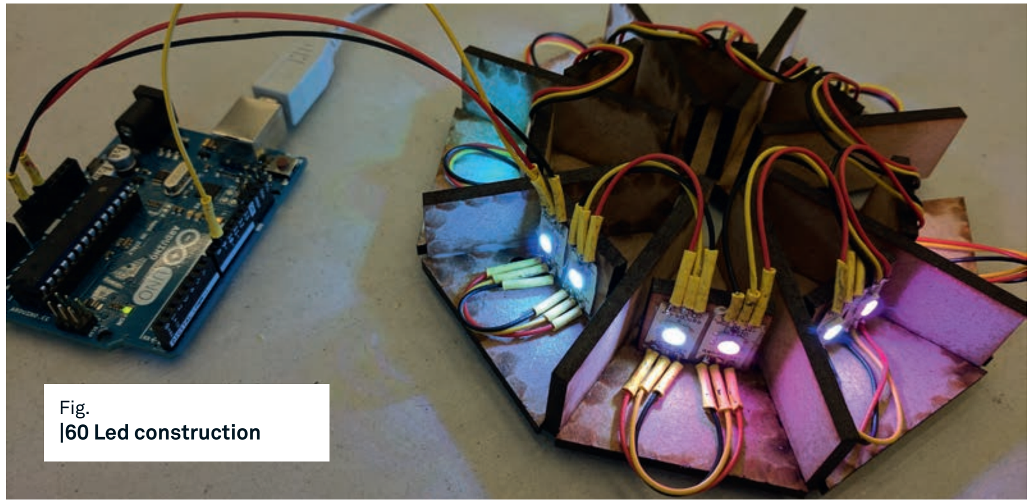


Fig.
|60 Led construction

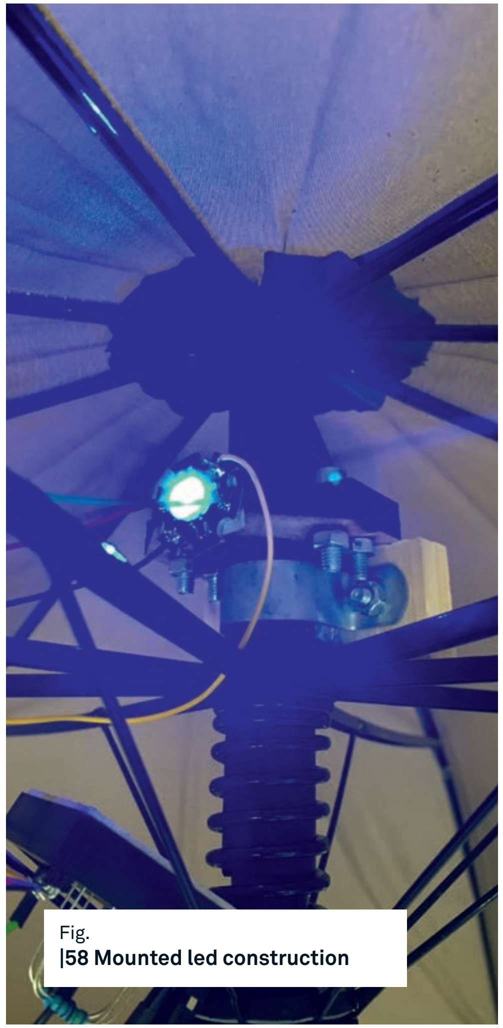


Fig.
|58 Mounted led construction

Fig.
|59 Sector of umbrella

Fig.
|61 Colorful umbrella

<u>Spectrum analyzer</u>

To find out what kind of frequencies we were surrounded with we wanted to build a RF spectrum analyzer. We tried different RF receivers and power meters to find an optimal detector.

For the first experiment, we got an NR-F24L01+ module with an external antenna to create a spectrum analyzer that scans the range between 2.4GHz and 2.5GHz. Based on instructions [cpixip, 2011] we coded a program that logs the current frequency spectrum. When a WiFi hotspot was sending on a certain frequency the spectrum analyzer showed the power level.

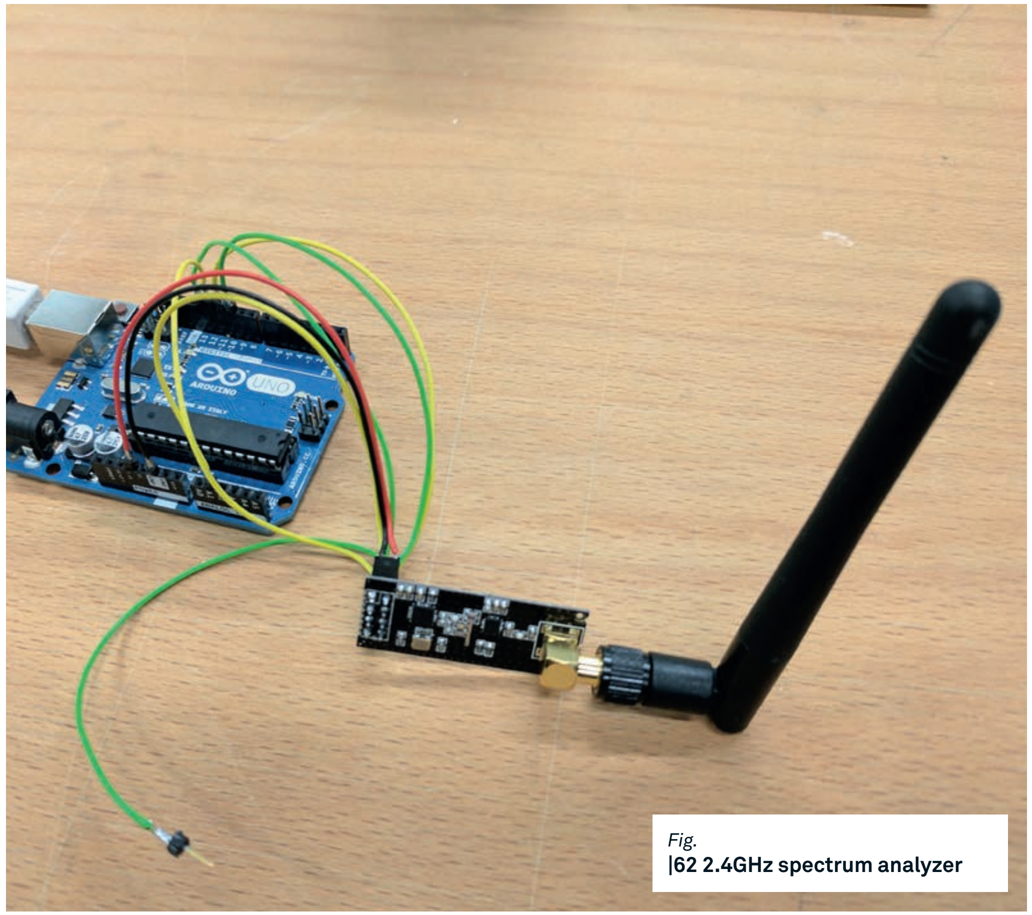


Fig.
|62 2.4GHz spectrum analyzer

Programming Arduino and Atmel Microcontrollers

Programming Arduino Boards is very easy. You just download and start the Arduino IDE, select the right board and port. Then you connect the board with an USB cable and upload you code. The Arduino Boards are great for general purpose. But if you want to build small prototypes they are too big.

Since we wanted to create small prototypes with our own PCBs we started looking for alternatives. Since most of the Arduino Boards run with Atmel microcontrollers we decided to use them too.

The electronics for the first prototype were quite simple which is why we could use the ATtiny85. It can run most code like an Arduino UNO but it is much smaller, has les I/O pins and requires special handling to program.

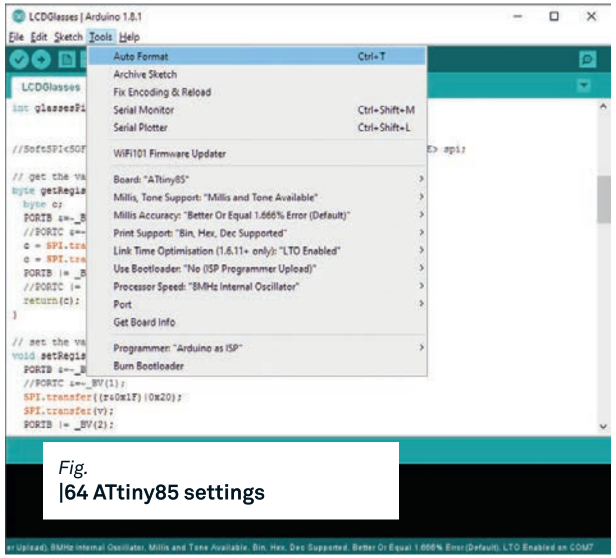


Fig.
|64 ATtiny85 settings

To program the ATtiny we used another Arduino UNO as ISP programmer and hocked it up as shown below:
Then we downloaded the required board profile, imported it into the Arduino IDE and adjusted the settings.

Fig.
|65 Arduino Uno as ISP Programmer

It was important to set "Use Bootloader" to "No (ISP Programmer Upload)" because we were using the Arduino as ISP. And we also had to set the "Processor Speed" to "8MHz Internal Oscillator" since were not using any external crystal. Finally, we had to change the "Programmer" to "Arduino as ISP" and upload the code using the programmer.

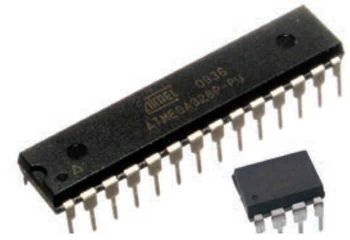


Fig.
|68 ATmega328 and ATmega85

Programming the ATmega328 worked the same way as the ATtiny85. By using the Arduino UNO as ISP Programmer could upload any code to the ATmega328. But since we wanted it to run at 3.3 V @ 8 MHz we had to burn a new bootloader. To burn the bootloader, we used the AVR programmer "TinyLoadr". Luckily the Arduino Pro uses the ATmega328 and can run at 3.3 V @ 8 MHz. Therefore, it was not necessary to use a custom board from GitHub. After burning the bootloader, we used the Arduino IDE to upload the code using the programmer.

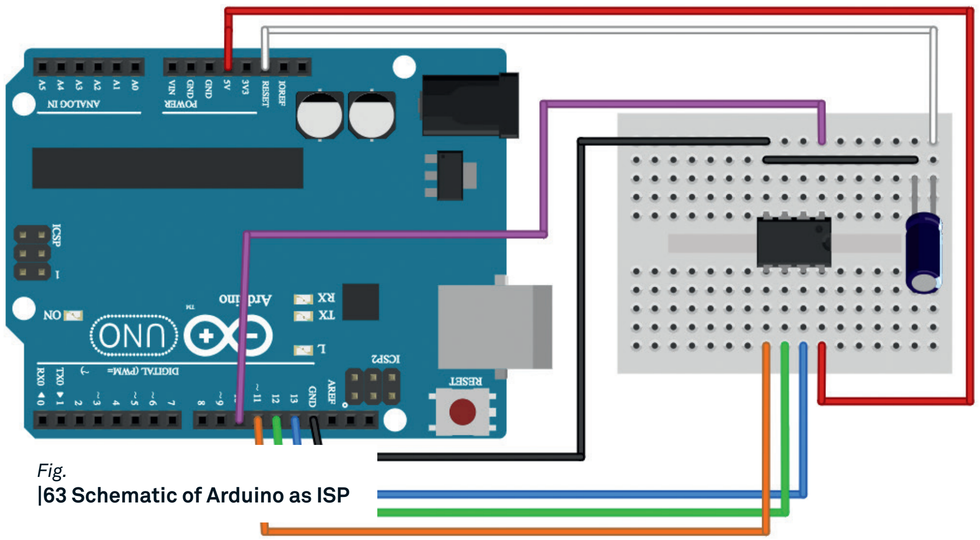


Fig.
|63 Schematic of Arduino as ISP

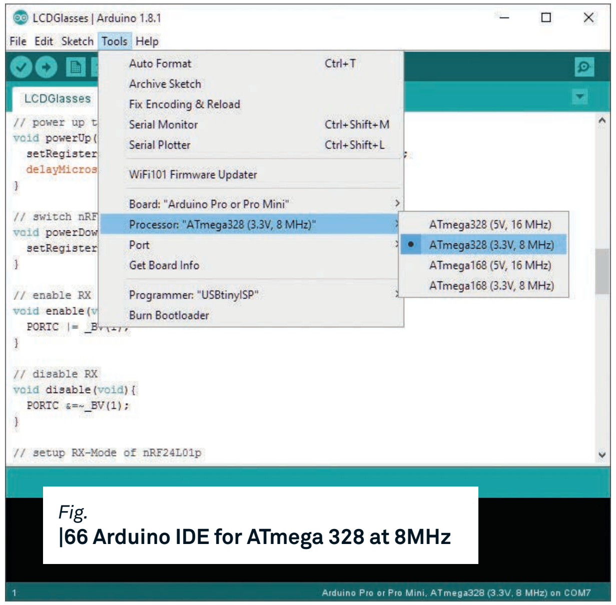


Fig.
|66 Arduino IDE for ATmega 328 at 8MHz

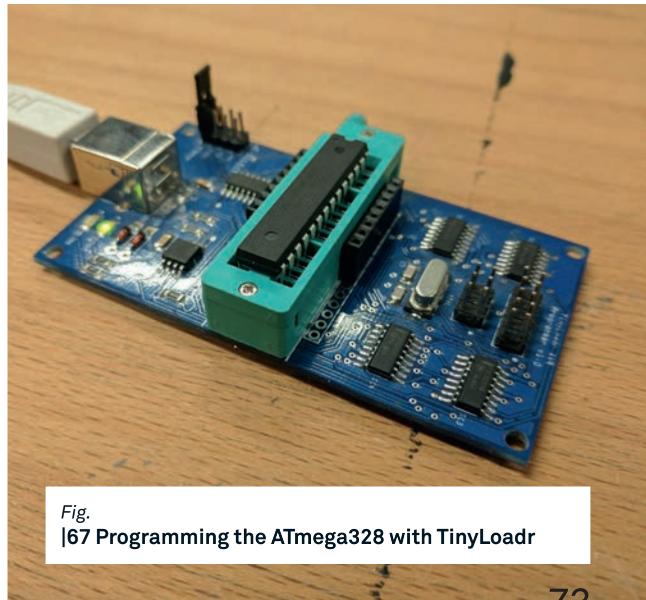


Fig.
|67 Programming the ATmega328 with TinyLoadr

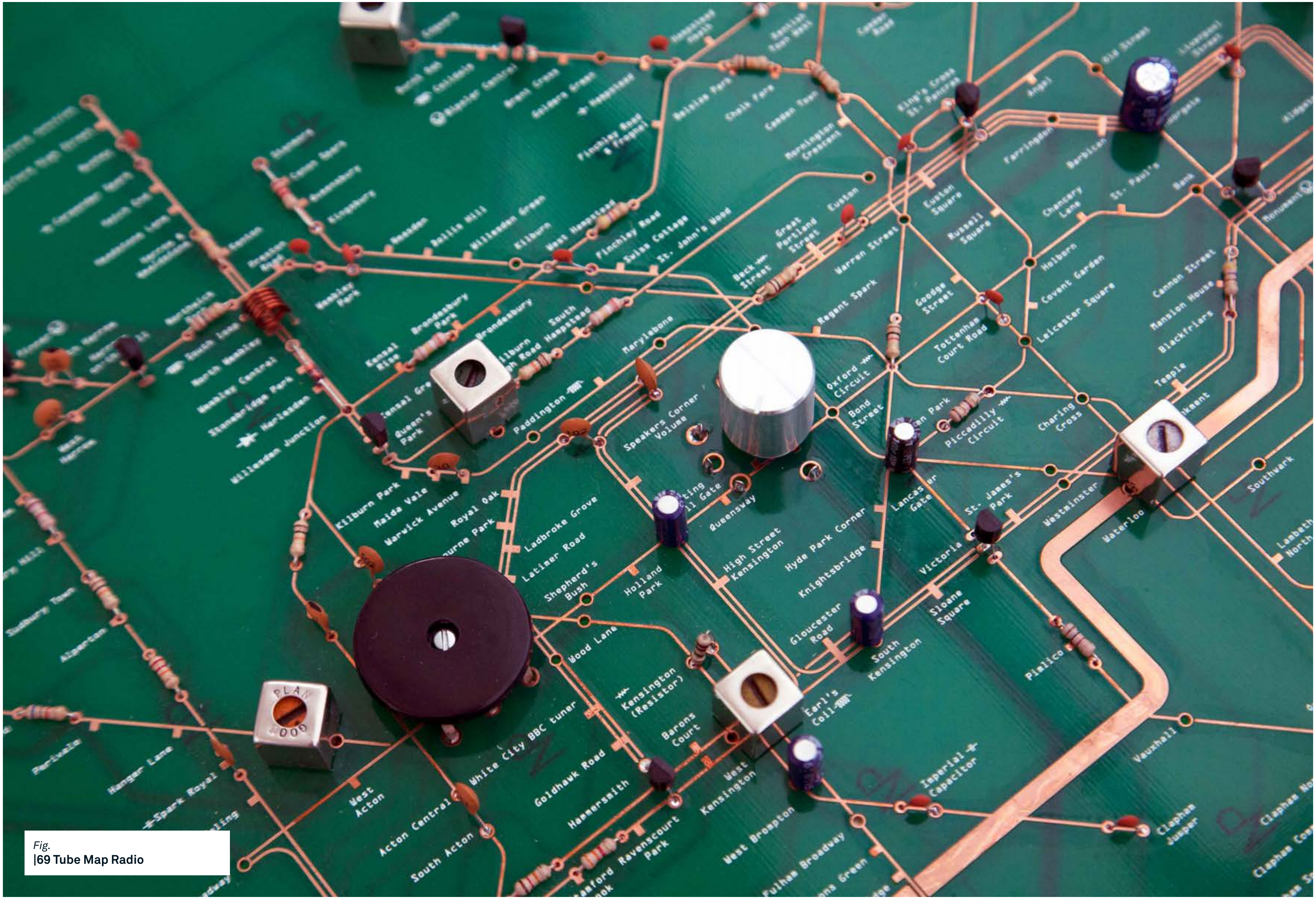


Fig.
|69 Tube Map Radio

<u>The aesthetics of electronics</u>

While researching electronic design projects we came across the work of Yuri Suzuki. In a lot of his projects he does not only not hide the electronics behind a nice case but also uses it to create a unique aesthetics. In his project Tube Map Radio, he created a radio that uses the metro map of London as circuit board [Suzuki, 2012].
For our prototypes, we looked to get a similar aesthetics. But all our prototypes till now where constructed with breadboards and jumper cables. That did not look very pleasant and was not handy at all. Therefore, we started researching the fabrication of PCB (printed circuit board).

With the software Eagle, we started to create the first PCB for the electromagnetic gloves.

Because any Arduino board would be too large and not comply with our aesthetic requirements we decided to use the micro controller ATtiny85. Over some detours the chip is also programmable with the Arduino IDE and moreover it is only the size of a thumb nail.

After finishing the plan, we mirrored and exported it as PDF and adjusted some faults with illustrator by hand. After printing it out on glossy photo paper we taped it to a copper plate. Then we used a laminator to transfer the toner from the paper to the copper plate. After 15 minutes water bath tape and paper were ready to be removed and to reveal the toner circuit on the copper.

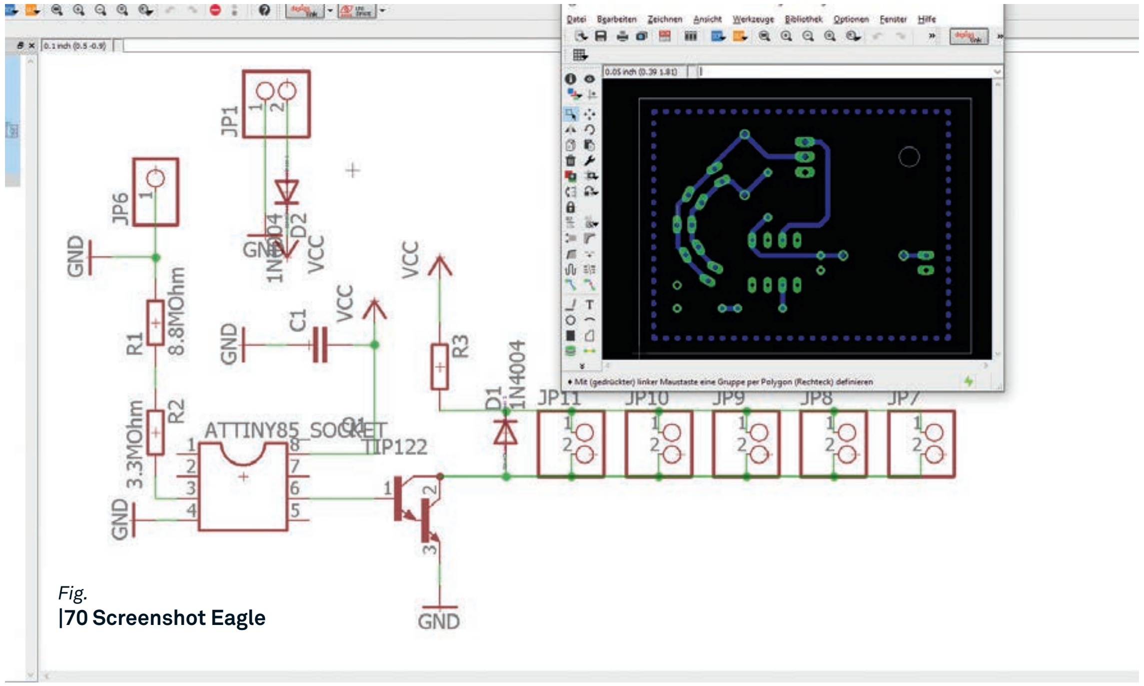


Fig.
|70 Screenshot Eagle

After a 30-minute bath in sodium persulfate by 50°C the copper was etched away. Washing away the toner revealed then the copper colored layer ready to be soldered.

The first try failed because at some places the copper was not etched away and at others the copper was already etched away too much. But the second try was alright. So, we drilled holes for the components and started soldering them on.

When everything was soldered, we started to test the PCB with a multimeter. Everything looked good but when connected to the power source nothing was working. After some further testing we realized that we were using the wrong diodes and one wrong resistor.

With some jump wires, we could fix the problems temporary and test the now functional board.

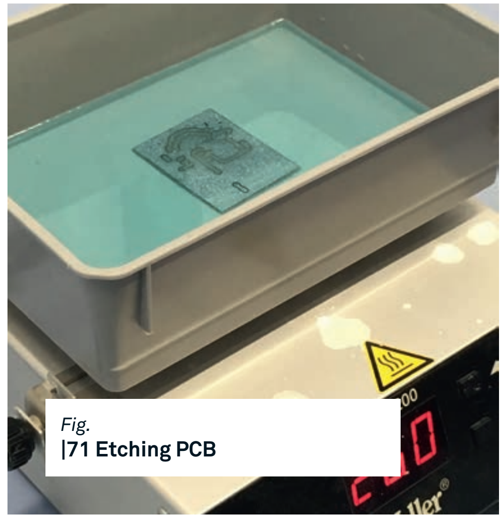


Fig.
|71 Etching PCB

Fig.
|72 PCB Shields

Fig.
|73 Selection of experiments

Placement of the experiments and prototypes in the wave spectrum

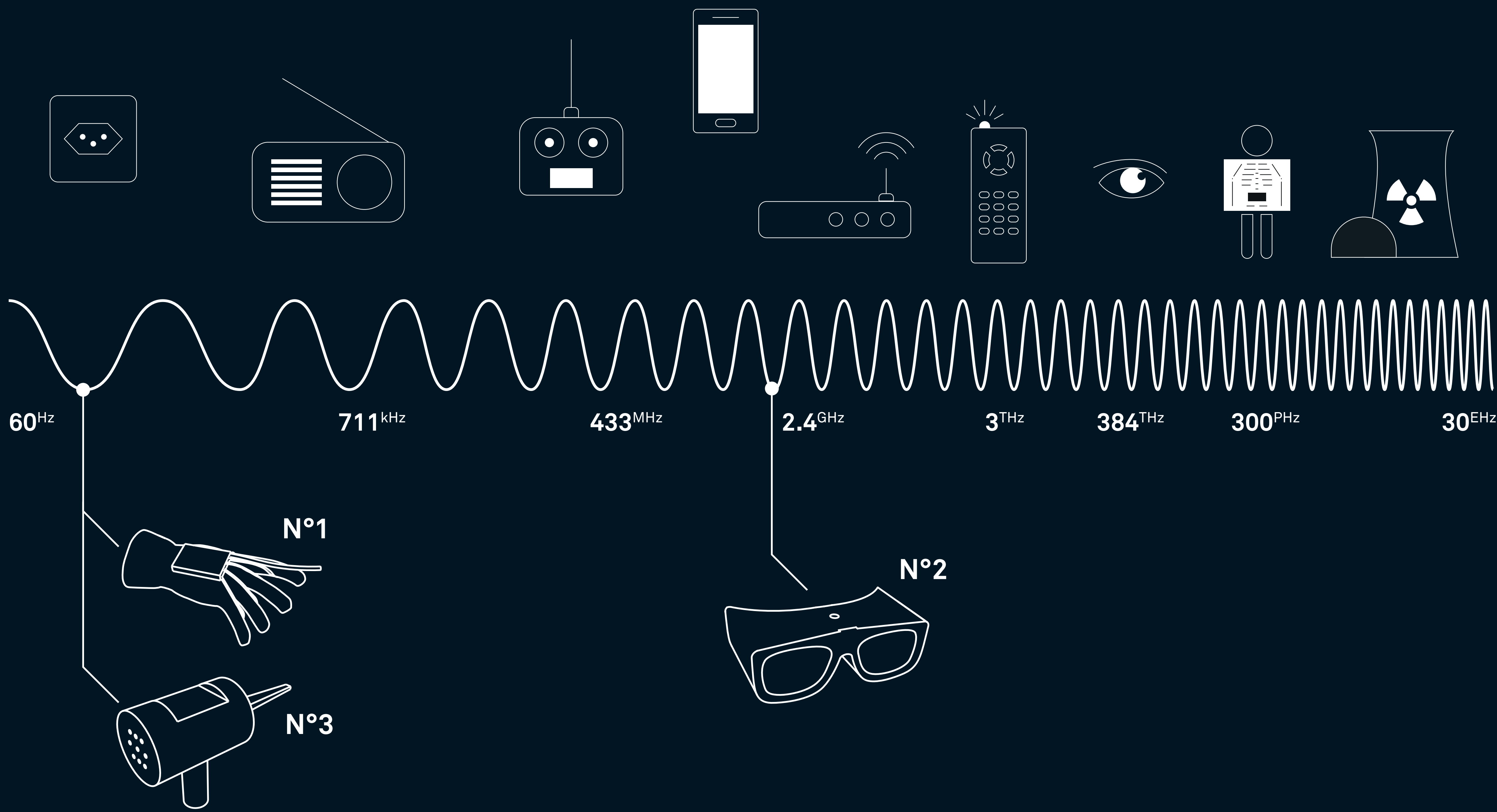


Fig.
|74 Placement in wave spectrum

Overview of experiments and prototypes

Fig.
|75 Final prototypes

Concept

The inspiration and research phase helped us to find an interesting direction for our concept. And the prototyping and experimenting phase allowed us to make the necessary design decisions for the final concept.
The final concept is defined by the following cornerstones.

„With three prototypes, we want to make the Hertzian space perceptible. We want to allow peoples through this body extensions to discover the hidden space. The three different body extensions will stimulate three different senses of our body. The prototypes will not explain the topic but it will create an experience to arouse curiosity. „

While experimenting with electromagnetic waves we more and more concentrated on three senses of our perception: hearing, sight and feeling. The idea to create one probe for every sense emerged. Thereby every probe should meet the following conditions:

- It should have one clear affordance for an interaction.
- It should only make one phenomenon explorable so the user does not get confused.
- It should be a mobile object that can be easily carried around.
- It should offer an experience and not education or explanation. The phenomenon will be explained on a post card with a link to the technical background on the blog.

Setting these criteria allowed us to create concepts for three different body extensions. Additional cards to every prototype will give some hints about how to use it and a short information about the background.

In daily life, we see our prototype as a object of a exhibition like the Technorama. With this object visitors can experience a scientific phenomenon and find the practical access into a technical topic. N°1 could also be a gadget for electro smog critics to inspect their homes.

N°1

Introduction

With the first extension, we wanted to stimulate the sense of touch. By embedding it in a glove we created a understandable affordance. The person carring the glove gets vibration feedback at the fingertips.

Concept

This prototype translates the electromagnetic waves to something tactile. The person carrying the prototype can walk around and feel the low frequency electromagnetic fields surrounding common electrical devices.
This experience of feeling something new animates to explore the space and discover the environment on a new level.
Because the glove is a portable device it can be taken everywhere to explore all different kinds of spaces. The instant feedback makes a real experience and prevents a boring discover.
The prototype is easy to handle, fast prepared and ready to explore.

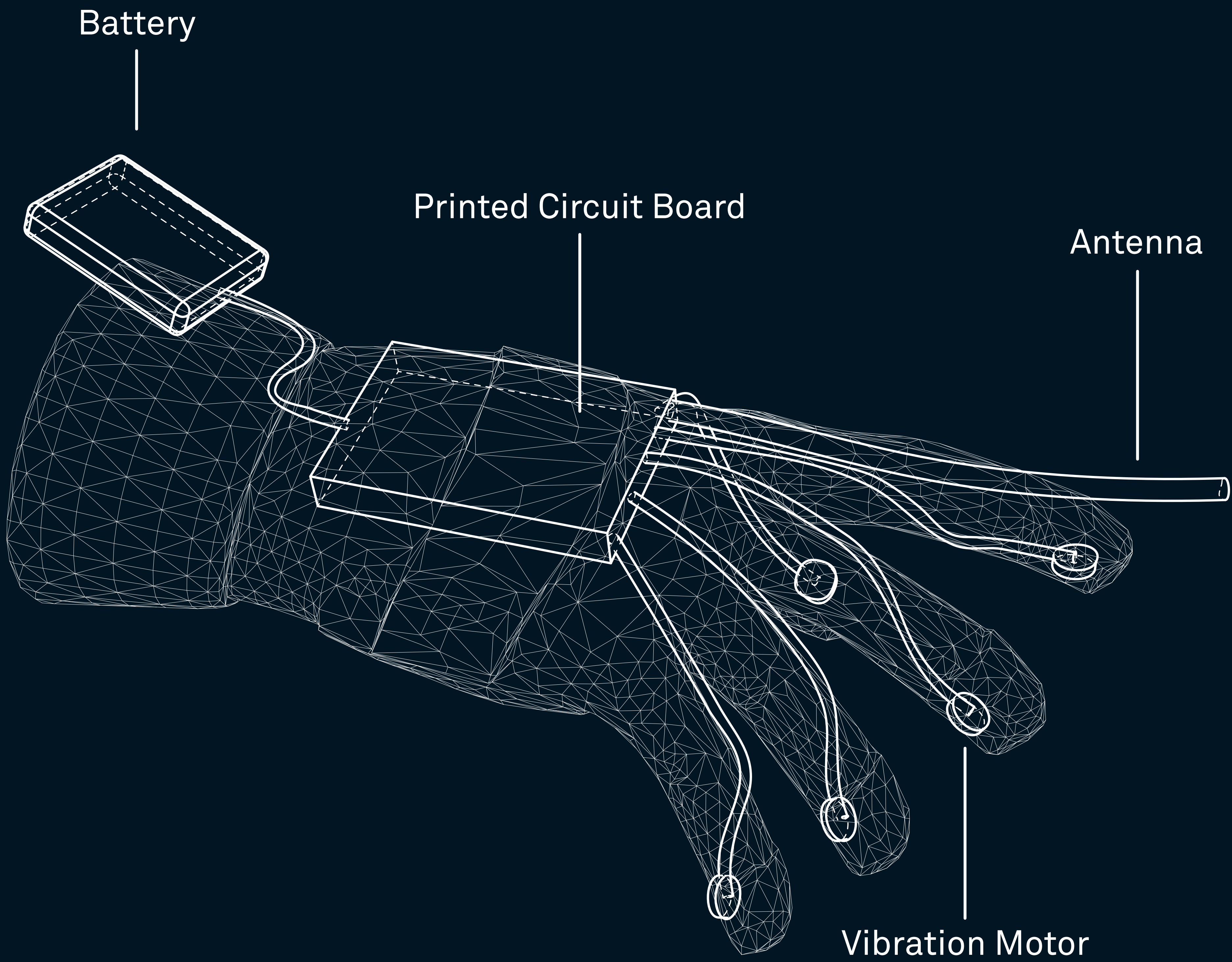


Fig.
|76 Technical draw, N°1

Working process

In the begin we focused on the glove as a object itself. We choose this object as one of our three extensions because it is a well-known object with a clear affordance. With a first rough prototype, we wanted to find out how it could work, what feeling we would experience and how it could look like.
It also was a test to see if the electronics would work. Only by building the first prototype we realized that the vibration motors themselves generated a strong electromagnetic field that influenced the sensor.
After building and testing the electronics with an Arduino and a breadboard we decided to create our own printed circuit board. On one hand, we had to fit everything on a small glove and on the other we intended to create an aesthetics of electronics. The glove should be a combination of the visible electronics and a fabric glove.

Before we started to etch the first circuit board we hooked up all the necessary electronics to a breadboard and tested it again. The result was not encouraging. Because we had never hooked up all the vibration motors before we only now realized that the microcontroller did not deliver enough current. Therefore, we had to adjust the schematics and integrate a transistor.
After this fix, we started etching the first PCB.

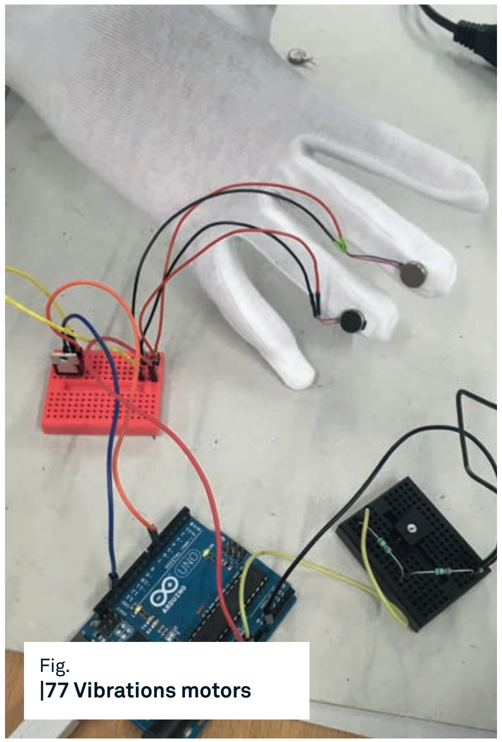


Fig.
|77 Vibrations motors


Fig.
|78 Possible Outcome

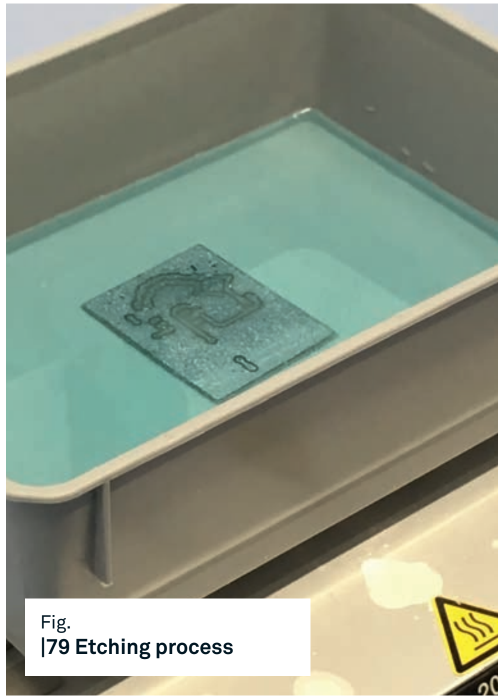


Fig.
|79 Etching process


Fig.
|80 Etched PCB

The first PCB totally failed. The etching solution was too old and the spacing between the trains were to narrow. So, we had to do it again and optimized the schematic. This trial and error was very helpful for the other two prototypes. We learned much about the manufacturing process. After two more tries we had managed to build a functional PCB. The whole programming was much easier thanks to the experiments we did before.

While building the PCB we started to prepare the glove for the motors and the battery pack. We decided to work with two gloves. One glove on the outside where the PCB is placed and one glove on the inside to hide the wires, the battery and the vibration motors.
We ordered the white gloves from the internet since did not want to waste time on producing them. While preparing the gloves we realized that sewing is not as easy as first assumed. We were both out of practice and made a lot of mistakes. Fortunately, we ordered enough gloves to practice. We combined this exercise with some material tests for the lashes of the electronic parts. We used different elastic and stiff fabrics and various stitch types. We decided to use a elastic fabric and started sewing the lashes and the PCB shield onto the glove.
After we finished this first prototype we gave it for testing to a few people. One finding of this first user tests was that the material of the gloves was problem. After several little tests with the first prototype the fabric began to tear up. The material was to fragile so that the seam got ripped open and the fabric got holes all over it. Therefore, we decided

Fig.
|81 Lash for vibration motor

Fig.
|82 Stitched glove

to build this prototype again. We looked for better material and ended up with black sport gloves.

Luckily the first tests also reviled some possible improvements of the prototype. Since the antenna was placed on the back of the hand and the feedback vibration motors were at the finger tips the tester got confused. To make it more intuitive we placed the antenna in the fingertip region. To do so we had to find a way to extend the antenna without increasing the sensitivity of it. We realized that some of the cables of WiFi antennas were shielded with an outer layer of aluminum or copper.
After testing it with the longer shielded antenna the improvement was amazing.

In our first concept, we wanted to create the white gloves. Since the sport gloves were only available in black we had no choice. Fortunately, the color black worked even better with the copper colored PCB. Before we started sewing the new gloves we went to get some help from the head of the textile workshop. We got many of helpful tips on what fabric to use and how to process the material.
To find out what would work and look good we did some material tests with felt and different types and colors of fabric. Furthermore, we got an introduction to the sewing machine. By using the machine, we hoped to make the gloves stronger.
In a next step, we started to sew new felt lashes to the glove. While reflecting on our first prototype we found another detail to improve. The cables of the first

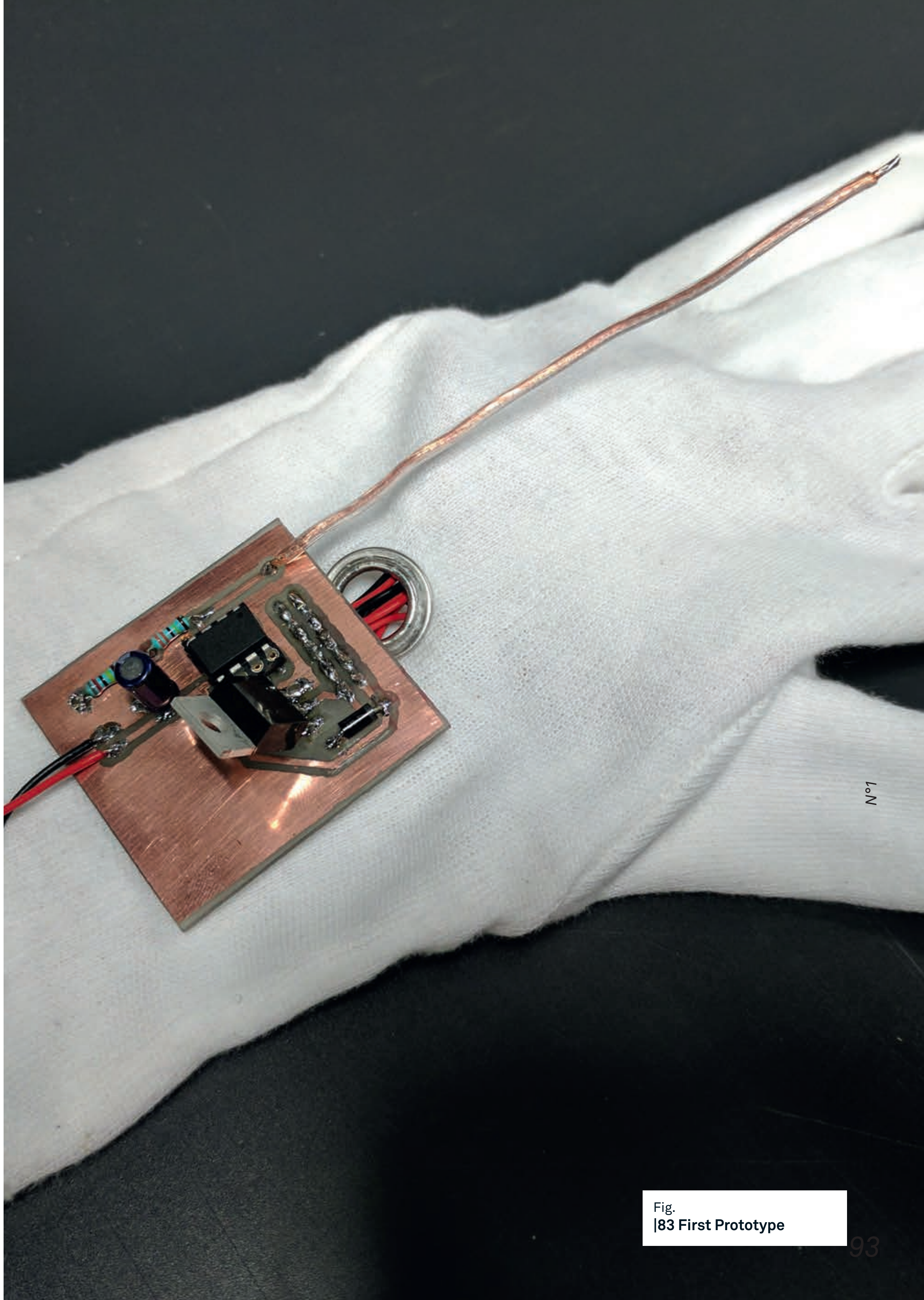


Fig.
|83 First Prototype

prototype where hidden in the fabric. To give the gloves a more electronic aesthetics we decided to also reveal the cables. To clean up the look we hid the cables in heat-shrink tubing.

Experience

A soon as the first prototype was ready to test we started walking around with it ourselves and giving it to people while watching their reactions.
The reactions were very positive and our testers wanted the prototype even longer to run around and explore the Hertzian space. Luckily there were also some suggestions how we could improve the prototype.
But besides the reactions it was very interesting what people discovered while running around. There were three identical 3D printers turned on but only one creating a strong electromagnetic field. There was a spot on a device that you could feel if you moved your hand from top to bottom but not the other way.

Fig.
|84 Sewing a glove

Fig.
|85 Final Prototype N°1

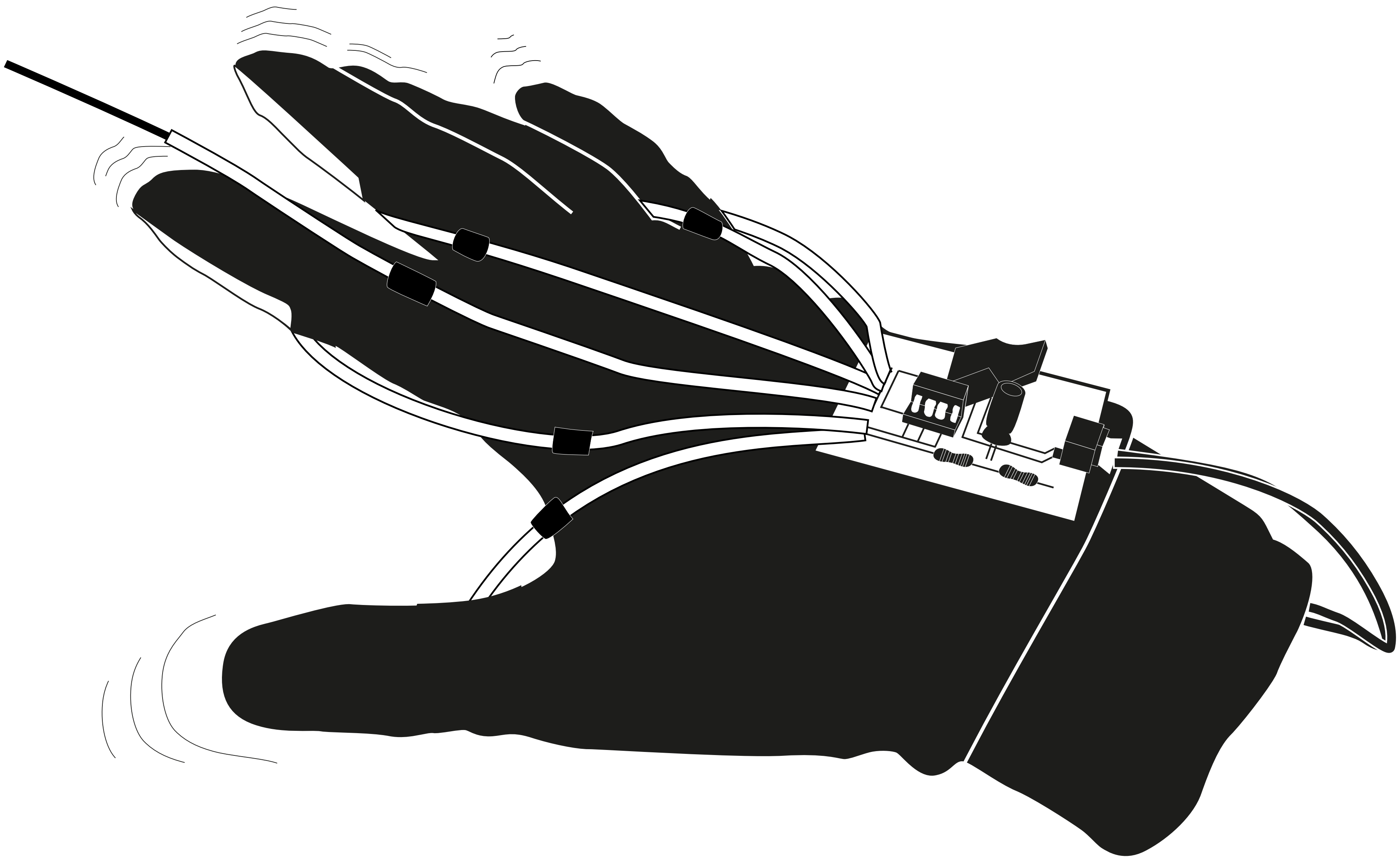


Fig.
|86 functional sketch N°1

N°1

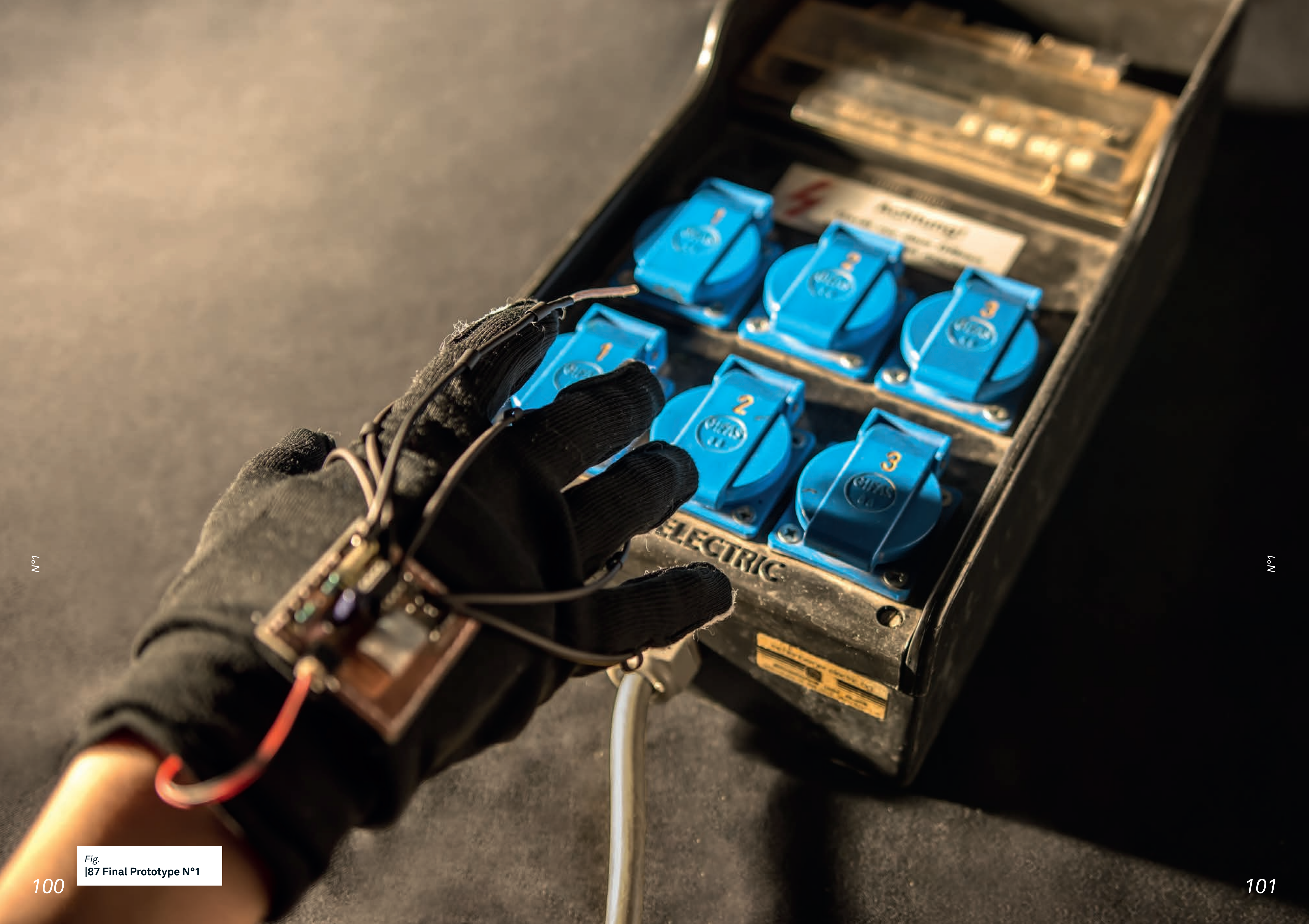


Fig.
|87 Final Prototype N°1

N°1

N°2

Introduction

For our second prototype, we focused on the sense of sight. We created a functional prototype in the shape of a headset. The headset interferes with the sight whenever it picks up WiFi radiation. Like the first prototype we tried to build it as portable as possible.

Concpet

The second prototype stimulates the perception sensory of sight. It is focused on high frequency waves that are often used for information technology like WiFi. The person carrying the headset will experience interference in sight whenever she or he looks at a high frequency radiation source. This creates an experience of sensory expansion and decrease and enable the viewer to see the sources of the invisible waves and explore the hidden space. A postcard offers some hints about possible use cases and some information to the phenomenon.

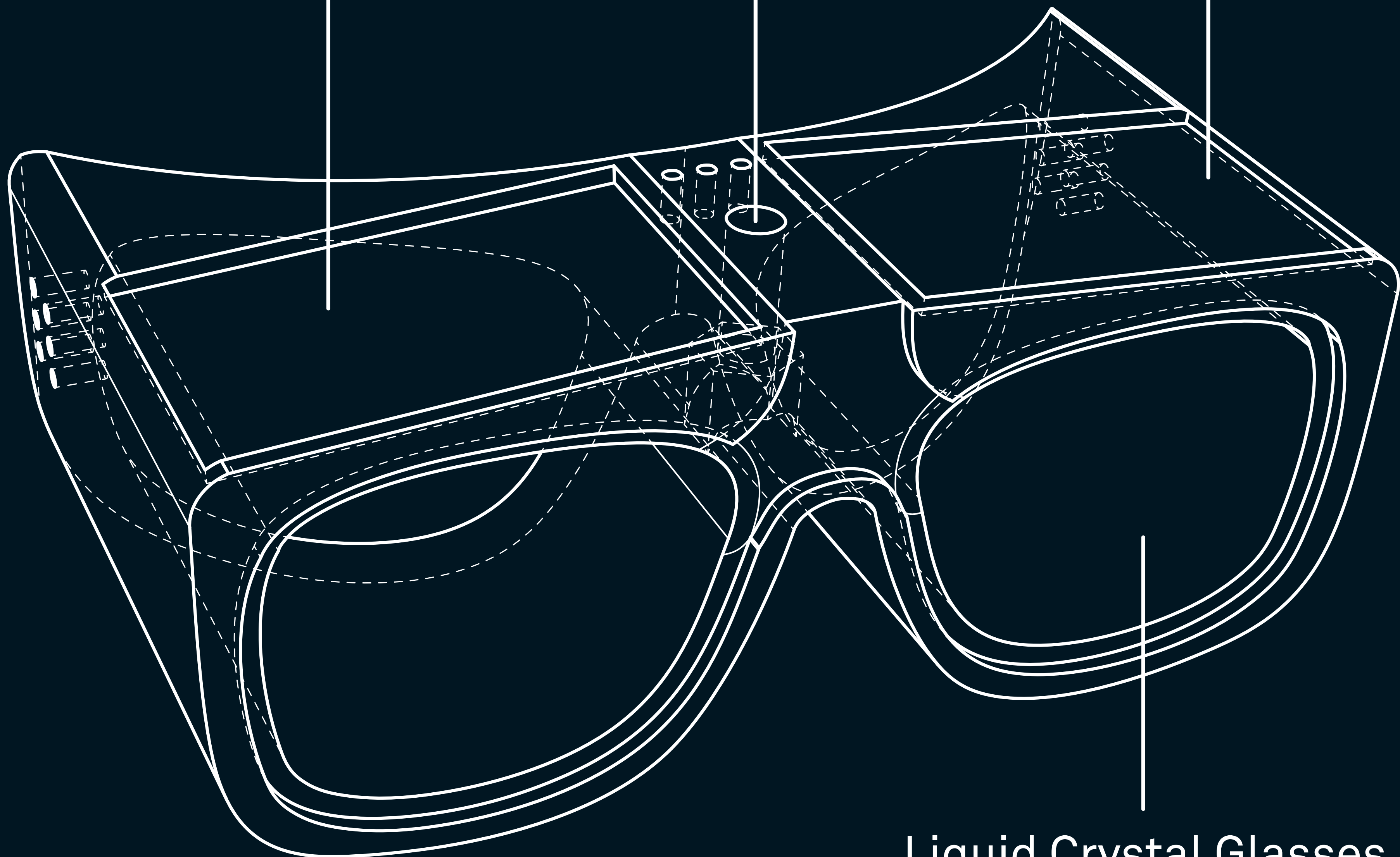


Fig.
|88 Technical draw N°2

Working process

We started to test some materials on their sustainability and suitability for the headset frame. We made different frames out of MDF wood, 3D printed PLA and glued wood.
During a mentoring, we realized that we need to conduct some more experiments concerning the shape. The current shape would not allow us to fit the necessary electronic on to it. Therefore, we started to create versions with different shapes and sizes. With the shape of current VR headsets in mind we sketched some first ideas on paper and built rough prototypes out of styropor, MDF wood and cardboard. We also modeled some shapes in Rhino3D and printed them with 3D printers.
Through this process, we came closer to a fitting solution. The 3D test prints allowed us to quickly test the models on

Fig.
|91 Styrofoam prototype

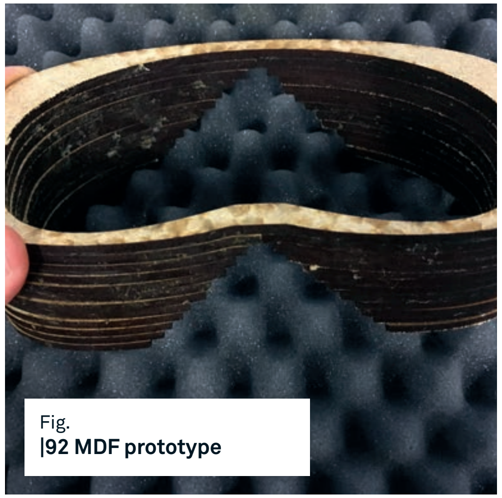


Fig.
|92 MDF prototype

Fig.
|89 PLA 3D printed prototype

Fig.
|90 Final shape N°2

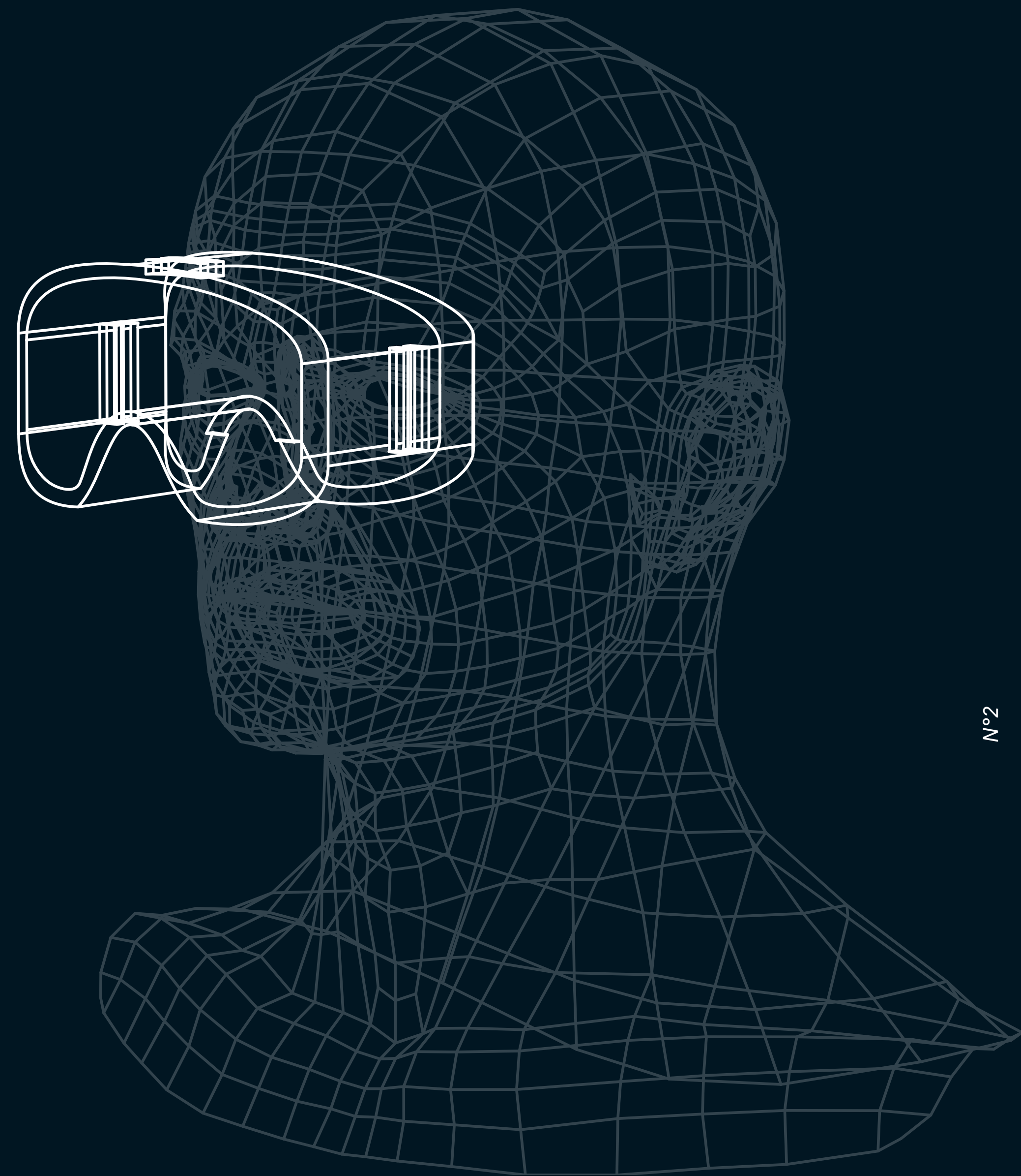


Fig.
|93 Figure N°2

our self and adjust small detail concerning the comfort.

To visualize the detected radiation, we were looking for something that could interfere with your sight. On our online research, we came across different methods. We did some test with a PDLC foil and disassembled electric sunglasses. Since we did not get the PDLC foil to work we choose the electric sunglasses. The experiments with the foil were very time consuming. But it was an interesting experiment where we learn much about liquid crystals and alternating current. Nevertheless, we were very glad to have the electric sunglasses as a functional backup.
To only receive the signals from the direction the person was looking at we reviewed our old experiments with directional antennas. We choose to use the can antenna for this prototype because it was smaller and it had better directio-

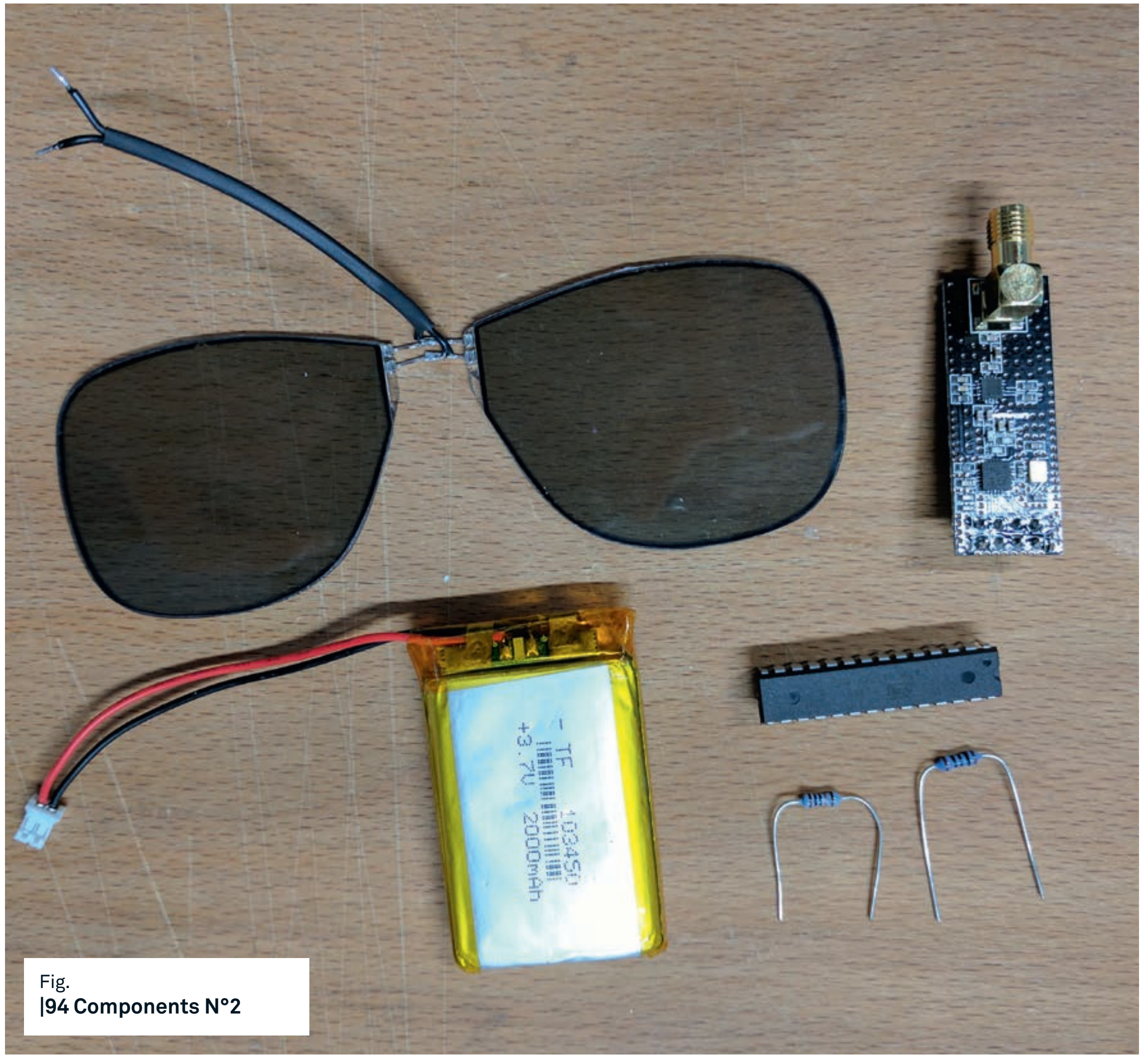


Fig.
|94 Components N°2

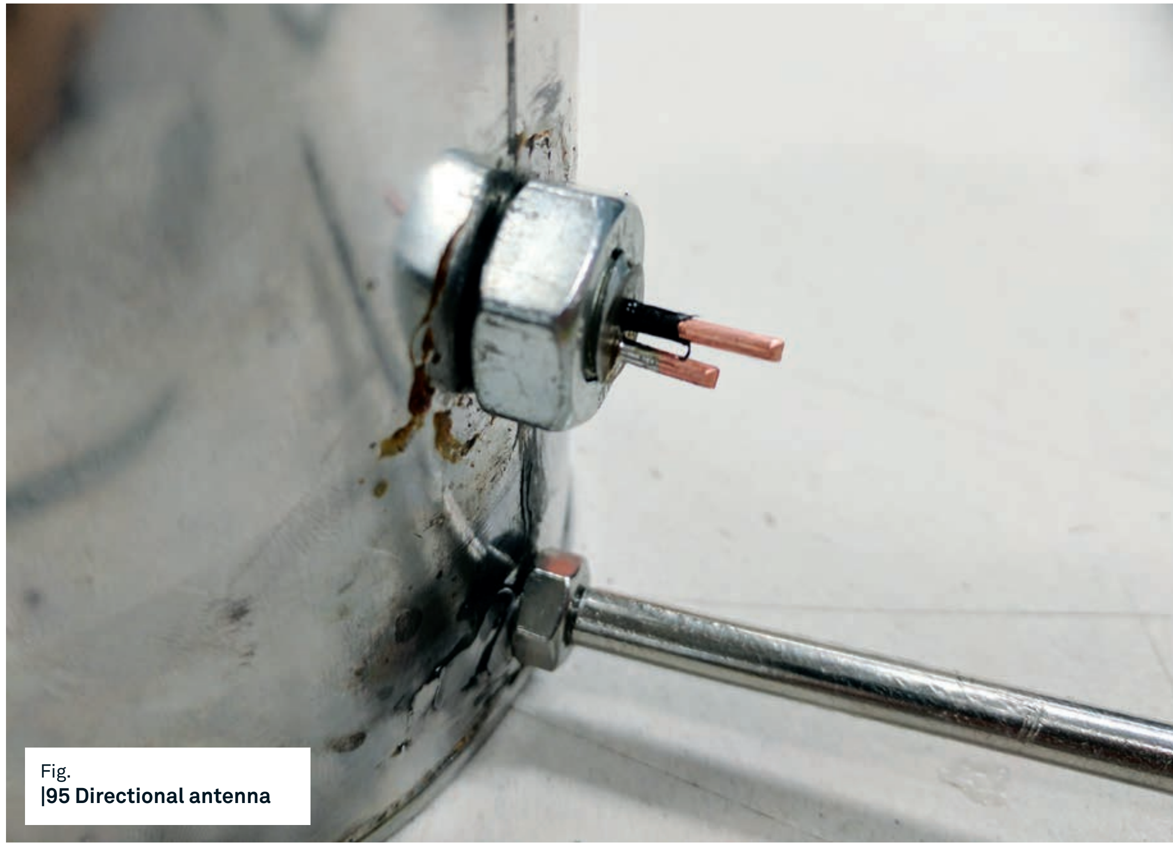


Fig.
|95 Directional antenna

nal characteristics. To find out how much radiation is coming from one direction we combined the can antenna with our spectrum analyzer experiment.

Therefore, we were now able to see which frequencies between 2.4GHz and 2.52GHz were in use in a certain direction once every second. For our final prototype, we wanted to have higher refresh rate to make it more reactive. Therefore, we changed the code so that it was less precise but much faster. Now we got between 5 - 10 refreshes per second.

To improve the durability of the antenna connector we decided to replace the broken N-connector with our own design. Since we cannot shield the connector as good as a coaxial connector, the signal could lose some quality.

Since we first planned to work with the PDLC foil we designed the frame without regards to the shape of the lenses. But since we were forced to use the sunglasses we had to rethink the frames shape.

We stared to model a new version that would fit the shape of the sun glasses perfect. The model also had to provide space for the PCB with the electronics, the LiPo battery pack, the can directional antenna and the liquid crystal glasses. After the modeling, we started printing and correcting some flaws of the model by sanding it. To give the raw frame a finishing lock we painted it completely black.
Since we had to fit all the electronics on the frame we did not come around a PCB.

On the first glimpse the electronics for the prototype seemed not very complicated. We only had fit an ATmega328, a receiver module NRF24l01+ and a voltage divider for the glasses onto it.
But after the first failed attempt on the breadboard we realized that it was recommended to use an external 8 MHz crystal. Therefore, we had to update our schematics. Furthermore, we added a capacitor for the power supply and changed the position of the battery connector so it would not obstruct the antenna socket.

Experience

The first feedbacks from people who tested the headset were positive. While walking around on the school premises they identified many WiFi routers and microwave ovens as radiation sources. But when we gave the headset to people at home it was more difficult to find sources. Since the headset only picks up radiation while transmitting information someone had to download or upload data over the WiFi network. At school this was no issue since enough people used the WiFi networks anyway.

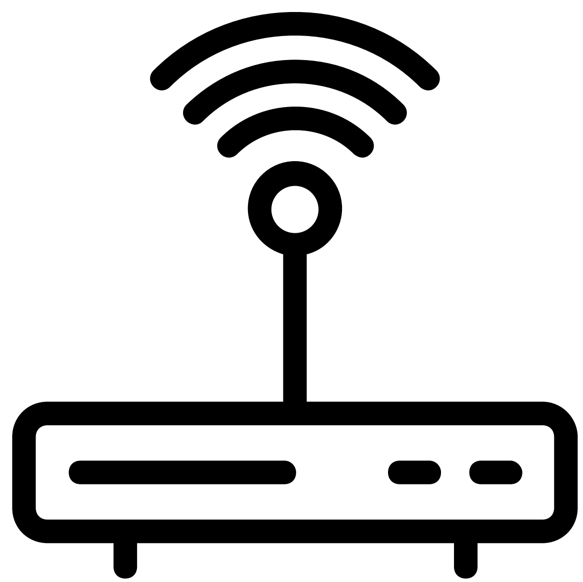
Fig.
|96 Prototype N°2 in use

N°2

N°2

Fig.
|97 Prototype N°2

Fig.
|98 functional sketch N°2



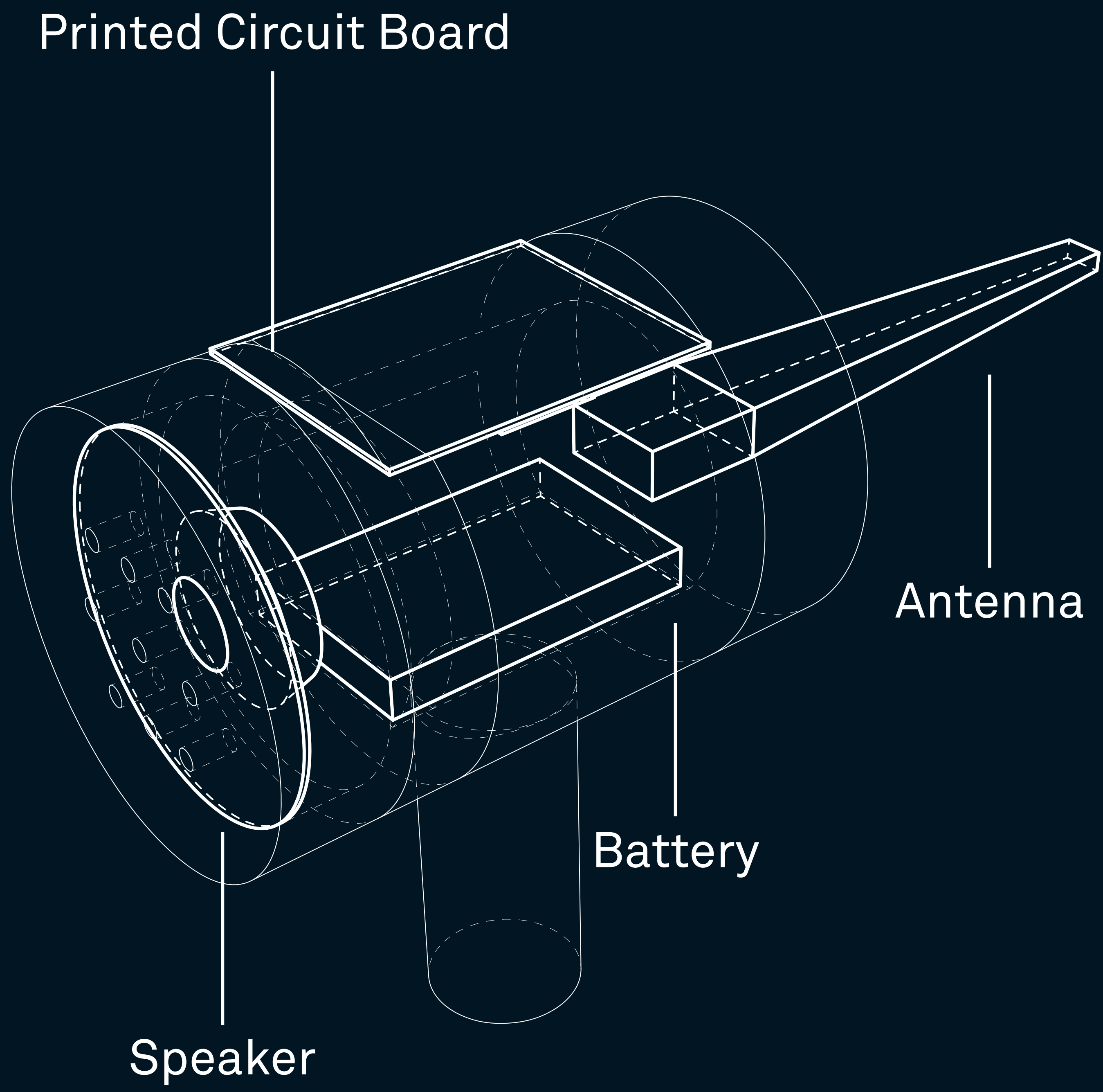
N°3

Introduction

With our third object, we set the focus on the sense of hearing. Unlike the two other objects we create this prototype to be held in a hand and not worn as a body extension.

Concept

The third object stimulates the sensory of hearing. By pointing the antenna to a certain direction, the prototype change s its radio FM frequency to the radio station located in this direction.
Since time run out to get the electronics for the FM radio working we decided to simplify the prototype. The prototype picks up low frequency fields like the first prototype we have built. The feedback is a sound imitation of a geiger counter. By moving the antenna, the prototype allows to hear where the hidden electromagnetic fields are.



N°3

Fig.
|99 Technical draw N°3

Working process

After a research phase, we started building the first prototypes to get an idea of the shape. We decided to work with wood because it really enhanced the quality of the sound. While prototyping we changed the shape to a more rounded form. Based on a round cylinder we started to add all the required properties. We added a space inside of the prototype for the battery and the wiring of the electronics. On top of it we created a plain surface to place the PCB on it.
In a further step, we had to find a practical way to change batteries and replace or repair internal wiring. For the grip, we had to build a strong construction which would allow save handling.

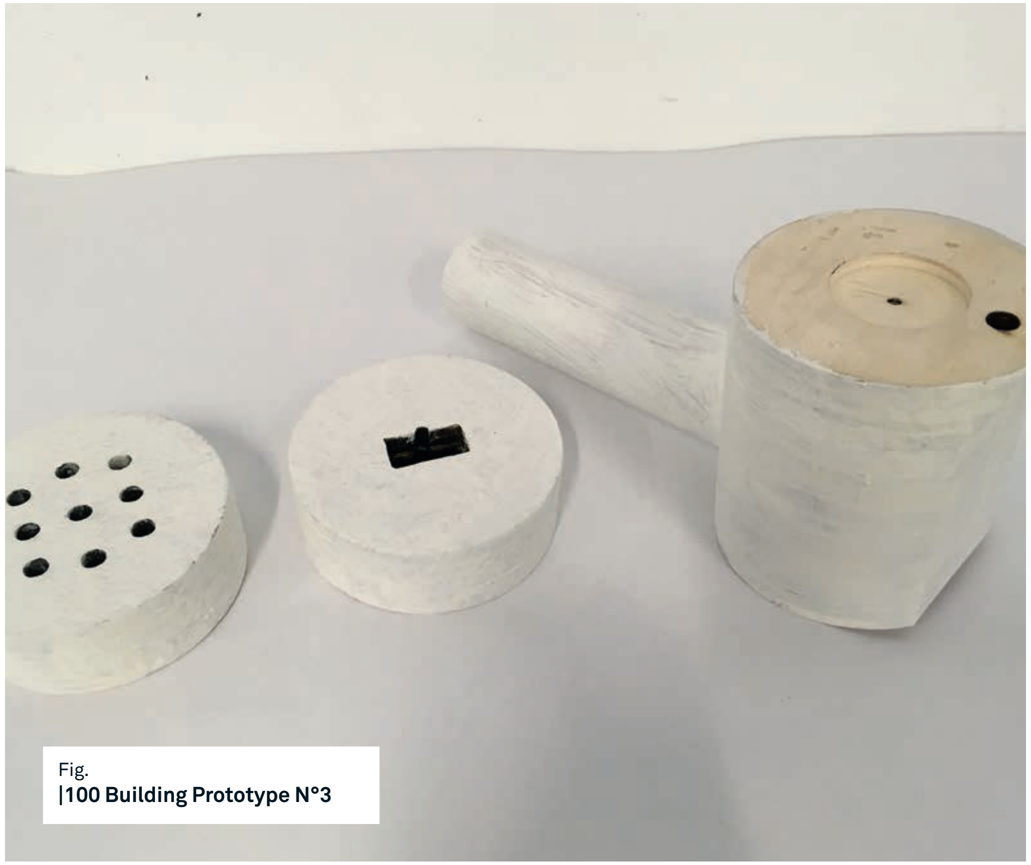


Fig.
|100 Building Prototype N°3

To continue the aesthetics of our other prototypes we colored the prototype black and white. This prototype resembled a mix of a radio tracker for animal research and an old telephone. On one end the antenna works as direction finder while the other end plays the corresponding acoustic feedback. With the directed antenna and the grip the prototype also has a clear affordance. The sanded and painted wood creates a smooth surface and a good sound effect.

Fig.
|101 Form case N°3

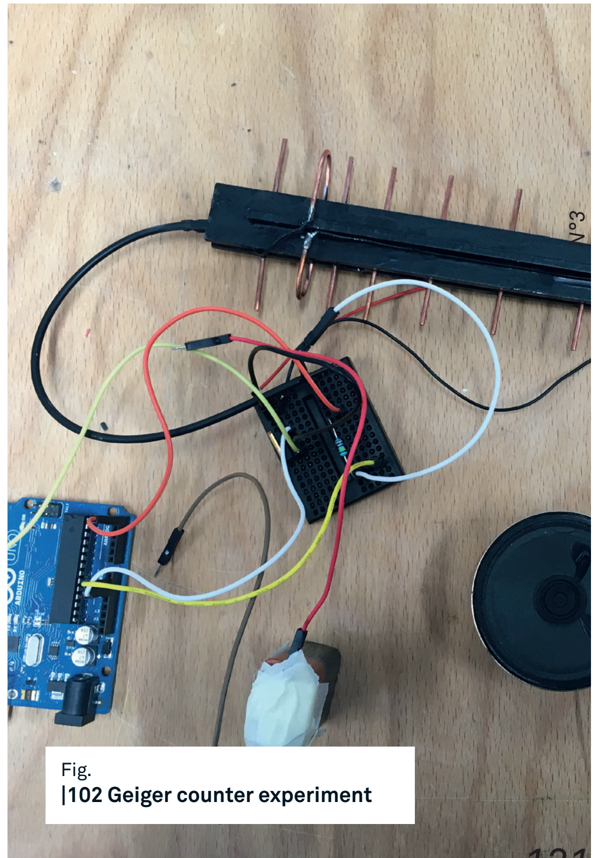


Fig.
|102 Geiger counter experiment

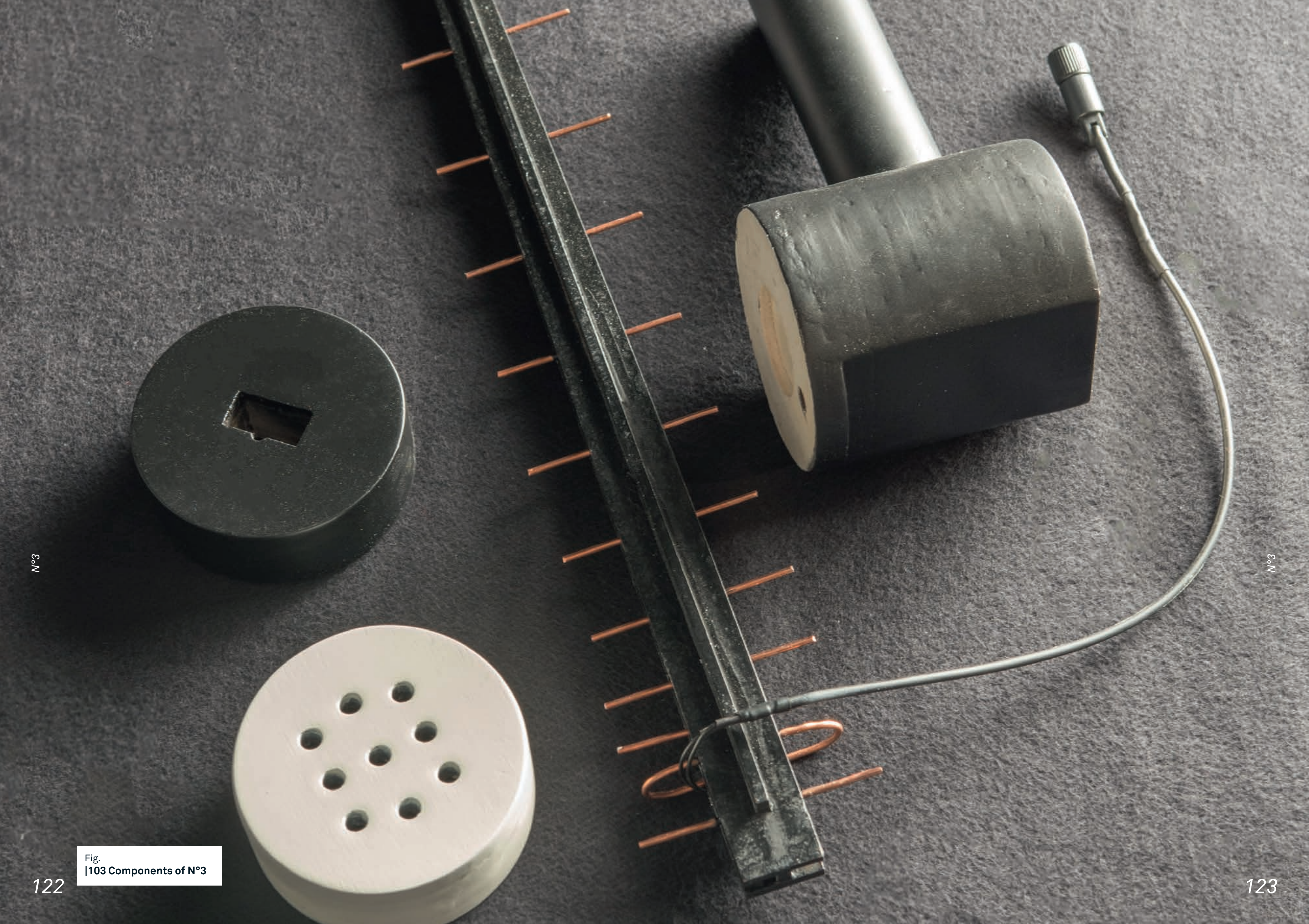


Fig.
|103 Components of N°3

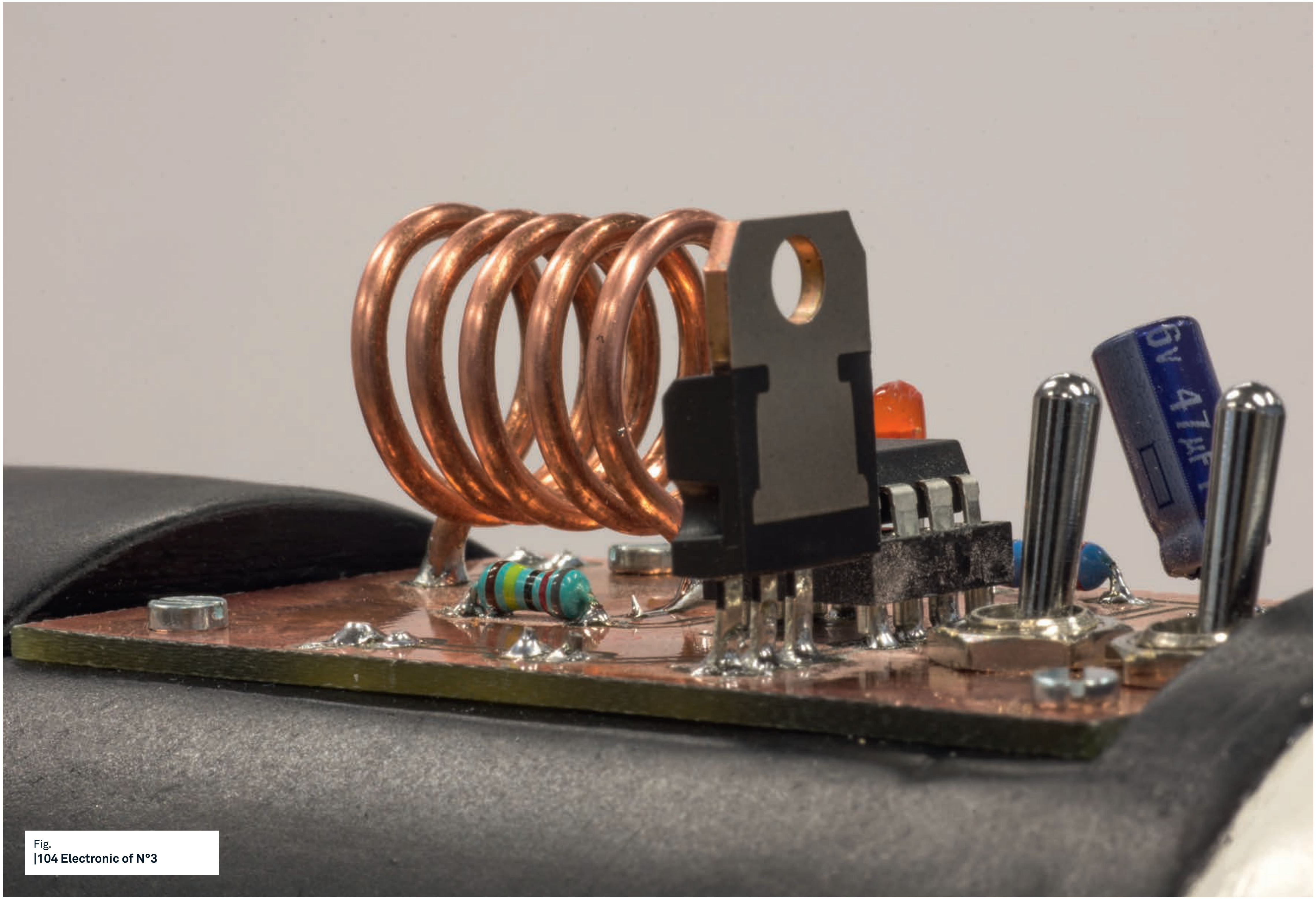


Fig.
|104 Electronic of N°3

N°3

Experience

As soon as the prototype was working we gave it to several persons to test. As they had received the prototype the started to walk around and explore the room. The faster ticking of the sound was quite intuitive. Most of the testers realized by themselves how the feedback reacted to their actions. It was also very clear for all the testers how to hold the prototype and which end to point where.
Most needed some time to find out what exactly the prototype was giving feedback to. But soon most of the testers had a suspicion of where to find electromagnetic fields. At some devices, they were surprised when there was no field around it because it was well shielded. And at other devices, they were surprised how strong the field was. It was also interesting for us when suddenly the prototype did not work properly because someone was wearing well isolated shoes. In the end, it was great experience for us to see how they rediscover a known space.

Fig.
|105 N°3 in use

Fig.
|106 Components N°3

N°3

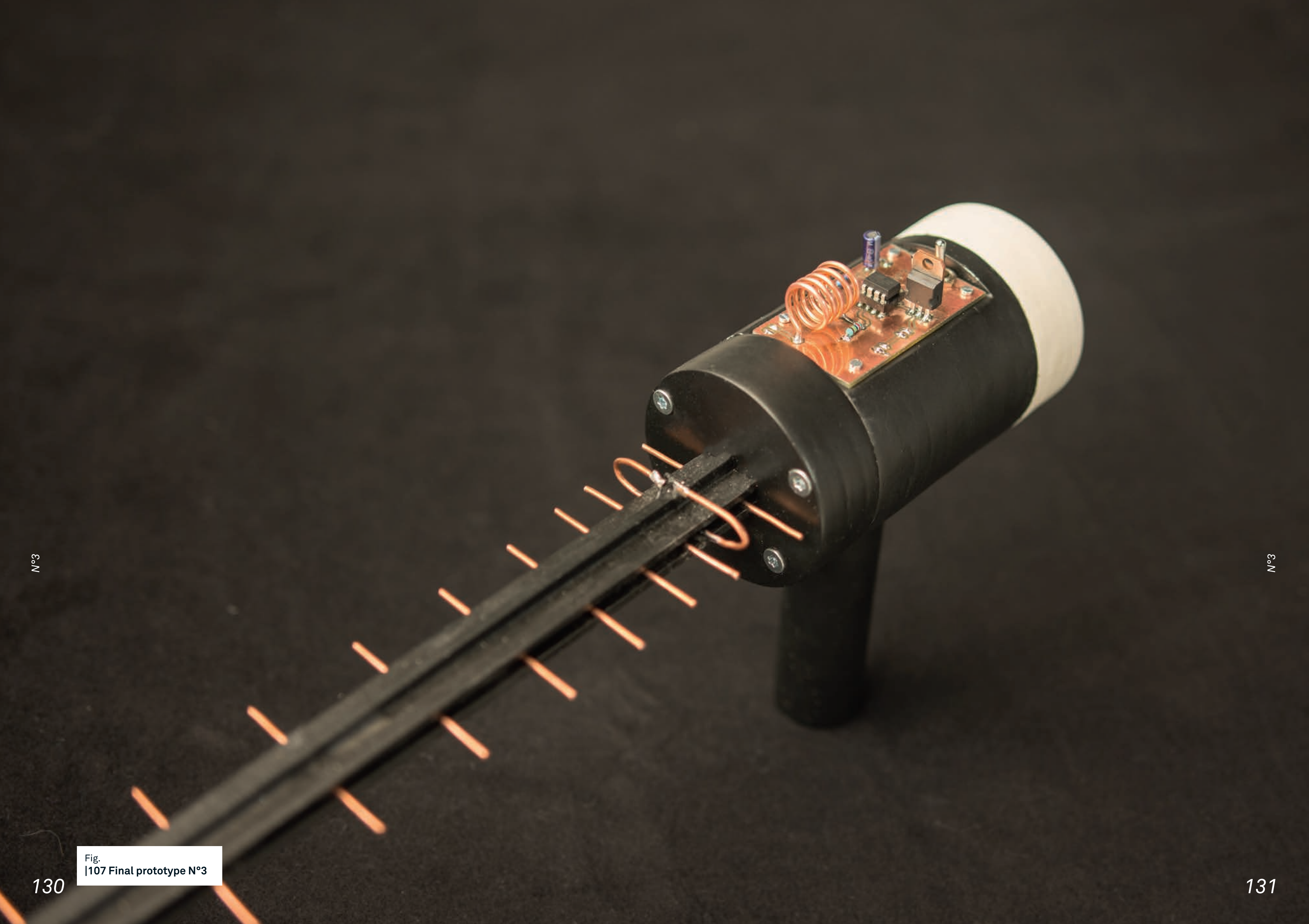


Fig.
|107 Final prototype N°3

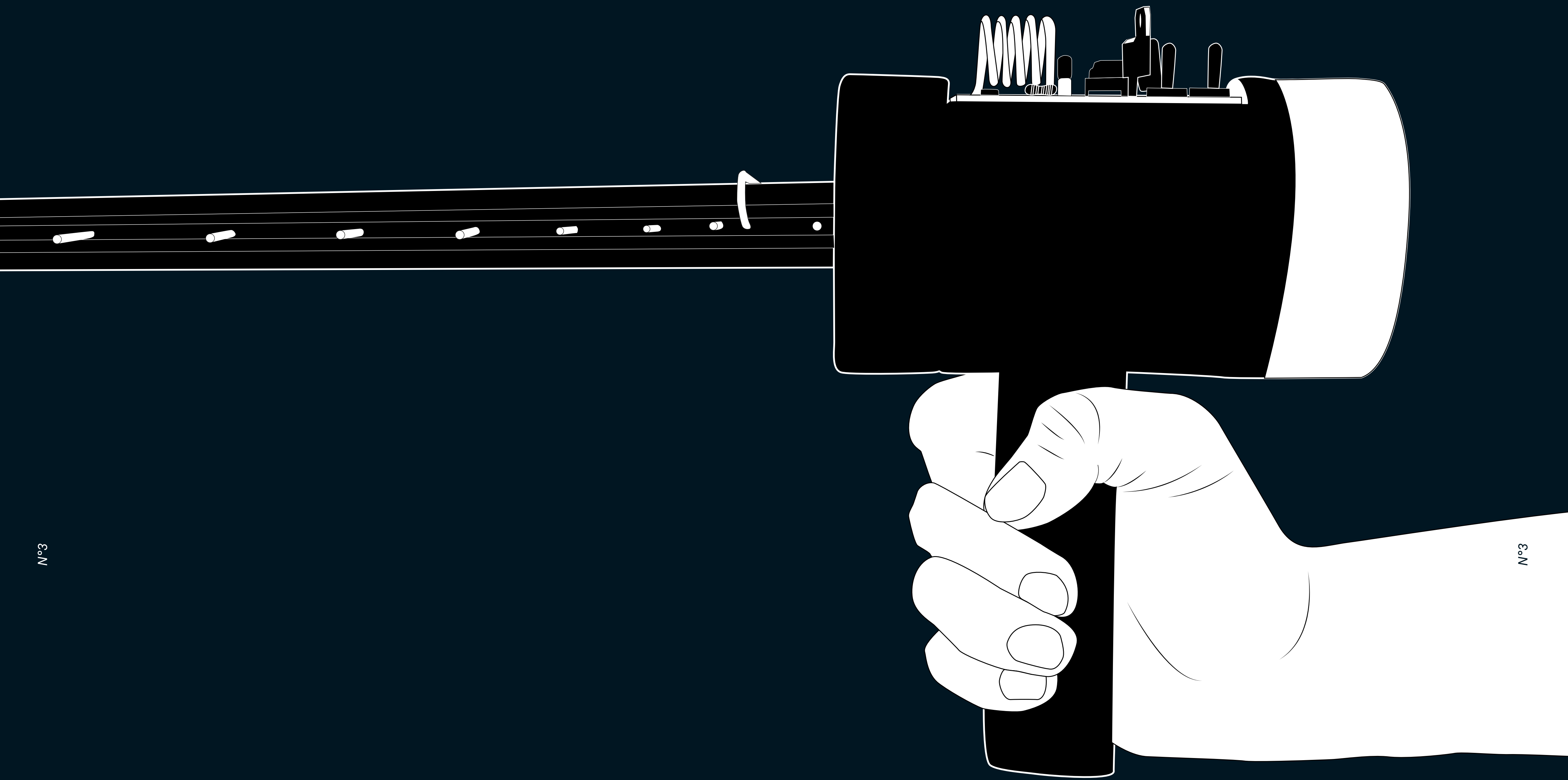


Fig.
|108 Functional sketch N°3

N°3

N°3

Conclusion

When looking back at the whole journey to these three functional prototypes we obtained some important findings. By using the method of rapid prototyping, we could produce a great variety of experiments and prototypes during the whole project. These quick iterations allowed us to find design flaws faster and make better design decisions based on real-world experiments. This and the detailed documentation on the blog helped us to better reflect and reuse the experiments for our final three prototypes. Moreover, the early experimenting allowed us to experience everything by ourselves and therefore control the experience in the direction we were looking for. While developing something we could not perceive it was crucial to have this fast feedback.

Furthermore, it was also very helpful to give the first prototypes to other people. Seeing them walking around and exploring the hidden space was a great motivation for us. And the following question and discussions showed us that the prototypes really could create curiosity and enhance the understanding. But even when we were testing the prototypes by our own we had a lot of wow moments. And whenever we discovered something unexpected we started investigating to find an explanation.

While building all these prototypes and experiments we encountered many difficulties with technology. Sometimes the mistake was ours, sometimes the material was flawed and sometimes we could not find out what was wrong. We had to rebuild multiple circuit boards because of inaccurate working and abandon ideas because we did not get them running. This process of failing, problem solving and success was very exhausting but also very educational.

Only by going through this whole process we were capable to create our three prototypes. And only by experiencing the work ourselves we were capable to create this experience of exploring and discovering the hidden world of Hertzian space by feeling, hearing and seeing.

Acknowledgment

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