MASTER THESIS

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Design and Development of a Refreshable Braille Display

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Vienna, 22.05.2017

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Kurzfassung

Visuell beeinträchtigte Menschen benötigen Assistive Technologien, um Informationen von Computer und Smartphones zu erhalten. Da Sprachsynthesizer in vielen Situationen unpraktisch sein können, bieten Braille Displays die Möglichkeit von Audio Feedback zu minimieren. Digitale Braille Displays können sehr teuer sein oder bieten nur eingeschränkte Funktionalitäten. Daher wird an alternativen Konzepten für eine digitale Blindenschrift gearbeitet. Diese Konzepte gilt es in deren Technologie und Kosteneffizienz zu analysieren. Aus der Evaluation geht hervor, dass motorbetriebene Braille Zellen die kosteneffizienteste Lösung bieten. Darüber hinaus soll die Kommunikation mit Schnittstellen zu Smartphone und Computer von großer Bedeutung sein, um eine größtmögliche Benutzerfreundlichkeit und Nutzungsmöglichkeit zu erhalten. Aus diesen evaluierten Anforderungen resultiert ein Konzept für einen Prototyp eines Braille Displays, welches aus 3D druckbaren Komponenten, der benötigten Elektronik und entworfenen Leiterplatte, sowie aus der Software besteht. Dieses Konzept ist ausgearbeitet und in Bezug auf Funktionsweise sowie Kosteneffizienz analysiert.

Schlagwörter: Digitale Blindenschrift, Braille Display, Braille Reader, Braille Zelle, Rapid Prototyping

Abstract

Visually impaired people require Assistive Technologies in order to use computers and smartphones for gathering information. Speech synthesizers can be impractical in lots of situations and therefore digital braille displays can be used to extend or even replace the audio feedback. As braille readers are either pricey or have a lack of functionality, the efforts to rework technologies of those devices is increasing. Available concepts for braille cells are analysed and requirements of an affordable alternative functional principle for the design is developed. The evaluation reveals a motor driven braille cell mechanism is most cost efficient. Furthermore, the interoperability with computer and smartphone interfaces is of high importance to achieve a great usability. From these deducted requirements a prototype concept is developed and implemented in form of 3D printed braille actuator cells, a microprocessor controlled main unit and a custom printed circuit board.

Keywords: — Braille reader; Refreshable braille display; Assistive technology; Braille cell; Rapid prototyping

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1 Introduction

According to the World Health Organization (WHO) statistics there are 285 million people worldwide suffering from either low vision or blindness, whereas 90 percent live in low-income settings [1]. Blind people rely on either audio or haptic feedback in order to gather information from the surrounding. Information in form of written texts can't be transformed to audio in a proper way in all situations. Therefore braille is a comfortable and fast way to substitute or extend a speech synthesizer. Refreshable braille displays are electromechanical devices enabling blind people to read texts and messages which are displayed on devices such as computers and smartphones. Reading documents, news and articles on a computer is made possible by using such a device. Those texts will be extracted line by line and transferred to the braille reader which will then operate mechanical pins. These pins are combined to a mechanical braille display enabling the reading process for the user. Braille readers can also include an input technique for blind people in order to write messages in an adapted way. Therefore it can have an inbuilt keyboard featuring all required buttons to control and write messages to the desired end-device.

Mechanical refreshable braille cells are based on different technologies in devices on the market. These have to be analysed and evaluated in order to find the appropriate one to implement. Since the most data about braille displays and readers on the market are not available as open source and their costs can exceed several thousand Euros, the aim of this thesis is to design and develop a concept and prototype of a universal and highly interoperable refreshable braille reader at low costs. Therefore it is required to analyse the usage behaviour of braille display users and evaluate the methods and technologies in order to find solutions if the manufacturing costs can be reduced significantly while keeping state of the art standards or optimizing them. Evaluations of manufacturing refreshable braille displays in terms of rapid prototyping technologies are to be conducted.

Thereby this thesis deals with the development of a design and if these can be transformed to a prototype while ensuring to meet the predetermined requirements. Therefore the research for requirements is based on:

- Evaluation of braille cell technologies
- Design and development of 3D printable components
- Implementation of open source available resources for the software application
- Design and implementation of required electronics
- Analyse, maintain and improve the state of the art standards

1.1 Braille Definition

Louis Braille got blind in his early years through an accident and an additional inflammation. At the age of 15 he developed a universal system to help reading and writing for visually impaired people. In 1829 he published a book explaining and teaching how this universal system works. The concept is that a specific arrangement of dots represent characters. Those dots are embossed and can be read by passing one's fingertips over them. Since then the braille concept has been adapted in nearly every known language and is essential for the daily routines for visually impaired people. Braille is not considered as a language, but another way to read and write a language. [2] [3] [4] [5]
The basic braille system uses a six dot arrangement as shown in figure 1. It holds up to 64 possible combinations, including the space where no dots are present.

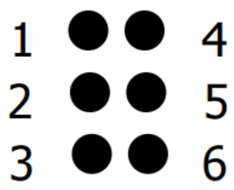

Figure 1 : Arrangement of the six dot braille configuration. [6]

Additionally a fourth line of dots can be added resulting in 8 dots. This expands the table of representable characters such as capital letters and special characters. An adapted form of the chart combining a table of braille codes published by the European Blind Union (EBU) is attached. [7] [8]

1.1.1 Grades of Braille

Grade 1 is considered as a one-to-one conversion. Each letter, punctuation sign, number or special braille character is represented individually. One cell can therefore not represent abbreviations. Grade 2 braille is implemented for space saving reasons. A single cell and combinations can represent a shortened form of a word and therefore the reading process can be fastened. For this reason, the most commonly used words and abbreviations have to be defined. This leads to different braille tables in grade 1 and grade 2 for every individual language. Braille includes additional formatting marks, which have to correspond with other written languages, such as the number and letter sign. These and other signs represent the sequence of characters in a defined meaning in order to be differentiated. [6]

1.2 Braille Dot Dimension

Braille differentiates in size and arrangement depending on country and language. Therefore the European Union announced directives to standardise it. There are regional norms and standards for different accessibility solutions. In order to rely on one commonly used standard, the EU Directive highly recommends the Marburg Medium size font for packaging and labelling. Braille displays already available on the market are using this standard, however some manufacturers increased the dot sizes. The EU recommends a braille specification which clarifies braille cell dimensions, spacing and dot size as seen in figure 2 and described in table 1 in detail. [9] [10]

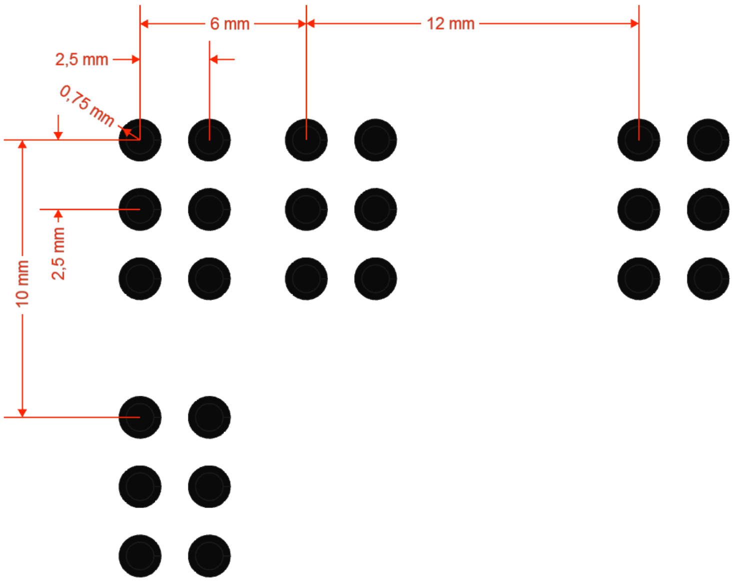

Figure 2 : Braille dot distance specifications according to Marburg Medium.

Parameter	Size [mm]
Horizontal dot to dot distance	2.5
Vertical dot to dot distance	2.5
Cell to cell distance	6.0
Cell to cell distance with single space in between	12.0
Line to line distance	10
Dot base diameter	1.5
Dot height	≥0.5
Tolerances	±0.1

Table 1 : Braille dot distance specifications according to Marburg Medium. [11]

1.3 Market Research

The market research for the worldwide visual impairment is conducted by the WHO. It is stated that 285 million people are estimated to be visually impaired worldwide while 39 million are blind and 246 have low vision. About 90% of the world's visually impaired live in low-income settings and about 82% of people living with blindness are aged 50 and above. [1] Table 2 represents the ratio of visually impaired people in world's population.

WHO Region	Total Population [millions]	Blindness [millions]	Low Vision [millions]	Visual Impairment [millions]
Africa	804.900	5.880	20.407	26.295
America	915.400	3.211	23.401	26.612
Eastern Mediterranean	580.200	4.918	18.581	23.499
Europe	889.200	2.713	25.502	28.215
South-East Asia (India excluded)	579.100	3.974	23.938	27.913
Western Pacific (China excluded)	442.300	2.338	12.386	14.724
India	1181.400	8.075	54.544	62.619
China	1344.900	8.248	67.264	75.512
World	**6737.500**	**39.365**	**246.024**	**285.389**

Table 2 : WHO statistics of blindness in world population regionally grouped. [1]

The data of the worldwide statistics of blindness is combined to age group distribution resulting in table 3.

Age Group [years]	Total Population [millions]	Blindness [millions]	Low Vision [millions]	Visual Impairment [millions]
0-14	1848.500	1.421	17.518	18.939
15-49	3548.200	5.784	74.463	80.248
50 and older	1340.800	32.160	154.043	186.203
All ages	**6737.500**	**39.365**	**246.024**	**285.389**

Table 3 : WHO Statistics of blindness in world population grouped in age. [1]

The group focused on for the usage of braille displays is the age above 15 as well as persons who are blind and have low vision.

$$\Sigma_{WorldWide(Age>15)} = \Sigma_{Blind(Age>15)} + \Sigma_{Low\ Vision(Age>15)}$$
$$= 5{,}784{,}000 + 32{,}160{,}000 + 74{,}463{,}000 + 154{,}043{,}000 = 266{,}450{,}000$$

The potential users of braille displays are worldwide 266.450 which results in a percentage of 4% of the overall population and 93% of all blind and severe visually impaired people.

1.4 Braille Profiling

The braille profiling is a market research conducted by the Royal National Institute of Blind People (RNIB). [12]

Demographics of Braille customers

According to the market research the average braille user is younger than 61 while around 50% are blind and 50% are partially sighted. Table 4 shows an age distribution of those users.

Age	Distribution
0-29	5%
30-49	15%
50-64	39%
65-74	23%
75+	18%

Table 4 : Age distribution of braille customers.

Braille Display Usage

The braille users conducted within the survey stated that 73% of them own either a computer or a laptop. Emailing, using web browsers and reading/writing documents are the most common uses although downloading podcasts, audio/e-books and social networks show a big trend in becoming more important. Table 5 describes the usage distribution amongst braille users.

Task	Usage
Emailing	82%
Reading/writing documents	80%
Surfing Internet	76%
Listening to radio	41%
Visiting news websites	38%
Downloading audio or e-books	20%
Participating in forums	20%
Downloading podcasts	18%
Social networking	18%

Table 5 : Computer usages of braille customers.

Braille tends to be used more often for reading than writing, although most braille customers use it for writing at least once a week as shown in table 6.

Usage	Reading	Writing
Never	1%	5%
Less often	0%	5%
Once every few months	5%	5%
Once a month or so	7%	13%
Once a week or so	13%	25%
Every day/almost every day	75%	46%

Table 6 : Frequency of using braille for reading and writing.

Non-Braille Users

Reasons for customers who don’t intend to get a refreshable braille display in near future can be seen in table 7.

Reason	Distribution
Too expensive or costly	51%
Wouldn't use it enough	44%
Don't know enough about them	29%

Table 7 : Reasons for not using braille readers

1.5 State of the Art

State of the art portable braille displays such as the Perkins Mini offer the ability to be connected with smartphones and computers via USB as well as Bluetooth. Therefore the device can be used as a stationary as well as a portable handheld braille display whereas the rechargeable battery included lasts up to 10 hours. A pre-installed SD card with a capacity of 4GB offers storage space for books and documents, which can be accessed. The user has the opportunity to use functions such as a notepad, book reader, calculator and clock. The Perkins Mini has an inbuilt keyboard for writing either directly to documents or in connection with other devices. Joysticks and function keys ease the navigation. The device is compatible with the major of screen reader applications designed for PCs, Apple computers, iPad, iPhones and soon Android. The display itself consists out of 16 refreshable 8-dot braille cells, which are capable of showing capitalized letters as well as specialized characters. [13]

Figure 3 : Perkins Mini Seika braille display covering 16 refreshable braille cells. [13]

This device is considered as a braille display and reader with a suitable number of possibilities in use and applications. However, the costs for the Perkins Mini is listed at 1,549 US Dollars. [13]

2 Material and Methods

The basic requirements for the braille display which has to be designed and developed are defined to house a braille display, braille keyboard and a number of necessary interfaces as shown in figure 4. The device shall be interoperable with computers as well as smartphones. Therefore a USB and Bluetooth connection is from high importance. Furthermore an SD card slot for storing readable files such as books and text files shall be built in. Since the braille reader is a stationary as well as a portable device, a rechargeable battery needs to be implemented. Moreover an integrated set of applications for the use without any additional device is required. Besides of the support of reading digital books this includes date and time as well as a calculator. The focus of the prototype to design and develop lies on high interoperability between the most widely used devices using open standards. Additionally it has to be based on technologies which will reduce the manufacturing costs compared to available devices significantly.

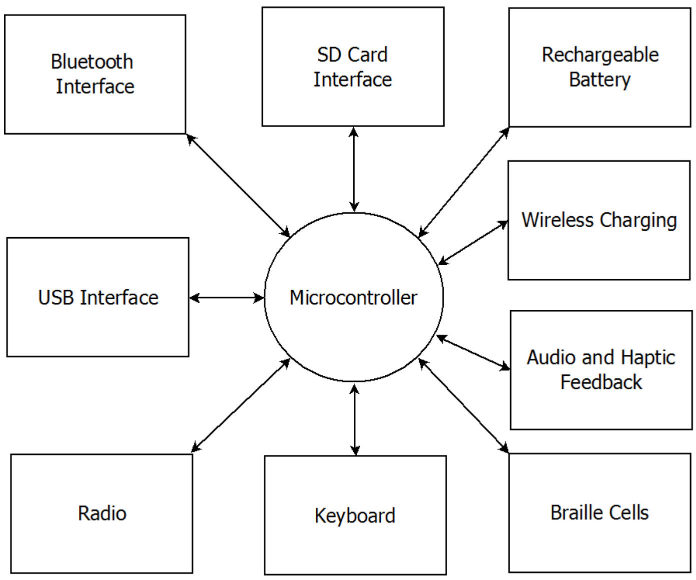

Figure 4 : Design of hardware components involved in the braille display.

The basic requirements are deducted from braille market research as well as state of the art devices:

- Refreshable display of minimum eight cells each holding six-dots
- Reading the content of files on an SD card for stand-alone operation
- Computers and portable devices can be connected via USB and Bluetooth
- Eight braille input keys and space bar
- Four-way arrow and selection control keys
- Two panning control bars
- Date, time and calculator function
- Rechargeable battery with additional wireless charging
- Audio and haptic feedback

2.1 Braille Cell Technologies

A braille cell requires a minimum of 6 dots which can be embossed in a combination according to the desired character. In order to fulfil the embossing of each individual dot there are a variety of technologies. The three commonly used and most promising ones are based on piezoelectric, electromagnetic and micro motor based mechanism.

2.1.1 Piezoelectric Braille Cell

The most common mechanism used for operating braille cells is the piezoelectric effect. The design of the braille cell consists out of piezoelectric bimorphs, a Printed Circuit Board (PCB) and the mechanical constructions. A high voltage of 200V has to be applied which will bend the bimorphs through electric excitation. Those bimorphs are connected to a lever that embosses a dot of the braille cell. [14] [15]

Figure 5 : Piezoelectric braille module with eight dots.

2.1.2 Electromagnetic Braille Cell

In this concept of a braille cell, each dot is moved by electromagnetic effects. A coil can move up and down small magnets which are placed in a cylindrical component. Two ferromagnetic materials hold the dot in the desired position. No extra energy required to hold the dot. A project covering this technology is the so called Modular Low cost Braille Electronic Display (MOLBED). This project is constructed and designed in a way that manufacturing in a prototyping area can be conquered. [16]

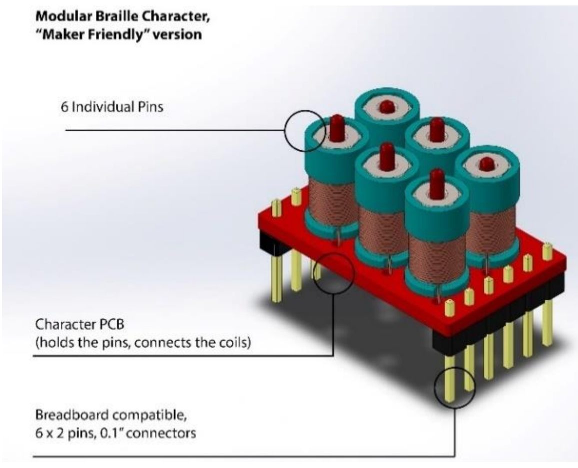

Figure 6 : Design of the braille cell using an electromagnetic concept. [16]

2.1.3 Micro Motor Based Braille Cell

The design of a motor driven braille cell is based on open source projects using prototyping techniques. The braille display is split up in modules holding two cells. Each cell consists out of 6 dots, which is enough to display required characters. Vibration motors are used to operate each dot individually, whereas one motor is required for a single dot. By tapering the metallic mass on the driveshaft of the vibration motor, it is possible to lift a pin vertically up and down if it turns to a certain degree. Those pins will represent the dots on the braille display. [17]

2.2 Implementation

The braille module implemented consists out of a number of separate components whereas one module will implement two braille cells. The basic concept contains micro motors and their holders, levers, movable braille dots and a cover plate.

Motor

The motor which is used to push up the lever is based on a vibration motor. The flywheel mounted on the shaft is bevelled on one side at 45 degrees. The motor has a radius of 2mm with a height of 8mm. This size allows a compact implementation in the braille cell, since six motors are required per character.

Figure 7 : Vibration motor in cylindrical case.

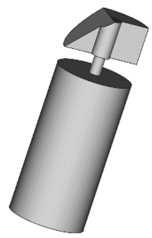

Figure 8 : 3D CAD design of vibration motor in a cylindrical case.

Figure 9 : Vibration motor with case and direct contacts. [18] [19]

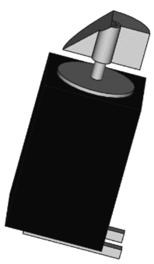

Figure 10 : 3D CAD design of vibration motor housed in a case.

Motor Holder

The motor holding components are holding twelve motors in total, which leads to two braille cells with six dots each per braille module. The construction has a mechanical limitation of close to 180 degrees for the motor to turn. This leads to two possible allocations of the bevelled flywheel.

Lever

The lever is placed on top of the motor holding construction where pins protrude. The bevelled flywheel of the motors lift up the levers when activated.

Movable Braille Dots

The braille dots are fixed between the cover plate and the lever. As soon as the lever gets pushed upwards by the motor, the individual braille dots are embossed.

Cover Plate

The cover is placed on top of the other components and can be screwed together with this construction. Therefore the plate fulfils on the one hand the task of providing a covering including the holes for the dots and on the other hand it is the basis for the construction to be mounted on.

2.2.1 Electronics

Microcontroller

The main controlling unit of the braille device is a microcontroller board based on a 32 bit ARM Cortex-M0+ chip. It features a processor speed of 48 MHz and implements 62KByte Flash, 8KByte RAM, 12 analogue input and output ports, hardware Serial, Serial Peripheral Interface (SPI), I2C and a total of 27 I/O pins. [20]

The Teensy LC is a development board housing the ARM Cortex-M0+ processor chip with all required communication ports and power supply. Therefore this board can be attached through header pins as the main processing unit on the mainboard of the braille display device [21]. As every single dot of the braille display requires an extra port in order to activate it, port expander chips are necessary. Therefore the MCP23017 offers 16 output ports which can be triggered through a two-wire interface via the microcontroller. The current of the outputs and inputs is limited to 25mA. Therefore combining two ports parallel are enough to drive the required motors. [22]

SD Card Support

The micro SD card support for the device is achieved through a module housing all required components. SD cards are operated at 3.3V which is achieved through a voltage regulator. The ports for controlling the SD card via SPI commands are regulated in voltage through a level shifting chip.

Power Supply

The rechargeable battery for the braille display is based on lithium ion compound in a standardised 18650 case. The Sony Li-Ion houses a capacity of 2600mAh at 3.7V output voltage. [23] A rechargeable battery in the same standardized case manufactured by Samsung offers a capacity of up to 3450mAh. [24]

As the device is operated with a 5V power supply, the voltage of the battery has to be increased. Therefore a step up module is included in the electronics design. This component is able to boost the voltage to 5V with a current limited to 500mA which is sufficient for the braille display. A charging controller TP4056 is used for charging the lithium ion battery. It has a built in voltage limitation for the battery at 4.2V at a maximum current of 1A. This leads to a short battery charging time. [25]

It shall be able to charge the device additionally wireless without any cables. This can be achieved through the implementation of sending and receiving coils. The sending component is implemented in a platform where the device can be placed on, while the receiving pad is mounted inside of the device. The output of this pad is rated at 5 Volts while achieving a current of 800mA.

Bluetooth Module

The Bluetooth connection is achieved via a module based on the Cambridge Silicon Radio BC417 2.4 GHz Bluetooth Radio chip. The communication between the module and the main processing unit is achieved through Universal Asynchronous Receiver Transmitter (UART). This enables an easy implementation and connection with devices such as smartphones and computers. [26]

Real Time Clock

As the braille display shall include a feature for date and time, a real time clock is implemented. Therefore a DS1307 chip is to be built in, which will be constantly powered by a lithium button cell. Via a two-wire serial interface the data can be read by the microcontroller for further processing. [27]

Radio Module

The access to Frequency Modulated (FM) radio signals is achieved through the implementation of a radio module housing the TEA5767 chip. It is a single chip radio receiver including automatic adjustments for the desired frequency which can be tuned for the international FM band between 87.5 MHz to 108 MHz as well as 76 MHz to 91 MHz. The chip can be controlled via an inbuilt two-wire interface. Two independent audio output channels capable of delivering up to 90mV each make the chip to a stereo FM receiver. [28]

Braille Keyboard

The prototype will provide several input possibilities. On the one hand there are eight buttons representing the whole set of characters when pressed in combination according to the braille table and on the other hand additional buttons for navigating through menu and settings are implemented.

2.2.2 Software

The following software applications are required in order to develop the prototype of the braille display.

CAD Design

In order to design the mechanical components as 3D models the CAD software program FreeCAD has been used in the version 0.16.6706 (Git). This allows to design and animate the parts and components for the braille cells, case and button interfaces. These components can be exported in a 3D printable format. [29]

GCode Slicer

The 3D CAD drawings designed have to be 3D printed with the Prusa I3 MK2. Therefore the files have to be converted to a format which is readable for the printer. This format is the so called G Code. It is a standard for operating machines while the code is human readable. This conversion is done by Slic3r Prusa Edition Version 1.31.6-prusa3d-win64, which is a tool optimized for the used 3D printer. [30]

In order to estimate the printing time for the 3D models, the Repetier-Host V1.6.2 software application is used, which is an application developed for the use with rapid prototyping 3D printers. [31]

Electronics and PCB Design

The schematic as well as the PCB for the individual electronic components are designed in EAGLE Version 7.6.0 (32 Bit). All packages and libraries required for this thesis are already implemented in this software tool. [32]

The three dimensional animation of the PCBs is achieved through the eagle3d plugin for EAGLE CAD as well as with POV-Ray for Windows – version 3.7.0.msvc10.win32. [33]

Dia

Dia 0.97.2 is an open source diagramming software application. It is used for generating flow charts and UML diagrams for the visualization of software and hardware components. [34]

RoboBraille

RoboBraille is a free available and web-based service capable of automatically transforming documents into alternative formats optimized for the visually impaired people. With this service it is possible to convert eBooks and other commonly used documents into pure text and into adapted braille formats. This includes different languages and notation procedures for a variety of options as well as audio implementation. Therefore digitally available books and papers can be pre-processed in order to be read via the braille display. [35]

Braille Display Simulator

In order to simplify the development and testing of the braille display, a simulation tool is developed. It shows the output of the device in ASCII characters on the computer as well as the log data. In this way the behaviour and all events of the device can be tracked easily. The software is developed in C# in Visual Studio VS2015. [35]

Braille Display Firmware

The Firmware for the braille display is developed in the Arduino IDE version 1.8.2 with the Teensyduino plugin 1.36. The plugin implements drivers and packages required for programming the microcontroller Teensy LC used in the device. [21]

Braille Protocol

The communication process between the braille display and other devices such as a computer is based on ASCII character sequences as summarized in the following table.

Communication Braille Display	Description
[EVENT] <Text>	Displays events concerning SD card, charging status, menu selections, vibration and sound
[KEY] <Text>	Displays the key which is pressed on the braille keyboard
[BRAILLE] <Text>	Text which is displayed through braille
[ERROR] <Text>	Logs errors which occurred

Table 8 : Communication protocol of braille display.

The braille device sends all occurring events in a text format after a description in brackets. This way the log data as well as the pressed keys and the displayed text can be easily analysed in a human readable way.

Computer Support

On the market there is a variety of screen readers for computers available. These allow to read texts which are highlighted or selected out loud through speakers and headphones. Since using braille can be more comfortable, most of those software applications already support the interface for braille devices. This connection can be used either wirelessly or cable based. The screen reading software application will transfer the selected text word by word in a formatted way to the braille display. The keyboard on the braille device allows to control the software as well as sending texts to the computer.

Mobile Phone Support

A Bluetooth connection allows to pair a braille display with smartphones, which makes it possible to extract messages shown on the display and transfer it to the braille cells. Android is using a service called BrailleBack. It is implemented in the settings of the operating system and can be activated when required. As soon as a supported braille device is connected, the touchscreen behaviour will change. Swiping and taping on the screen will highlight elements on it and display the information on the braille device. To perform a click event, it is required to tap twice or use the buttons on the braille keyboard.
Similar to Android also Apple iOS includes a support for braille displays and readers. These assistive technologies are implemented for the most widely available and known braille displays. [4]

2.2.3 3D Printer

For 3D printing the required hardware components of the designed device the Prusa I3 MK2 is used. It is a widely available printer with high precision to a relatively low price which makes it optimal for a rapid prototyping as required. The filament material used for printing is an ABS thermoplastic polymer compound with 1.75mm diameter. [30]

3 Results

The results are split into the sections of design and prototyping of mechanical components, software applications and electronics.

3.1 CAD Designs

All required mechanical parts are designed in a three dimensional way in order to be further processed for the rapid prototyping technique.

3.1.1 Buttons and Switches

The keyboard buttons contain individual braille dots on top for being recognizable by tactile reading. The animation in figure 11 shows a button with the digit seven.

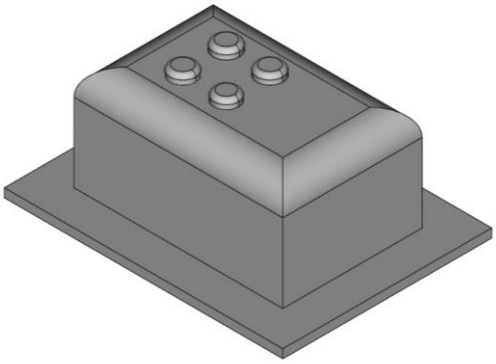

Figure 11 : Design of a button for the keyboard including a braille labelling.

The power switch in figure 12 is designed in a way that visually impaired people can recognize the state through braille labels.

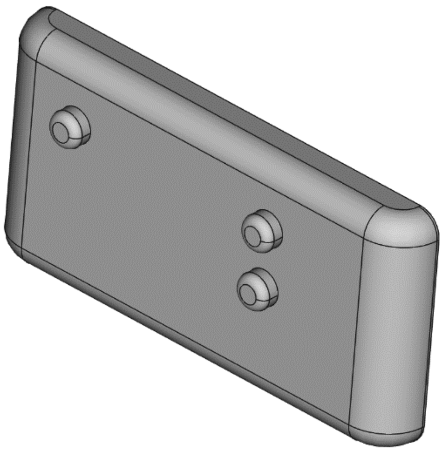

Figure 12 : 3D design of the power switch housing braille labels.

3.1.2 Case

The case consists of an upper and lower component which can be attached on top of each other through screws. The animation of the design of both parts are shown in the two figure 13 and figure 14.

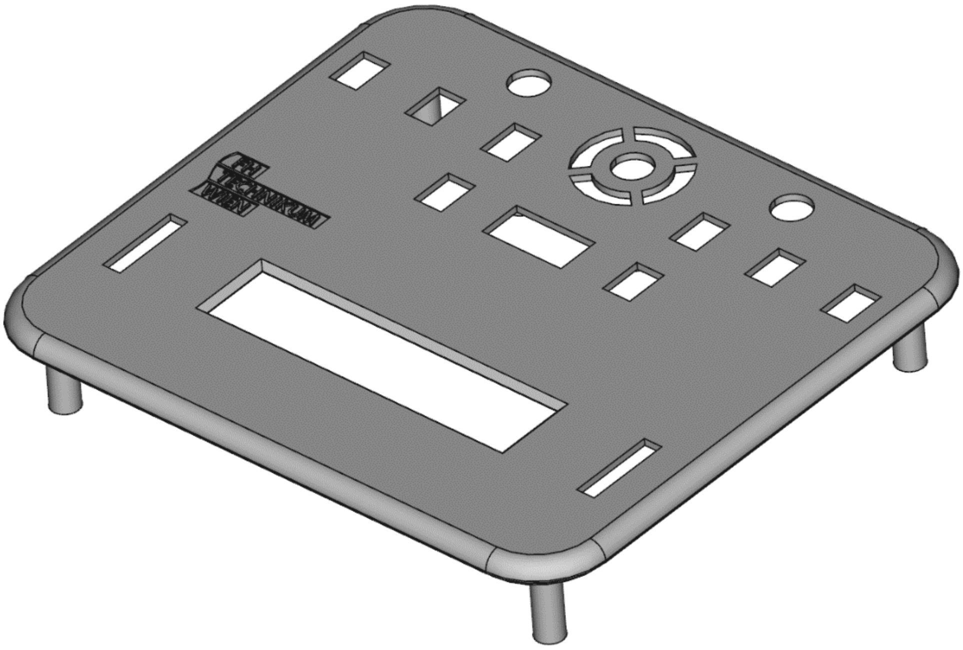

Figure 13 : Design of the top part of the case.

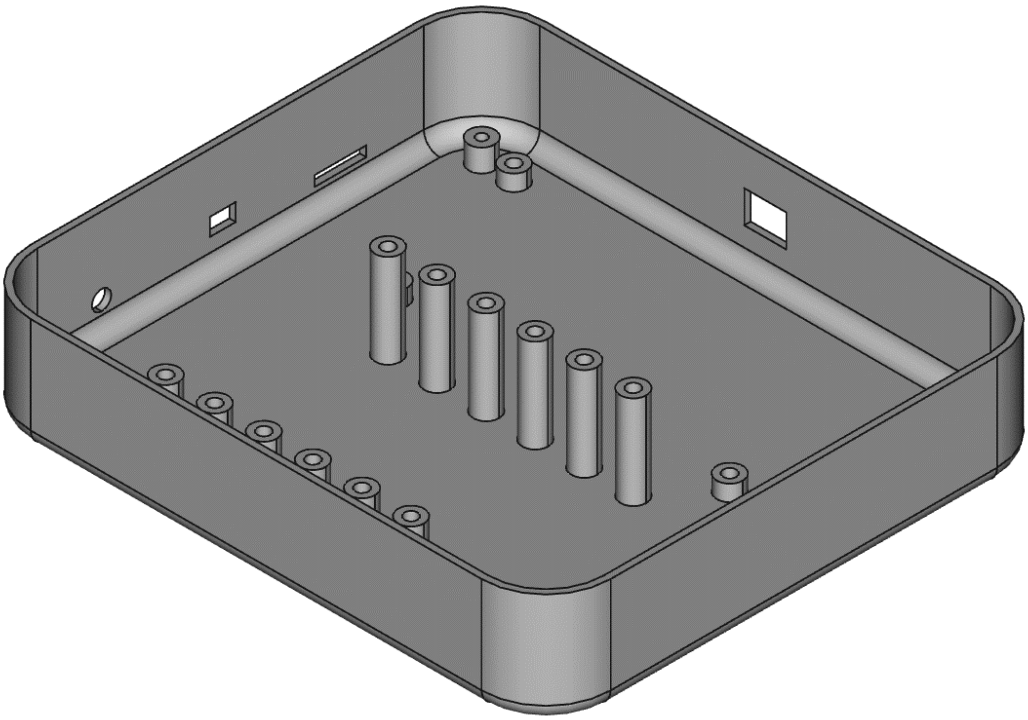

Figure 14 : Design of the bottom part of the case.

3.1.3 Braille Module Version 1

The braille module consist of the cover plate, pins, lever as well as the motor holding component.

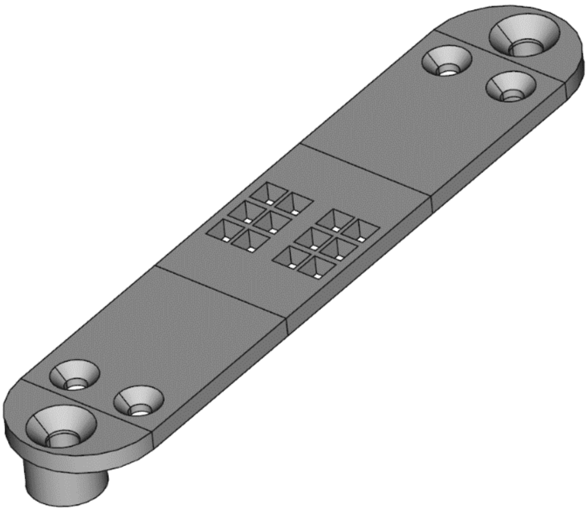

Figure 15 : Cover plate for the braille module.

Figure 16 : Pin component for braille module.

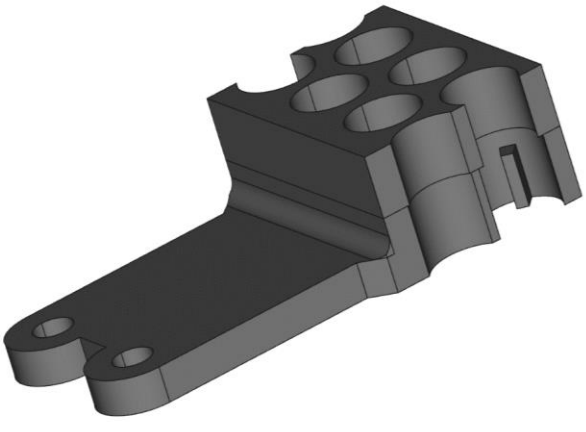

Figure 17 : Motor holder of braille module.

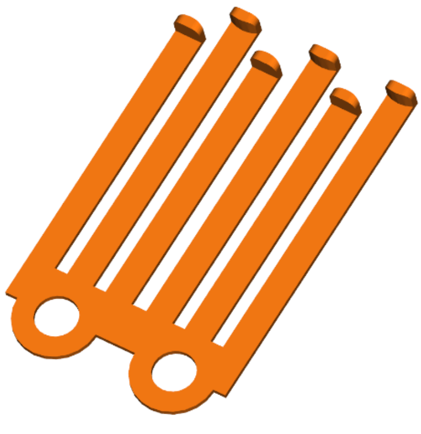

Figure 18 : Lever of braille module.

The explosion view and combined animation is shown in figure 19 and figure 20.

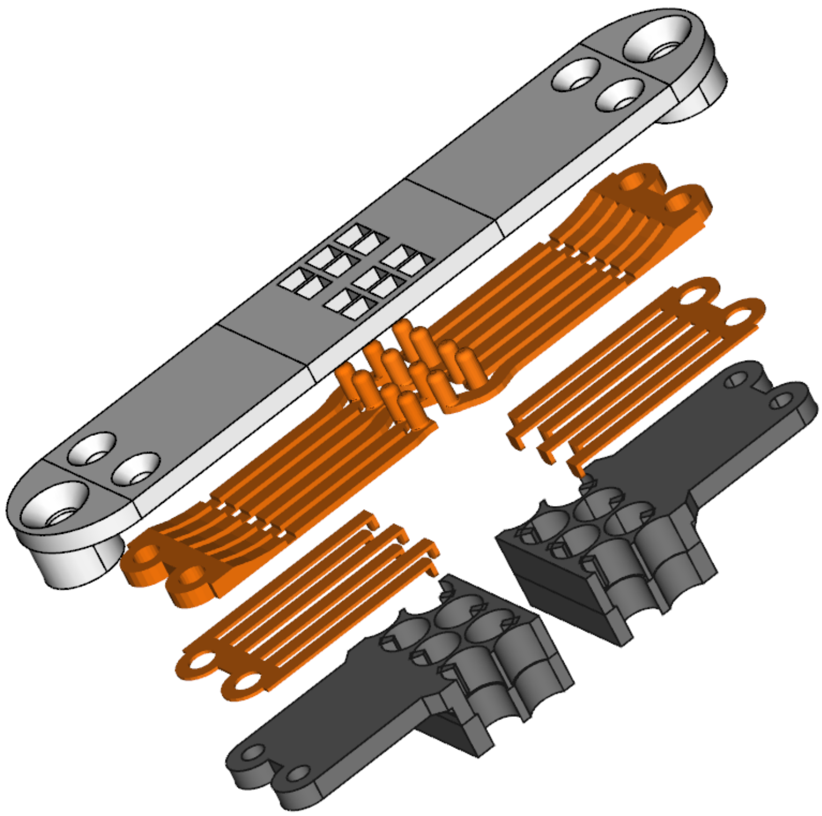

Figure 19 : Exploded view of braille module version 1.

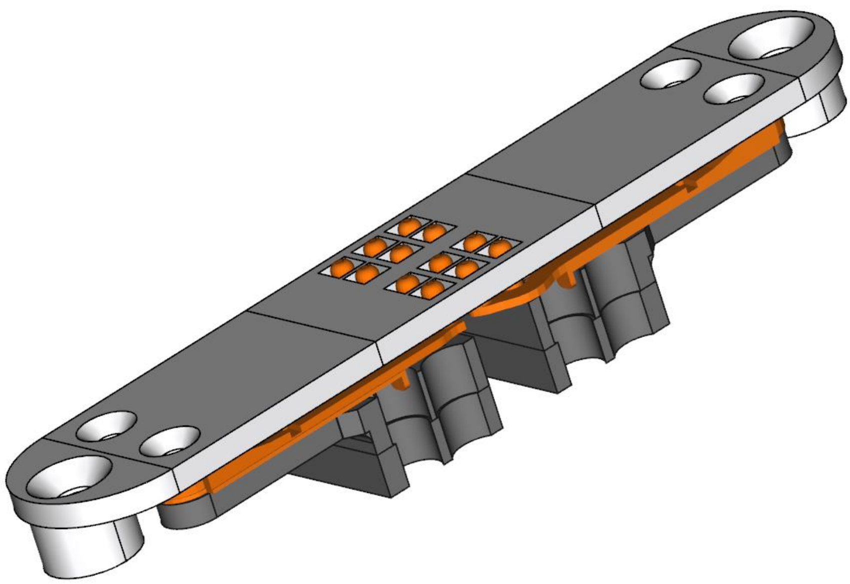

Figure 20 : Combined assembly animation of braille module version 1.

3.1.4 Braille Module Version 2

As in the first version of the braille module this design consists out of a cover plate, pins, lever and the motor holding component.

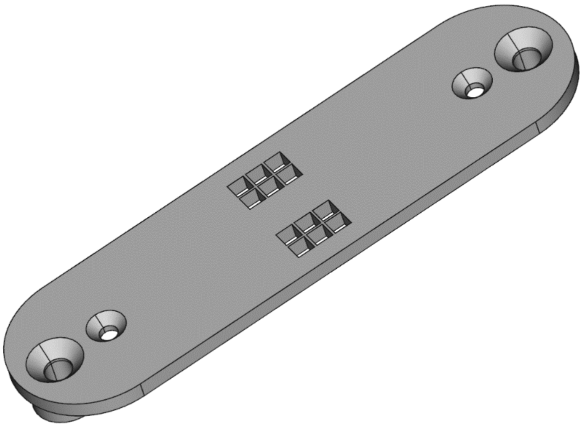

Figure 21 : Cover plate of braille module.

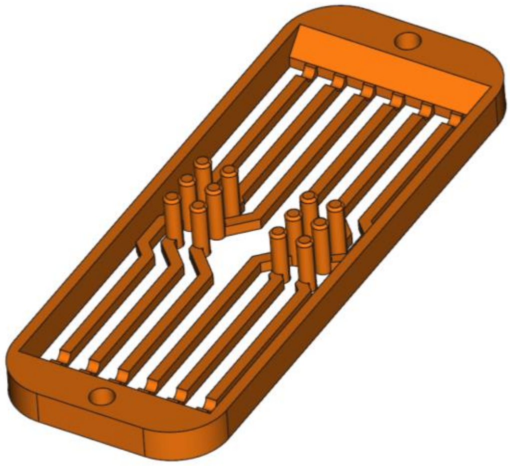

Figure 22 : Pins for braille module.

Figure 23 : Motor holding component.

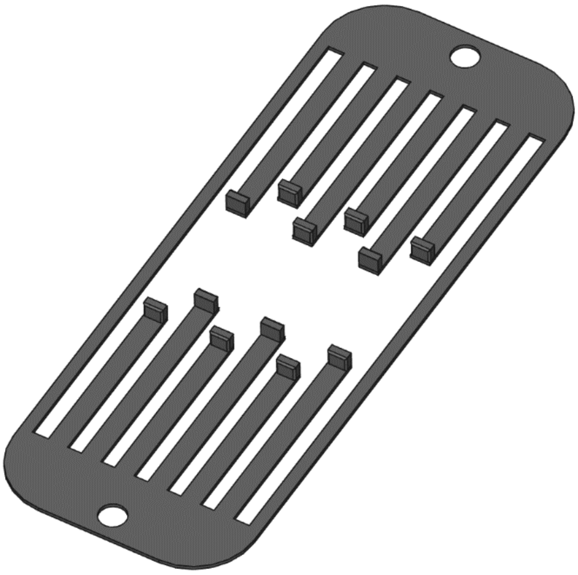

Figure 24 : Lever component.

The individual required mechanical parts for one braille module are animated in an explosion view in figure 25.

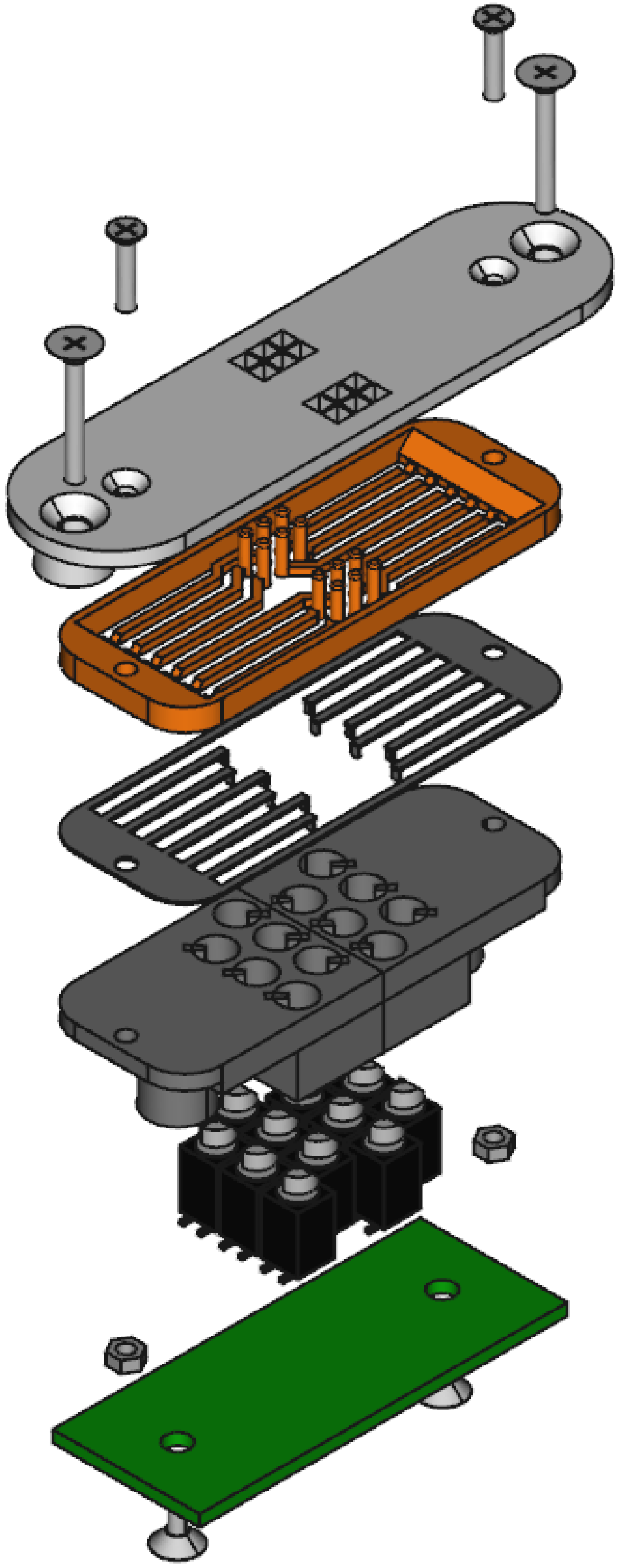

Figure 25 : Exploded view of all required components for braille module.

The assembly animation of the required components for one braille module holding two individual cells is shown in figure 26.

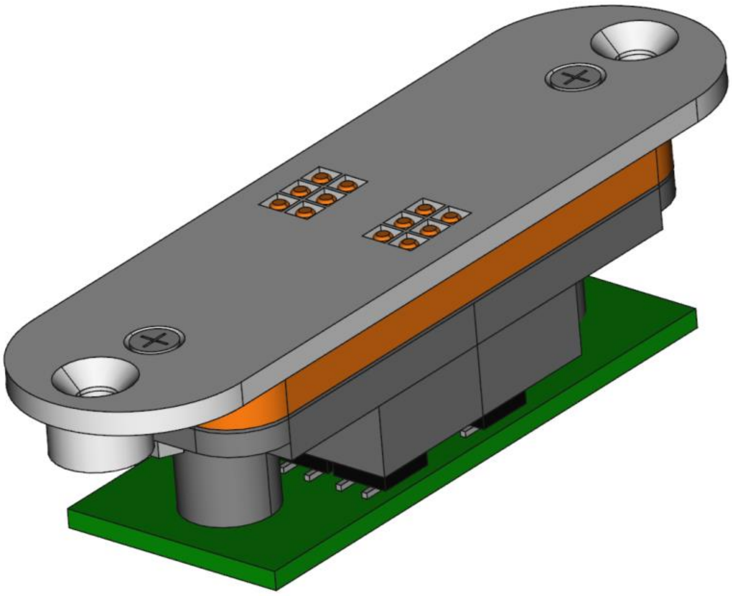

Figure 26 : Assembled animation of all parts for one braille module.

3.1.5 Wireless Charging Platform

The wireless charging platform in figure 27 consists of one three dimensional CAD design holding the outlets for the charger module as well as the required cable.

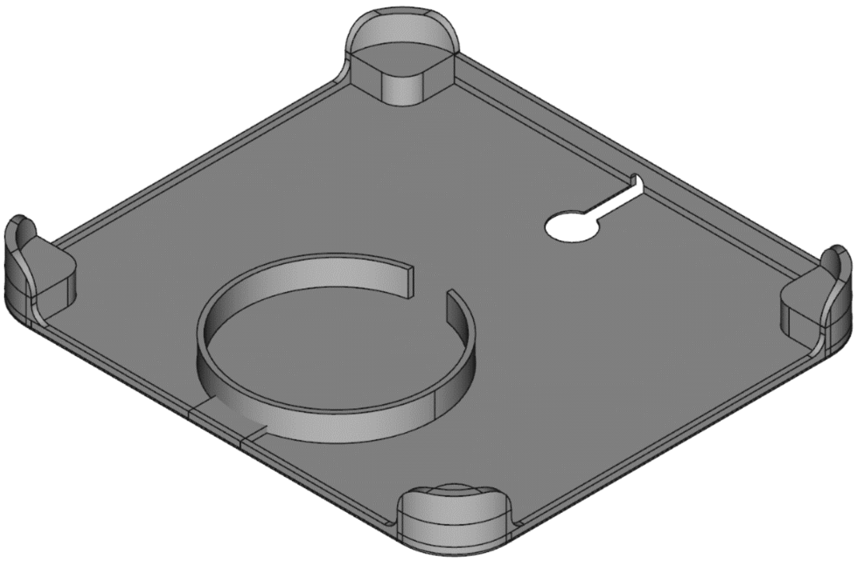

Figure 27 : Design of the wireless charging platform of the braille display.

3.2 3D Printed Components

This section shows the results of the 3D printing process for the case and braille module components.

3.2.1 Case

The results of the rapid prototyping process through 3D printing of the case is shown in figure 28 as well as figure 29.

Figure 28 : 3D printed part of upper case including the buttons.

Figure 29 : 3D printed component of the bottom half of the case.

3.2.2 Braille Module Version 1

The 3D printed components for the braille module in version 1 are shown in figure 30, figure 31, figure 32 and figure 33. The assembly of these parts can be seen in figure 34.

Figure 30 : 3D printed cover plate.

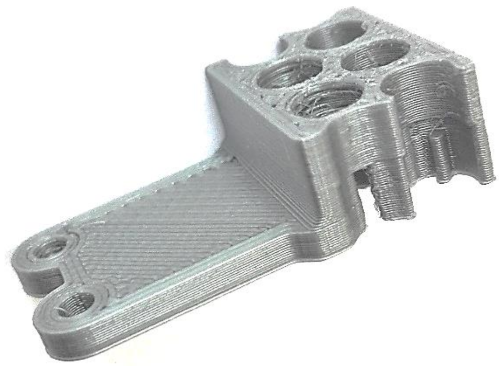

Figure 31 : 3D printed motor holder.

Figure 32 : 3D printed lever.

Figure 33 : 3D printed pins.

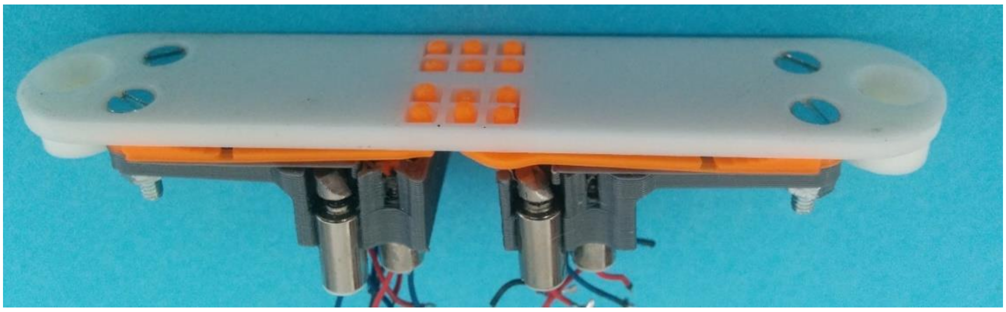

Figure 34 : Assembled braille module version 1.

3.2.3 Braille Module Version 2

The 3D printed components for the braille module in version 1 are shown in figure 35, figure 36, figure 37 and figure 38. The assembly of these parts can be seen in figure 39.

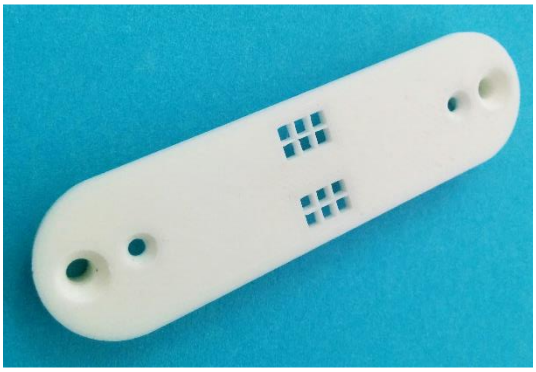

Figure 35 : 3D printed cover plate.

Figure 36 : 3D printed motor holder.

Figure 37 : 3D printed lever.

Figure 38 : 3D printed pins.

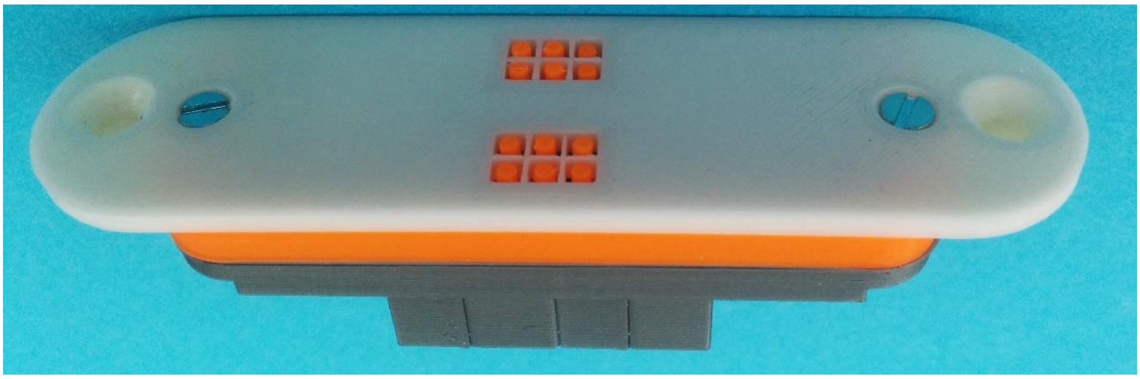

Figure 39 : Assembled braille module version 2.

3.2.4 Wireless Charging Platform

The 3D printed component for the wireless charging platform including the charger is shown in figure 40.

Figure 40 : 3D printed part of wireless charging platform.

3.3 Electronics

The designed electronic schematics and printed circuit boards are attached at section B-I. Following figures show the three dimensional animation of all required PCBs.

3.3.1 Electronics PCB Animation

The mainboard houses the main processing unit, required electronic components as well as all interfaces to modules and secondary PCBs.

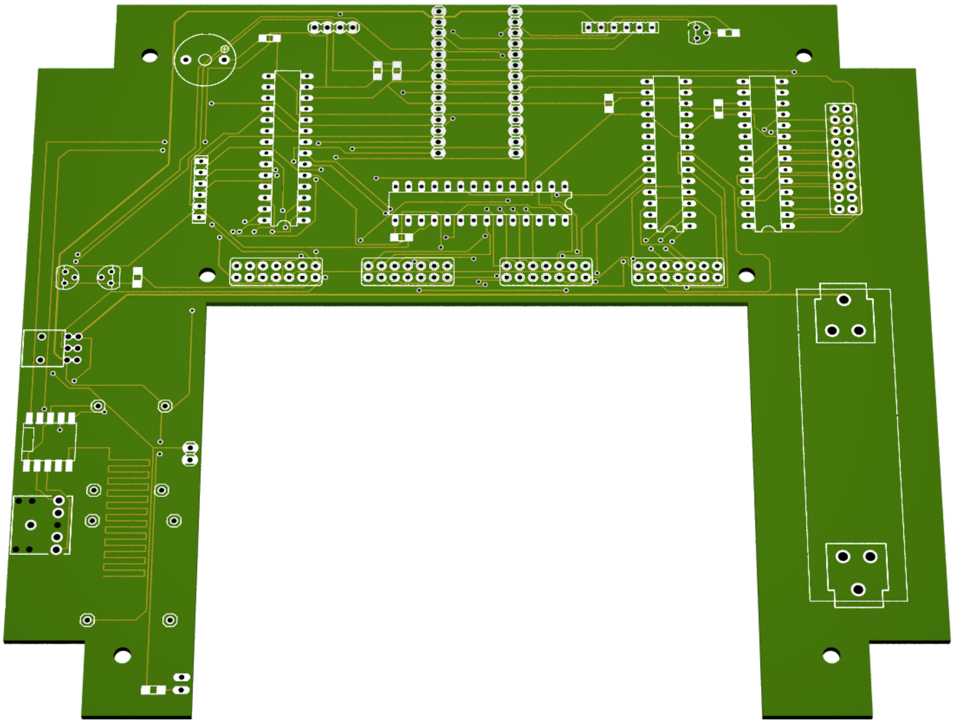

Figure 41 : Animation of mainboard PCB.

The top layer of the keyboard PCB houses the buttons while connectors to the mainboard and panning boards are placed on the bottom layer.

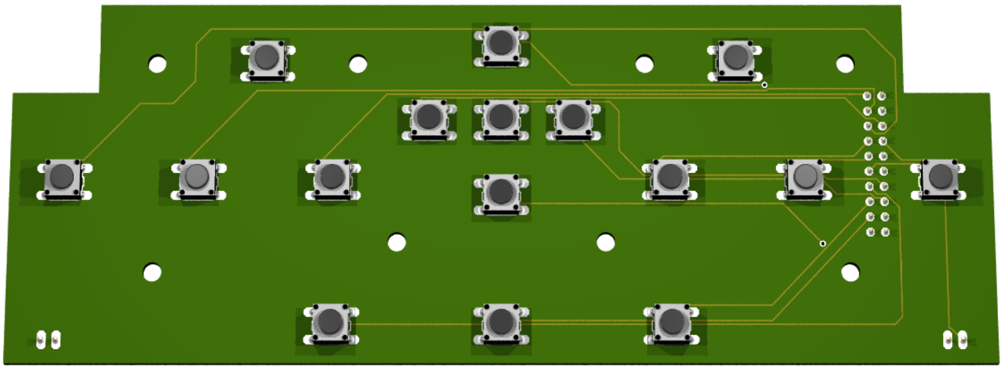

Figure 42 : Animation of keyboard PCB.

The printed circuit board housing the button as well as the connector is animated as shown in the figure 43.

Figure 43 : Animation of panning board PCB.

Each braille module requires a PCB housing the contact pads and a connector on the bottom layer. The PCB is therefore simulated with all components from both sides.

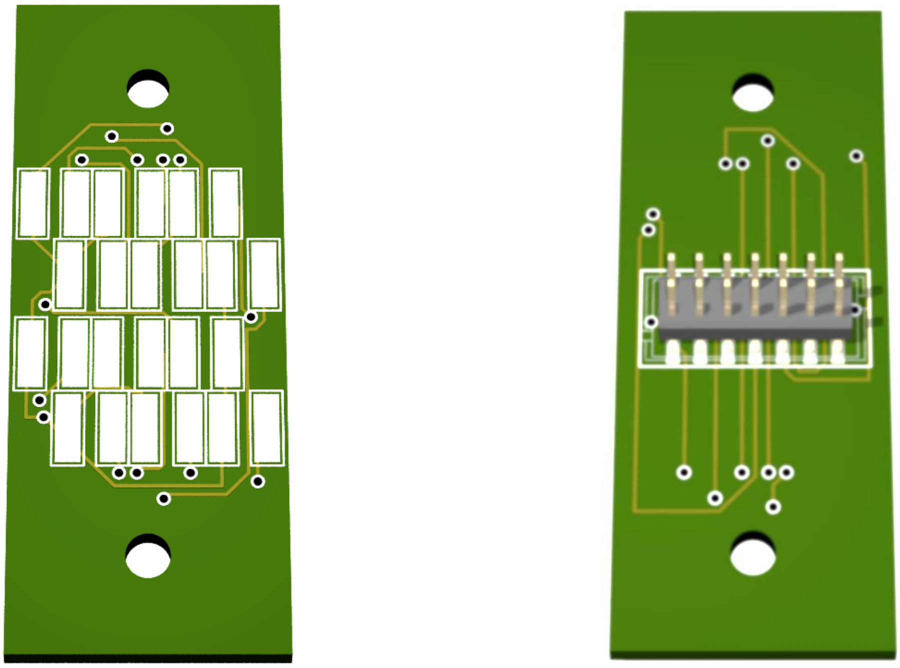

Figure 44 : Animation of upper (left) and bottom (right) side of the braille module PCB.

3.3.2 Electronics Prototyping

Figure 45, figure 46 and figure 47 show the result of the soldered circuit boards of the braille display prototype.

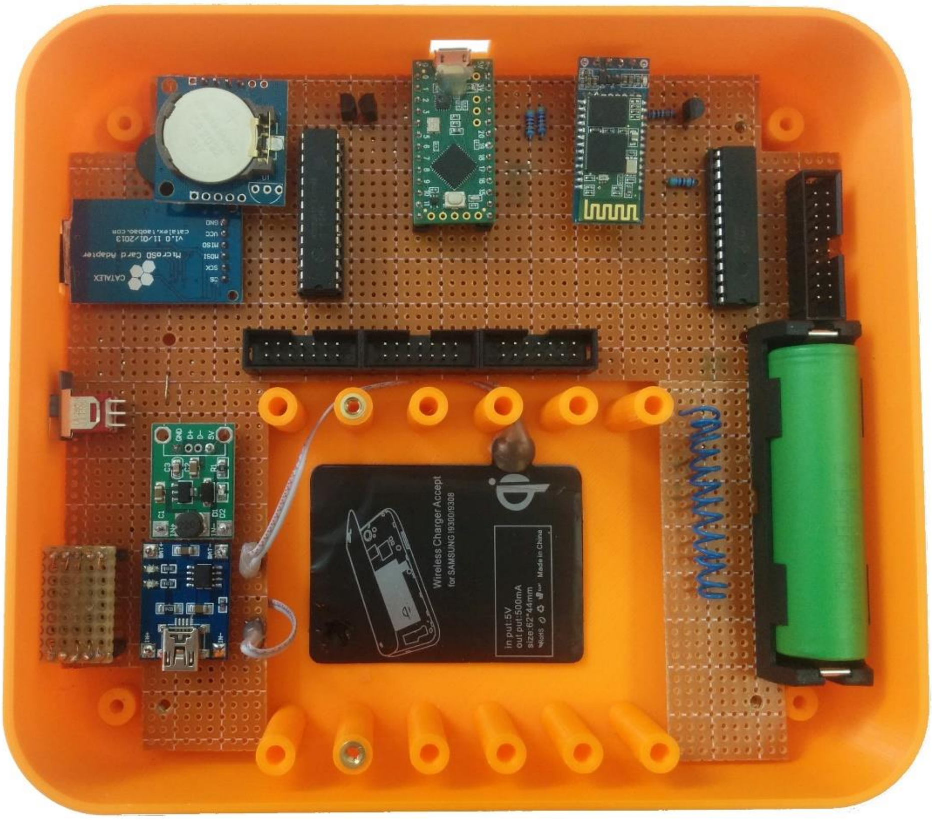

Figure 45 : Mainboard assembly of prototype in the case.

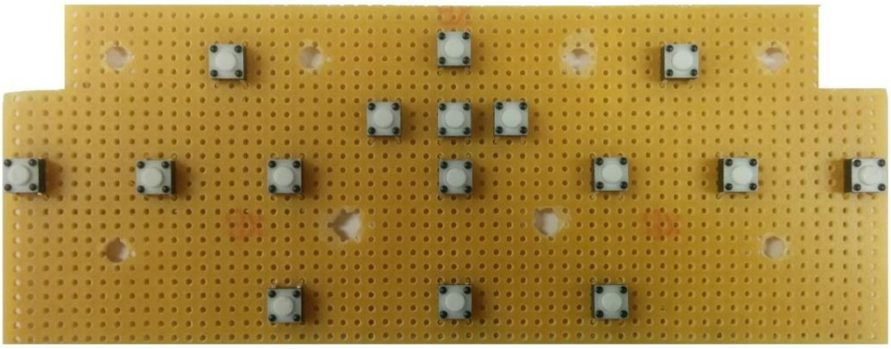

Figure 46 : Prototype of keyboard PCB.

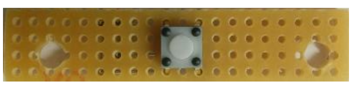

Figure 47 : Prototype of panning board PCB.

3.4 Cost Calculation

The costs for the prototype of the braille display is split up into the different required mechanical and electronic components.

3.4.1 Braille Cell Costs

The analysed braille cell technologies are evaluated in their cost. Therefore it is differentiated in piezoelectric, electro mechanic and motor based mechanism.

Cost per Braille Cell with Piezoelectric Mechanism

The costs for a braille cell with eight refreshable dots using piezoelectric mechanism are estimated at 35 USD which comes to 4.38 USD per dot. [36]

Cost per Braille Cell with Electromagnetic Braille Cell

The costs of a single dot when manufactured using this technology is calculated with 0.85€. [16]

$$Costs\ per\ Braille\ Cell = Costs\ per\ Dot\ x\ Number\ of\ Dots\ per\ Cell = 0.85\ €\ x\ 6 = 5.1\ €.$$

Cost per Braille Module Version 1

The total costs of a module are summed up in the following table.

Part	Costs [€]
3D Printed Parts	0.16
Motors	3.59
Screws and Bolts	0.30
Total Costs [€]	**4.05**

Table 9 : Total costs of material of braille module version 1.

As one braille module holds two cells, the calculated costs can be divided by two.

$$Cost\ per\ Braille\ Cell\ [€] = \frac{Cost\ per\ Braille\ Module\ [€]}{2} = \frac{4.05€}{2} \approx\ 2.03\ €$$

Cost per Braille Module Version 2

The costs of a braille module in the second version are evaluated in consideration of all required components.

Part	Costs [€]
3D Printed Parts	0.263395
Motors	3.936
Screws and Bolts	0.1965
PCB	1,228
Total Costs [€]	**5,62**

Table 10 : Total costs of material of braille module version 2.

As one braille module holds two cells, the calculated costs can be split.

$$Cost\ per\ Braille\ Cell\ [€] = \frac{Cost\ per\ Braille\ Module\ [€]}{2} = \frac{5{,}62€}{2} \approx\ 2{,}81\ €$$

3.4.2 Costs of Electronic Components

The costs for the required PCBs including electronic components, connectors and PCB manufacturing for the Prototype of the braille display are listed in table 11.

Part	Costs [€]
Mainboard	28.688
Keyboard	7.96
Panning Board	1.165
Additional Parts	31.129
Total Costs [€]	**68.942**

Table 11 : Costs of electronic components of the prototype.

3.4.3 Costs of 3D Printing

The costs for the 3D printing is evaluated by using a calculation tool for the filament in the GCode slicing application. The material used for printing is ABS which costs 24.99€ per kilogram [37]. Out of the volume of the required material and density, the costs for each individual part can be calculated accurately.

$$Price\ per\ Volume\ \left[\frac{€}{cm^3}\right] = Density\ \left[\frac{g}{cm^3}\right]\ x\ Price\ Per\ Gramm\ \left[\frac{€}{g}\right]$$

$$= 1.24\ \left[\frac{g}{cm^3}\right]\ x\ 0.02499\ \left[\frac{€}{g}\right] =\ 0.0309876\frac{€}{cm^3}$$

$$Costs\ Per\ Piece = Filament\ Volume\ Required\ [cm^3]\ x\ Price\ Per\ Volume\ \left[\frac{€}{cm^3}\right]$$

The overall material costs for the 3D printing is calculated with 7.81€. The calculations in detail can be found in the attachment section S.

3.4.4 Cost Comparison of Braille Cells

The following table 12 states the comparison of the costs of previously discussed technologies.

Cell Technology	Number of Dots	Costs Per Dot [€]	Costs Per Cell [€]
Piezoelectric Cell	8	4.375	35
Electromagnetic Cell	6	0.85	5.1
Motor Based Cell Version 1	6	0,338	2.03
Motor Based Cell Version 2	6	0.468	2.81

Table 12 : Cost comparison between the varieties of braille cell technologies.

3.4.5 Total Costs of Braille Display Prototype

The total material costs of all required components for the braille display are listed below in table 13.

Component	Costs [€]
3D Printed Components	7.81
Electronic Components	68.94
Screws and Brass Inserts	4.91
Motor Based Cell Version 2	22.48
Total Costs [€]	**104.14**

Table 13 : Total costs of braille display prototype.

3.5 Printing Time

The overall required printing time can be seen in table 14.

Part	Quantity	Estimated Printing Time Per Piece [HH:MM:SS]
Case	1	30:32:23
Braille Cell Version 2	8	01:34:18
Wireless Charging Platform	1	05:50:29
Total Estimated Printing Time [HH:MM:SS]		**48:57:16**

Table 14 : Estimated printing time of components.

3.6 Power Consumption

The power consumption of the braille display depends strongly on the usage. Therefore the consumption and battery life is calculated on the one hand for standby mode and on the other hand for continuously reading.

Standby Power Consumption

At 5V supply voltage the braille display has an average current consumption in standby of 53.1mA and a power consumption of 266mW.

$$P = U\ x\ I = 5V\ x\ 53.1mA = 0.2655\ W$$

$$P \dots Power\ [W]$$
$$U \dots Voltage\ [V]$$
$$I \dots Current\ [A]$$

The implemented battery has a capacity of 2600mAh which leads to a battery life close to 49 hours.

$$t_{standby} = \frac{C}{I} = \frac{2600\ mAh}{53.1\ mA} = 48.96\ h$$

$$t \dots Battery\ discharge\ [h]$$
$$C \dots Battery\ capacity\ [Ah]$$
$$I \dots Current\ [A]$$

Power Consumption in Use

The power consumption in use adds the energy required for the braille cells to the standby consumption. Studies evaluated a braille reading speed of 11.50 dots per second, which is equivalent to 57.08 words per second and 4.86 characters per second. This leads to an average of 2.37 dots per character.

As the prototype of the braille display houses eight cells it is assumed that on average 18.96 dots are embossed and can be read within 1.65 seconds. It takes 20 milliseconds to clear each dot which results in a total clearing time of all dots of 0.96 seconds.

Afterwards the average of 2.37 dots per character have to be embossed which takes 0.38 seconds in total. As each motor is driven individually after each other, the timing schedule of clearing all dots and embossing the required ones is followed by the average reading time. [38]

$$t_{Line} = t_{Clear} + t_{Emboss} + t_{Read} = 0.96s + 0.38s + 1.65s = 2{,}99s \approx 3s$$

During the clearing and embossing time, an average of 66.96 dots have to be driven, whereas the current consumption during clearing increases to 147.5mA and during embossing to 159mA.

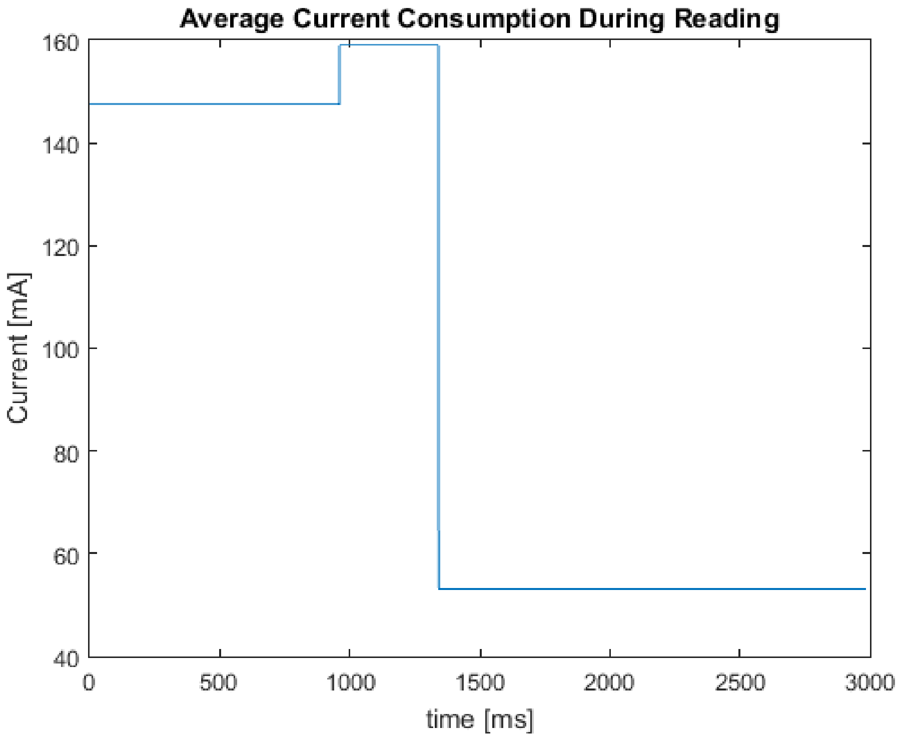

Figure 48 : Average current consumption during reading of 8 characters.

The root mean square of the current results in 108.44mA.

$$P = U\ x\ I = 5V\ x\ 108.44mA = 0.54W$$

The implemented battery has a capacity of 2600mAh which leads to a battery life of about 24 hours.

$$t_{reading} = \frac{C}{I} = \frac{2600\ mAh}{108.44mA} = 23.97h$$

Using a battery with a higher amount of capacity of 3450mAh, the battery life can be extended in standby close to 65 hours as well as to 31.8 hours at continuous usage. [24]

$$t_{standby} = \frac{C}{I} = \frac{3450\ mAh}{53.1mA} = 64.9h$$

$$t_{reading} = \frac{C}{I} = \frac{3450\ mAh}{108.44mA} = 31.82h$$

3.7 Software

3.7.1 Braille Display Firmware

The firmware developed for the braille display houses several software modules which are visualized in figure 49.

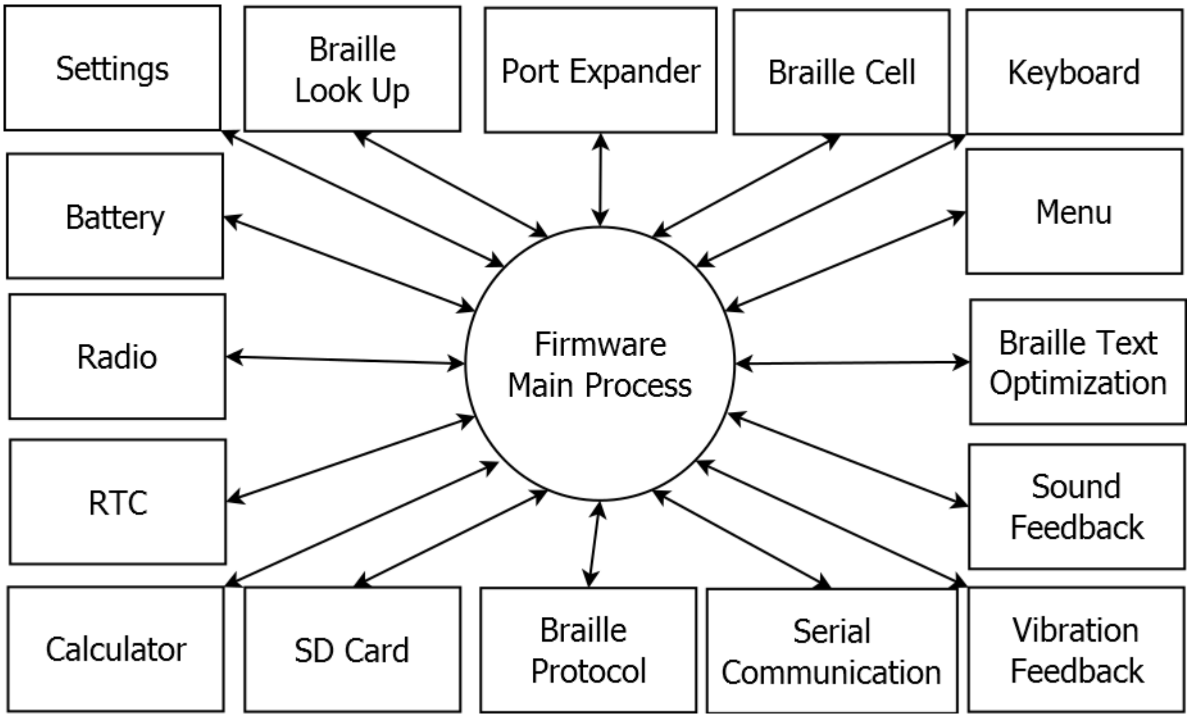

Figure 49 : Visualization of software modules for the firmware.

The main process enables the interaction of the different modules. The settings keep predefined states and adjust the behaviour as required. The menu structure lets the user select desired applications. These applications such as SD card reading, calculator, time and date as well as radio are handled in different module sections. A hardcoded braille table ensures the translation between braille and alphabetic characters, which can be additionally adapted. Software modules for the input and output expanders for addressing the braille cells as well as the keyboard are required. A communication via USB and Bluetooth is achieved through an extracted protocol interface. The haptic and audio feedback is controlled through separated sections adapted for the desired use. The overall firmware consists of 2434 lines of code.

The basic structure of the firmware developed for the braille display is shown in the diagram in figure 50.

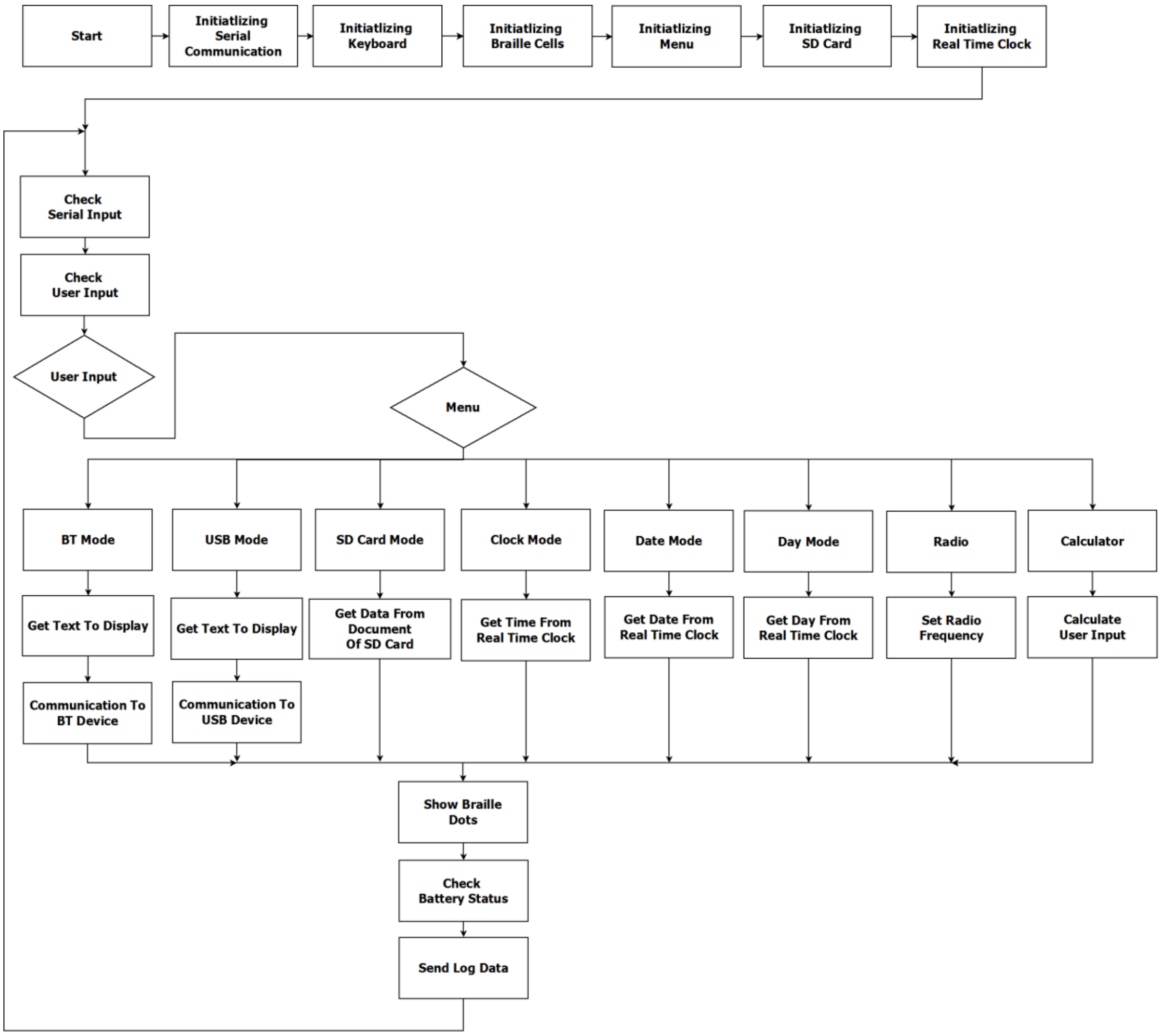

Figure 50 : Flow chart of the firmware of the braille display.

First, the braille display will initiate all required hardware components during start up. This includes the serial communication through a USB as well as a wireless Bluetooth connection. Furthermore, the keyboard and braille cells are prepared for use. This is followed by the initialisation process of the menu tree, the SD card and real time clock. After the initialisation is successfully done, the main body of the firmware is started.

In this loop the commands received either by the user through keyboard inputs or by commands via serial interface are processed. Depending on the currently activated intended use of the braille device, the text which should be displayed is gathered. These characters are prepared in a reader friendly way through pre-processing. The battery status is checked continuously in order to give a feedback to the user. All occurring events and errors are logged and sent to connected devices such as smartphones or computers for analysis.

Bluetooth Mode

By selecting this mode, the device will transfer all data in a formatted way to the desired device via Bluetooth. The connection is established by selecting the braille display in the Bluetooth settings of the smartphone, tablet or computer.

USB Mode

The braille device is able to connect to other devices via USB through a serial interface as well as a Human Interface Device (HID). This allows the braille reader to send characters and keyboard inputs directly to the desired device. Additionally all occurred events and pressed keys are transferred through a serial interface to the device in a formatted protocol.

Book Reader

The book reading application of the braille reader is capable of opening every document containing ASCII formatted characters. Books and other documents in an electronic format can be translated to the required standard through RoboBraille and other converting tools. Scrolling through the document is automatically achieved through pressing the panning bars.

Date and Time

The braille display houses a real time clock with an additional battery. Therefore the user can gather information about the current time, date and weekday by selecting the desired information in the menu.

Radio

A digital radio receiver allows visually impaired people to hear music and gather information on the news. The user can therefore plug in commonly used headphones and adapt the volume. The frequency of the radio can be changed and adapted by pressing the panning bars and is displayed in braille. Additionally eight radio stations are preconfigured and can be directly accessed by pressing the button on the corresponding keyboard.

Calculator

An additional application allows the user to calculate simple mathematical tasks. The calculator includes the four basic operators and displays the input as well as the result in a formatted way.

3.7.2 Braille Simulator

The software application developed to simulate the input and output of the braille display is visualized in the figure 51.

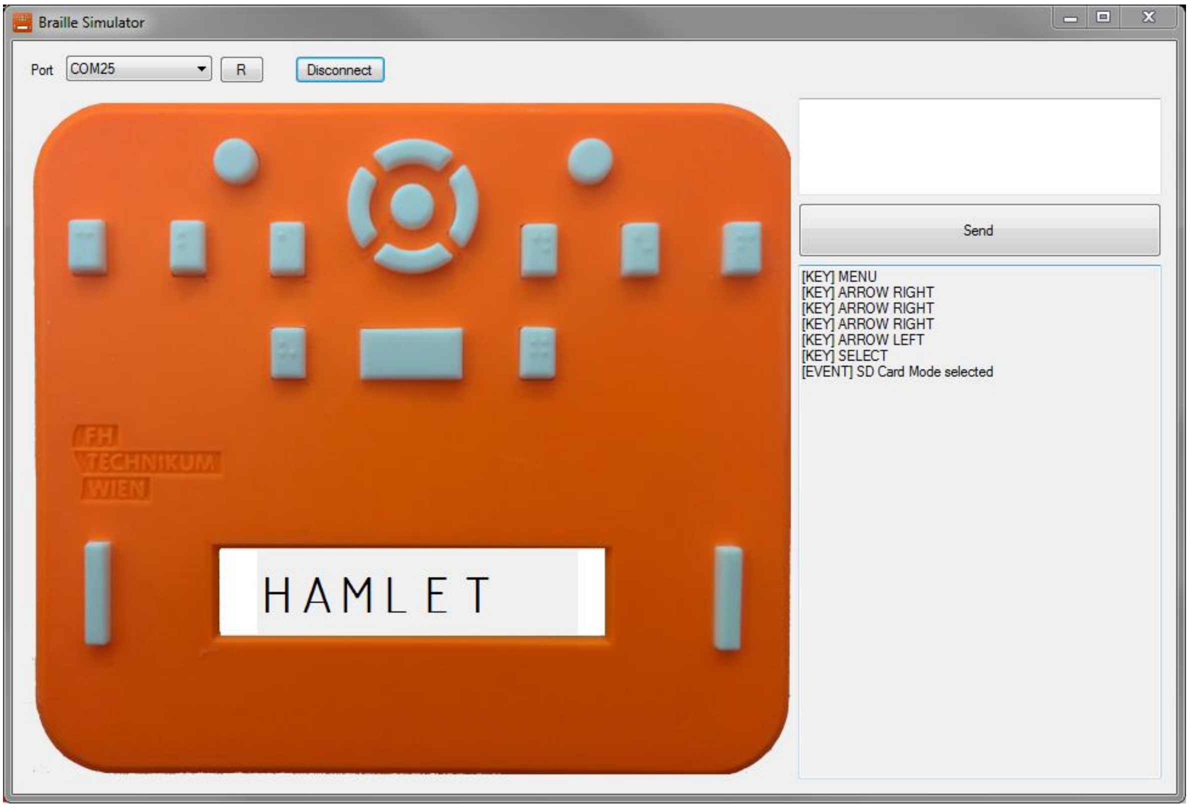

Figure 51 : Graphical user interface of Braille Display Simulator software application.

The user interface of the braille simulator is kept intuitive as the connection is fulfilled by selecting the desired serial port as well as the button to actively initiate the communication. On the right top side a textbox is used to transfer the containing text to the display.
The right bottom box displays all events that occurred on the device. Theoretically displayed text on the device in braille is simulated in visually readable characters.

3.8 Braille Display Usage

The interfaces of the braille display and reader are visualized in figure 52.

Figure 52 : Assembled braille display including numbering of implemented interfaces.

Braille Display Component	Description
1	Menu
2	Back/Delete
3	Select
4 - 7	Navigation
8	Space
9 - 10	Panning bars
11 - 18	Alphabetic keyboard
19	Power switch
20	SD card slot
21	Audio jack
22	USB connection
23	Braille display

Table 15 : Description of the components on the braille display.

The menu button activates the menu interface, which allows the user to navigate through the applications featured on the device, while the navigation is conquered by the four arrow buttons. The selection of the desired application for usage is done by using the selection button. The space button sends a space character to the selected document and software application. The writing process to such documents is done by using the eight keyboard buttons which represent the 8 dots on a braille cell. The back and delete button on the one hand navigates the user out of the menu interface and on the other hand deletes one character on the desired application in the means of the backspace key. As the text which is to be read has mostly more characters than the device can display at once, panning buttons enable the user to scroll through the text. A power switch activates on the one hand the mobile application which implements the battery and on the other hand a power supply through USB which is additionally capable of recharging the battery. The SD card slot supports memory cards with the standardized microSD card format for eBooks and other documents. In order to plug in headphones an audio jack is built in which is standardized to provide commonly used headphone types. For the application with devices using a USB connection or recharging the built in battery, a micro USB slot is available.

4 Discussion

Comparing the variety of concepts for braille cells, the aspects of this master thesis have to be considered. The focus lies on prototyping and manufacturing in a cheap and easily reproducible manner. The widely spread technology covering the piezoelectric effect has the advantage of easy access and high precision. However the dots require high voltage to be embossed. This high energy needed, leads to additional effort in designing the power supply. Furthermore the costs for the cells, even in higher amounts, is a significant disadvantage for this technology. The promising concept using electromagnetic mechanism shows a possibility to be manufactured as a prototype using available materials. The construction is relatively small in size and easy to replace due to the modular design. The costs compared to the piezoelectric mechanism is reduced, which makes this technology attractive. Additionally the number of dots can be adapted as required without significant additional effort. The number of individual parts as well as the balancing of the electromagnetic effects are less promising than the technology using micro motors. This version has the best cost efficiency among the covered technologies for braille cells. All required components can be either 3D printed or ordered. Therefore this braille cell technology fits best for the prototyping and research application.

The first version of the braille cell based on micro vibration motors has less production costs compared to the second version. However, all motors have to be soldered individually by hand, which increases the time and effort to manufacture significantly. Therefore the second version simplifies it by using a printed circuit board which has the contact pads already printed on. This can be screwed to the braille module and decreases the manufacturing time. Additionally the number of individually required components per module is minimized.

The dot size dimensions within a cell is designed according to the recommended standard referred as Marburg Medium. Due to the size of the motors, the spacing between the cells had to be increased.

As the wireless charging solution compared to a cable based one is limited in current, the charging time is increased. Nevertheless the effort for blind people to recharge the handheld device is decreased significantly, as it just has to be placed on top of it without any further actions.
As one of the purposes of this device is the handheld usage, high battery lifetime is a high priority. The low energy consumption of the components leads to a lifetime of up to 24 hours of continuous usage. The rechargeable battery is standardized in size and can be replaced easily as required. During the development phase, batteries with higher capacity were unavailable for delivery. However, for a similar price there are rechargeable batteries on the market with a capacity of 3450mAh, which increases the continuous reading capability to nearly 32 hours.

The case is designed for four braille modules, which result in a maximum of 8 characters. As the modules are easily replaceable and extendable, the braille display can be designed and manufactured in any size. For prototyping and testing reasons the number of characters is limited to eight. A major advantage of the designed case and construction is that all parts can be 3D printed as required. This includes the buttons and switches, which have printed braille labels implemented. Therefore the user can recognize the designated use of the individual buttons by tactile reading.

Braille varies significantly in different languages. This is not only limited to abbreviations but also concerning special characters and punctuations. At the current state of the development of the braille display, there is a hardcoded braille chart implemented. This chart consists out of braille in grade 1 in an adapted form of the published table from EBU. For further usage and development, the chart has to be expanded for most commonly used languages. As the braille device has an inbuilt SD card slot, a major improvement would be to store predefined and adjustable braille tables of the desired languages on it. This allows the user and distributor to set the device in a state of biggest advantage.

5 Conclusion

As the focus lies on the possibility to manufacture braille cells according to CAD drawings via rapid prototyping technologies, the micro motor based version shows great promises. Further improvements on the design have to be made in order to minimize the distance between the braille cells to comply completely with the recommended Marburg Medium dot dimensions. Software applications are implemented using either open source resources or free available products. This results in an easy extension related to additional application to be supported by the device. The communication between the braille display with computer and smartphones is achieved through a developed protocol. In order to be supported by commonly used software application on those devices, either a protocol of available products on the market has to be adapted or the developed protocol has to be implemented in the software plug-ins of smartphones and computers.

All in all the concept and implementation proves that a braille display can be manufactured and developed through prototyping techniques as well as open source software applications in order to decrease the costs significantly while keeping state of the art technologies. The predetermined requirements can be met while being additionally extendable.

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List of Figures

List of Tables

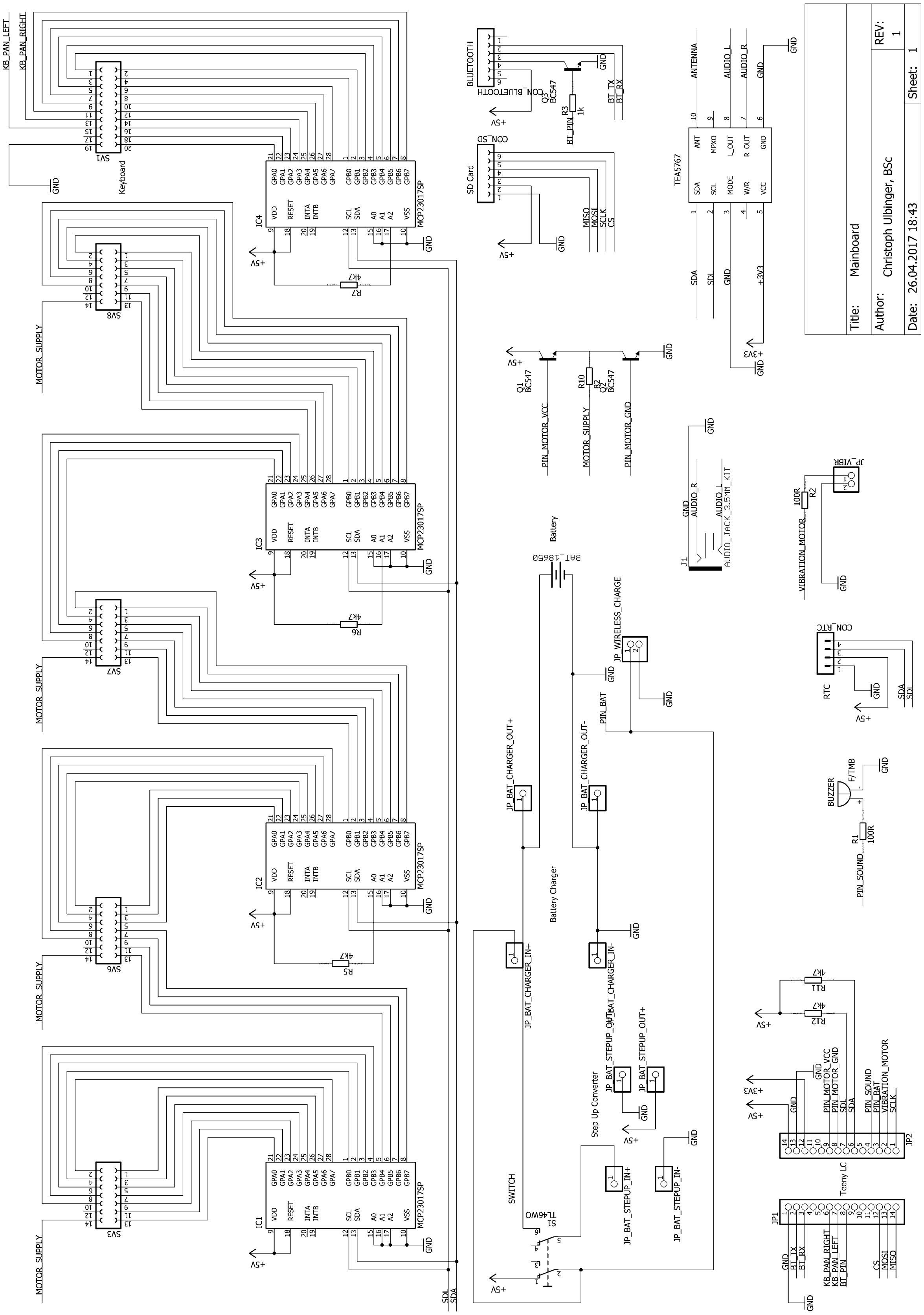
List of Abbreviations

EBU	European Blind Union
FM	Frequency Modulation
HID	Human Interface Device
MOLBED	Modular Low cost Braille Electronic Display
PCB	Printed Circuit Board
RNIB	Royal National Institute of Blind People
RTC	Real Time Clock
SD Card	Secure Digital Card
UART	Universal Asynchronous Receiver Transmitter
WHO	World Health Organization

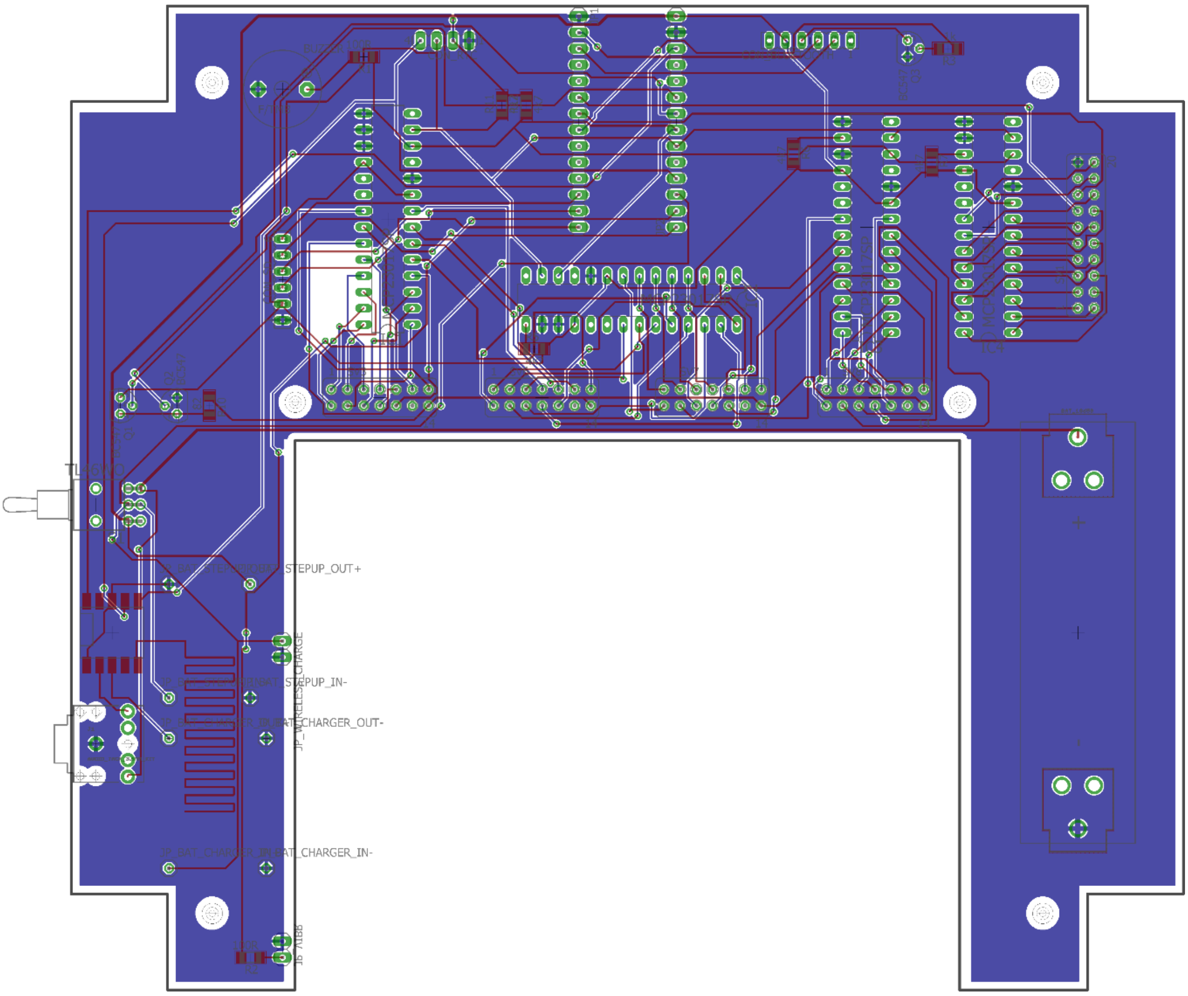
A: Adapted Braille Table

Character	Braille	Braille Dots	Character	Braille	Braille Dots
a	⠁	1	1	⠁	1
b	⠃	12	2	⠃	12
c	⠉	14	3	⠉	14
d	⠙	145	4	⠙	145
e	⠑	15	5	⠑	15
f	⠋	124	6	⠋	124
g	⠛	1245	7	⠛	1245
h	⠓	125	8	⠓	125
i	⠊	24	9	⠊	24
j	⠚	245	0	⠚	245
k	⠅	13	Space		
l	⠇	123	Capital Letter	⠠	6
m	⠍	134	Number	⠼	3456
n	⠝	1345	!	⠖	235
o	⠕	135	?	⠢	26
p	⠏	1234	(	⠶	2356
q	⠟	12345	:	⠒	25
r	⠗	1235	,	⠂	2
s	⠎	234	;	⠆	23
t	⠞	2345	+	⠬	346
u	⠥	136	-	⠤	36
v	⠧	1236	/	⠌	34
w	⠺	2456	*	⠡	16
x	⠭	1346	.	⠄	3
y	⠽	13456	“	⠦	236
z	⠵	1356			

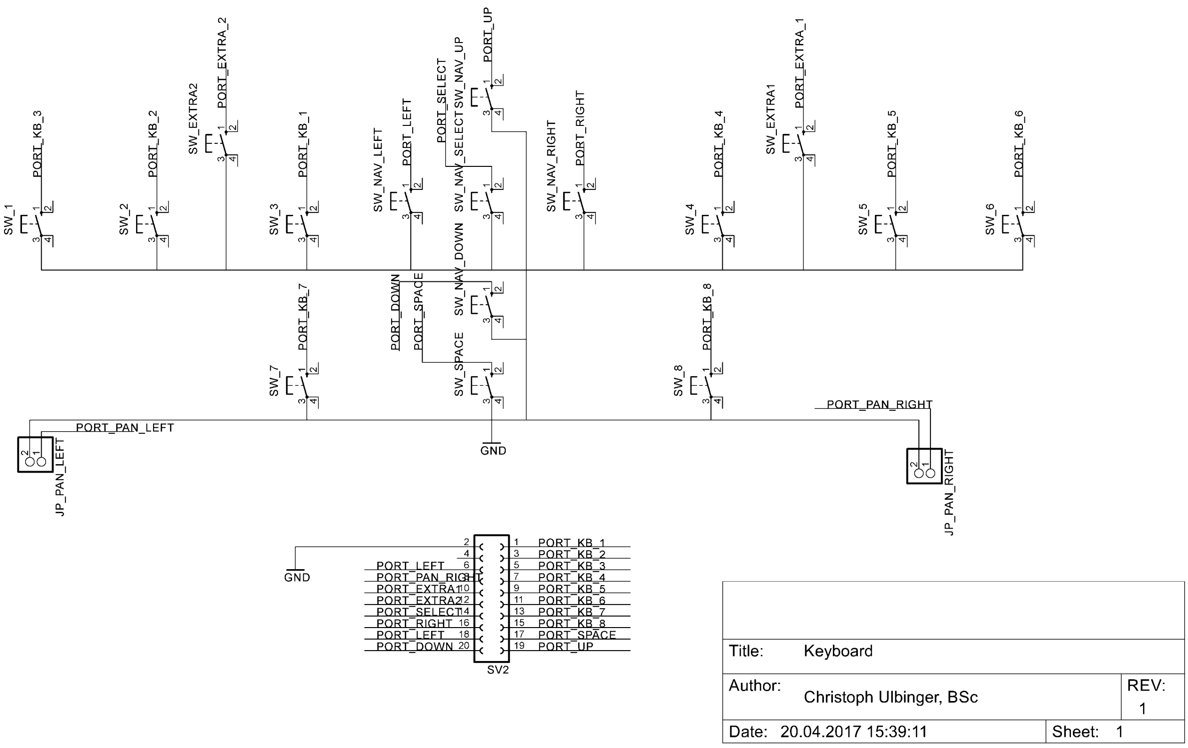
B: Mainboard Schematic



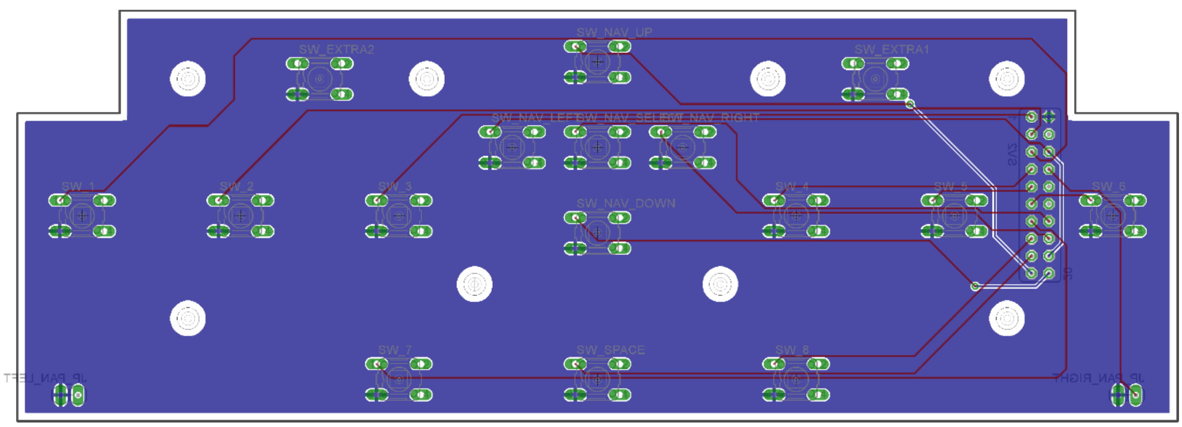
C: Mainboard PCB Layout



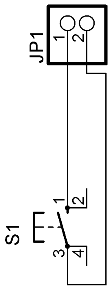
D: Keyboard Schematic



E: Keyboard PCB Layout

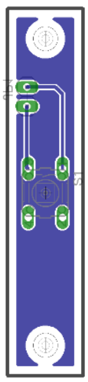


F: Panning Board Schematic

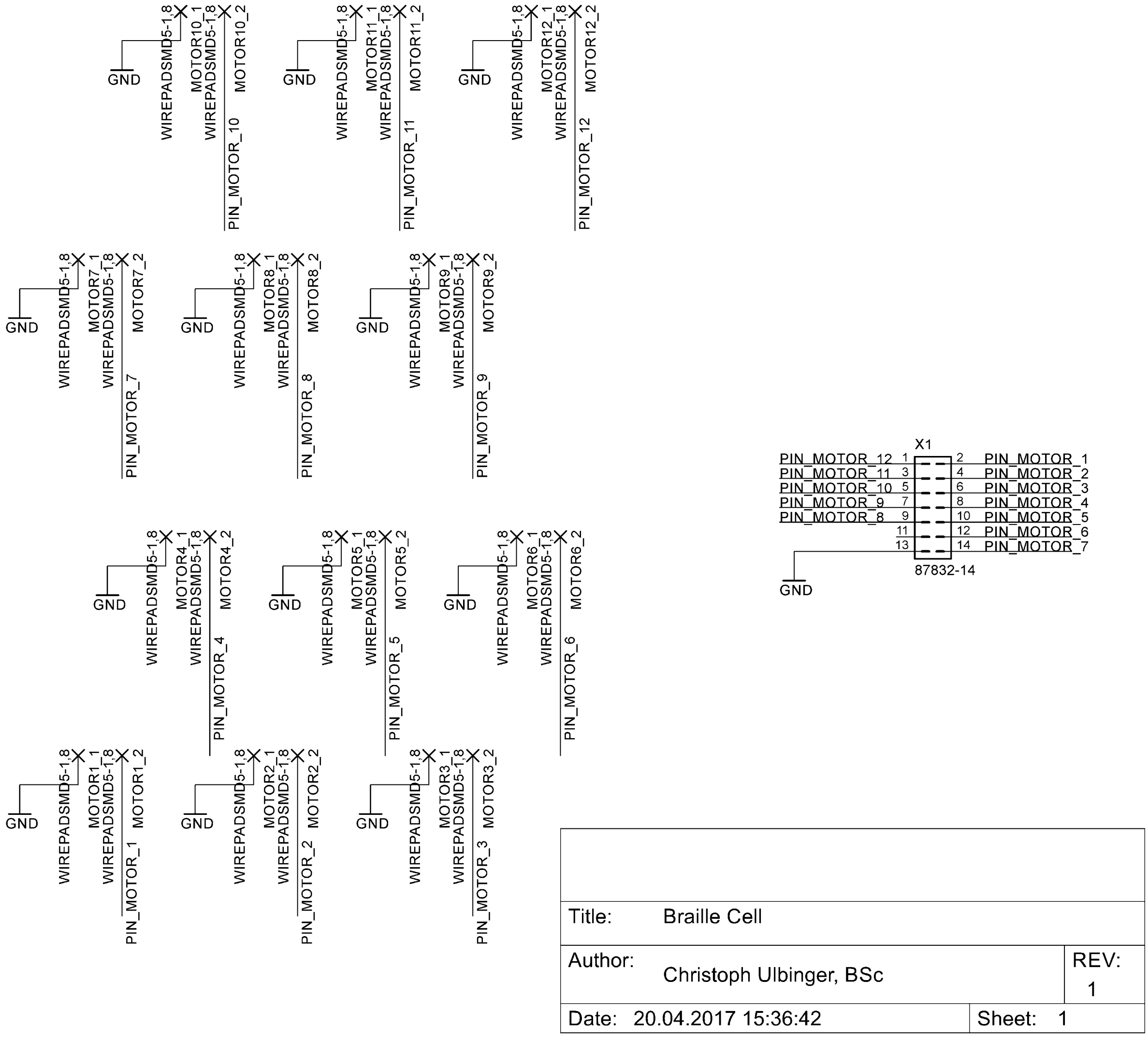


Title: Panning Board		
Author: Christoph Ulbinger, BSc		REV: 1
Date: 20.04.2017 15:38:25	Sheet: 1	

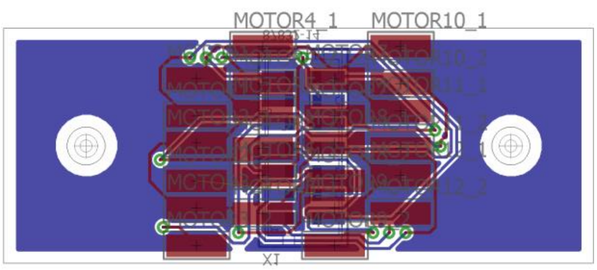
G: Panning Board PCB Layout



H: Braille Module Schematic



I: Braille Module PCB Layout



J: Mainboard Part List

Parts	Value	Package	Description	Price Per Piece [€]	Part Number	Reference
R1, R2	100Ω	R1206	RESISTOR	0.028	721-9740	1
R3	1kΩ	R1206	RESISTOR	0.004	125-1190	1
R5, R6, R7, R11, R12	4.7kΩ	R1206	RESISTOR	0.004	125-1191	1
R10	82Ω	R1206	RESISTOR	0.078	721-9737	1
BAT_18650		18650 HOLDER	Single Cell Battery Holder	4.99	651027 - 62	2
CON_BLUETOOTH, CON_SD		FE06	FEMALE HEADER	0.527	495-8565	1
SV3, SV6, SV7, SV8		FE07-2	FEMALE HEADER	0.56	832-3594	1
SV1		FE10-2	FEMALE HEADER	0.59	832-3499	1
CON_RTC		FE04-1	FEMALE HEADER	0.35	681-6814	1
JP_BAT_CHARGER_IN+, JP_BAT_CHARGER_IN-, JP_BAT_CHARGER_OUT+, JP_BAT_CHARGER_OUT-, JP_BAT_STEPUP_IN+, JP_BAT_STEPUP_IN-, JP_BAT_STEPUP_OUT+, JP_BAT_STEPUP_OUT-		1X01	PIN HEADER	0.118	828-1588	1
JP1, JP2		1X14	PIN HEADER	0.18	1498262-62	2
JP_VIBR, JP_WIRELESS_CHARGE		1X02	PIN HEADER	0.058	178-9552	1
J1	AUDIO JACK 3.5MM	AUDIO JACK	Audio Jack	0.834	913-1021	1
Q1, Q2, Q3	BC547	TO92	NPN Transistor	0.26	155012 - 62	2
BUZZER	F/TMB	F/TMB	Buzzer	0.47	303-0161	1
IC1, IC2, IC3, IC4	MCP23017SP	DIL28-3	Port Expander	1.118	403-806	1
S1	TL46WO	TL4XWO	SWITCH ON - ON	1.33	734-7258	1
PCB Manufacturing	154x174mm			10		3

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K: Keyboard Part List

Parts	Value	Package	Description	Price Per Piece[€]	Part Number	Reference
SW_1, SW_2, SW_3, SW_4, SW_5, SW_6, SW_7, SW_8, SW_EXTRA1, SW_EXTRA2, SW_NAV_DOWN, SW_NAV_LEFT, SW_NAV_RIGHT, SW_NAV_SELECT, SW_NAV_UP, SW_SPACE		B3F-10XX	OMRON SWITCH	0.107	758-1925	[4]
SV2		FE10-2	FEMALE HEADER	0.59	832-3499	[4]
JP_PAN_LEFT, JP_PAN_RIGHT		1X02	PIN HEADER	0.058	178-9552	[4]
PCB Manufacturing	174x60mm			5.6		[5]

L: Panning Board Part List

Parts	Value	Package	Description	Price Per Piece[€]	Part Number	References
S1		B3F-10XX	OMRON SWITCH	0.107	758-1925	[4]
JP1		1X02	PIN HEADER	0.058	178-9552	[4]
PCB Manufacturing	10x48.5mm			1		[5]

M: Braille Module Board Part List

Parts	Value	Package	Description	Price Per Piece[€]	Part Number	References
X1	87832-14	87832-14	Milli-Grid Header	0.728	670-6574	[4]
PCB Manufacturing	50x20mm			0.5		[5]

[4] RS Components Handelsges.m.b.H., 3950 Gmünd Albrechtser Straße 11, Austria. [Online]. Available: http://at.rs-online.com/web/. [Accessed: 24-Apr-2017].

[5] HK Weiku information & Technology Co. Ltd. Hangzhou Weiku information & Technology Co. Ltd, "PCB Manufacturing" 12th Floor,West No.2 Building, XinTianDi Business Center, No.71-8 ShiXiang Road,XiaCheng District,Hangzhou, China. [Online]. Available: https://www.pcbway.com/orderonline.aspx. [Accessed: 27-Apr-2017].

N: Additional Part List

Parts	Quantity	Value	Package	Description	Price Per Piece[€]	Part Number	References
Battery	1	2600mAh	18650	Li-Ion Battery	10.99	1499572-62	[6]
IDC Connector	2		FE10-2	IDC Female	0.64	832-3623	[7]
IDC Connector	8		FE07-2	IDC Female	0.63	832-3512	[7]
Flat Ribbon Cable	1	28 AWG	20 Way	1 Meter Cable	2.09	609968 - 62	[6]
IDC Connector	6		2 Way	IDC Female	0.136	543-7700	[7]
Vibration Motor	1		4x8mm	Vibration Motor	0.299	381851088495	[8]

O: Part List of Screws and Brass Inserts

Piece	Quantity	Cost per Piece	Costs [€]	Part Number	Reference
M3x14mm DIN 965 Screw	4	0.01995	0.0798	134493 - 62	[6]
M3x4mm DIN 963 Screw	16	0.01595	0.2552	134155 - 62	[6]
M3x4mm DIN 7985 Screw	2	0.02845	0.0569	145899 - 62	[6]
M3 Brass Insert	34	0.133	4.522	278-534	[7]

[6] Conrad Electronic GmbH & Co KG, Durisolstraße 2 4600 Wels, Austria. [Online]. Available: https://www.conrad.at. [Accessed: 24-Apr-2017].

[7] RS Components Handelsges.m.b.H., 3950 Gmünd Albrechtser Straße 11, Austria. [Online]. Available: http://at.rs-online.com/web/. [Accessed: 24-Apr-2017].

[8] eBay Inc., "eBay Headquarters," *2025 Hamilton Avenue, San Jose, California 95125, USA*. [Online]. Available: http://www.ebay.at. [Accessed: 12-May-2017].

P: Additional Part List of Modules

Parts	Quantity	Description	Price Per Piece[€]	Part Number	References
Real Time Clock	1	I2C RTC DS1307 AT24C32 Real Time Clock Module	1	381692768706	[9]
SD Card Module	1	Micro SD Storage Board SD TF Card Memory Shield Module	1	172395517775	[9]
Bluetooth Module	1	Wireless Bluetooth RF Transceiver Module Serial RS232 HC-05	2.96	132092156280	[9]
Step Up Converter	1	Step Up Wandler Boost Modul DC-DC Stepup	1	272420372127	[9]
Battery Charging Module	1	5V Mini USB 1A Lithium Li-ion Battery Charger Module	1	191981163834	[9]
Wireless Charging Receiving Pad	1	Wireless Charging Receiving Pad	1.73	201793089180	[9]
Wireless Charging	1	Wireless Charger	1	331933255565	[9]
FM Radio Module	1	TEA5767 Philips Programmable Low-power FM Stereo Radio Module	1	272503792705	[9]

[9] eBay Inc., “eBay Headquarters,” *2025 Hamilton Avenue, San Jose, California 95125, USA*. [Online]. Available: http://www.ebay.at. [Accessed: 12-May-2017].

Q: Costs for Braille Cell Version 1

Costs for 3D Printing

Piece	Quantity	Filament Length [mm]	Filament Volume [cm³]	Cost per Piece [€]	Costs [€]
Top Plate	1	987.1	2.4	0.0743702	0.07437
Motor Holder	2	416.5	1	0.0309876	0.061975
Lever	2	26.9	0.1	0.0030988	0.006198
Pins	2	129.9	0.3	0.0092963	0.018593
				Total Costs [€]	**0.161136**

Costs of Motors

Piece	Quantity	Cost per Piece [€]	Costs [€]	Part Number	Reference
Vibration Motor 8x4mm	12	0.299	3.588	381851088495	[10]

Costs of Screws and Bolts

Piece	Quantity	Cost per Piece	Costs [€]
M3x14mm DIN 965 Screw	2	0.01995	0.0399
M2x10mm DIN 963 Screw	4	0.0349	0.1396
M2 Bolt	4	0.0299	0.1196
		Total Costs [€]	**0.2991**

[10] eBay Inc., “eBay Headquarters,” *2025 Hamilton Avenue, San Jose, California 95125, USA*. [Online]. Available: http://www.ebay.at. [Accessed: 12-May-2017].

R: Costs for Braille Cell Version 2

Costs for 3D Printing

Piece	Quantity	Filament Length [mm]	Filament Volume [cm³]	Cost per Piece [€]	Costs [€]
Top Plate	1	1231.6	3	0.0929628	0.092963
Motor Holder	1	1743.2	4.2	0.1301479	0.130148
Lever	1	96.8	0.2	0.0061975	0.006198
Pins	1	458.5	1.1	0.0340864	0.034086
				Total Costs [€]	**0.263395**

Costs of Motors

Piece	Quantity	Cost per Piece [€]	Costs [€]	Part Number	Reference
Vibration Motor 12x5x5mm	12	0.328	3.936	182525942181	[11]

Costs of Screws and Bolts

Piece	Quantity	Cost per Piece [€]	Costs [€]
M3x4mm DIN 7985 Screw	2	0.02845	0.0569
M2x10mm DIN 963 Screw	2	0.0349	0.0698
M3x14mm DIN 965 Screw	2	0.01995	0.0399
M2 Bolt	1	0.0299	0.0299
		Total Costs [€]	**0.1965**

PCB Costs

Piece	Quantity	Cost per Piece [€]	Costs [€]
50x20mm PCB	1	0.5	0.5
Pin Header DIN 41651	1	0.728	0.728
		Total Costs [€]	**1,228**

[11] eBay Inc., “eBay Headquarters,” *2025 Hamilton Avenue, San Jose, California 95125, USA*. [Online]. Available: http://www.ebay.at. [Accessed: 12-May-2017].

S: Printing Costs

Piece	Quantity	Filament Length [mm]	Filament Volume [cm^3]	Cost per Piece [€]	Total Costs [€]
Bottom Case	1	47039.4	113.1	3.50470	3.5046976
Top Case	1	26936.8	64.8	2.00800	2.0079965
Wireless Charging Platform	1	16671.5	40.1	1.2426028	1.2426028
Top Plate	4	1231.6	3	0.0929628	0.3718512
Motor Holder	4	1743.2	4.2	0.1301479	0.5205916
Lever	4	96.8	0.2	0.0061975	0.02479
Pins	4	458.5	1.1	0.0340864	0.1363456
Key Button	8	216.3	0.5	0.0154938	0.1239504
Space Button	1	575.3	1.4	0.04338	0.0433826
Navigation Button	4	205.2	0.5	0.01549	0.0619752
Panning Button	2	308.4	0.7	0.0216913	0.0433826
Round Button	3	173.4	0.4	0.01240	0.0371851
Inner Switch Component	1	76.3	0.2	0.00620	0.0061975
Outer Switch Component	1	151.1	0.4	0.012395	0.012395
				Total Costs [€]	**7.8088753**

T: Estimated Printing Time

Braille Cell Version 1

Part	Quantity	Estimated Printing Time Per Piece [HH:MM:SS]
Top Plate	1	00:26:12
Pins	2	00:05:06
Lever	2	00:01:01
Motor Holder	2	00:16:18

Braille Cell Version 2

Part	Quantity	Estimated Printing Time Per Piece [HH:MM:SS]
Top Plate	1	00:29:46
Pins	1	00:14:26
Lever	1	00:02:53
Motor Holder	1	00:47:13

Case

Part	Quantity	Estimated Printing Time Per Piece [HH:MM:SS]
Top Case	1	09:40:02
Bottom Case	1	17:45:02
Switch Inner Component	1	00:03:30
Switch Outer Component	1	00:05:27
Key Button	8	00:09:20
Space Button	1	00:18:09
Navigation Button	4	00:09:11
Panning Button	2	00:13:02
Round Button	3	00:07:35

Wireless Charging Platform

Part	Quantity	Estimated Printing Time Per Piece [HH:MM:SS]
Wireless Charging Platform	1	05:50:29