Badge Maker

Developing an Easy-to-use System to Design and Build Illuminated Acrylic Name Tags for Children

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List of Acronyms

API Application Programming Interface

CAD computer-aided design

CAM computer-aided manufacturing

CD Compact Disc

CNC Computer Numeric Control

CO2 Carbon Dioxide

DC Direct Current

DIA Design Implement Analyze

DIY Do-It-Yourself

DOM Document Object Model

DXF Drawing Interchange File Format

LASER Light Amplification by Stimulated Emission of Radiation

LED light-emitting diode

fabber digital fabricator

fab lab fabrication laboratory

GNU General Public License

GUI graphical user interface

HCI Human-computer interaction

IDE Integrated Development Environment

JRE Java Runtime Environment

MDF Medium-Density Fibreboard

MIT Massachusetts Institute of Technology

MOSFET Metal-Oxide-Semiconductor Field-Effect Transistor

PC personal computer

PCB Printed Circuit Board

RPM Revolutions per Minute

PWM Pulse-Width Modulation

STEM Science, Technology, Engineering and Mathematics

SVG Scalable Vector Graphics

UI user interface

USB Universal Serial Bus

W3C World Wide Web Consortium

XML Extensible Markup Language

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Abstract

So far, most fabrication machines have been developed for industrial applications with user interfaces mainly designed for experts. Since personal fabrication is becoming more popular and ordinary people are getting into touch with the fabrication technology, a new user group has emerged coming along with new requirements for better suited user interfaces. Working with these devices, however, requires a basic understanding of the underlying technology. One approach of providing people with knowledge about the involved technologies is an early integration of them into the educational process. By engaging children within practical manufacturing applications people can gather first experiences at an early stage of their lives.

This work proposes an easy-to-use stand-alone computer numeric control (CNC) milling machine to design and build illuminated acrylic name tags for children. The thesis covers the user-oriented development process of the device, including the mechanical and electro technical realization of a linear motion and milling system, the implementation of a suited user interface and the integration of both on hardware as well as on software side. To evaluate the final prototype an informal user study was conducted by observing children who were operating the device during a kids workshop. The observations unveil that the developed device offers an intuitive user interface which can be operated by children on their own. As the apparatus aroused great interest by involving the children in the whole manufacturing process, the proposed device shows to be a successful approach of enabling novice users to gather early experiences with the fabrication technology in a safe and self-directed way.

Überblick

Zuvor wurden Fabrikationsmaschinen hauptsächlich für industrielle Zwecke mit Benutzerschnittstellen für Experten angefertigt. Seit dem jedoch der Trend der 'selbst gestalteten Fabrikation' (Personal Fabrication) auflebt, hat sich die Gruppe der Anwender verändert und auch unerfahrene Benutzer haben vermehrt mit den verschiedenen Fabrikationstechnologien zu tun. Für diese neue Anwendergruppe können neue, geeignetere Benutzerschnittstellen geschaffen werden, die ihren Anforderungen entsprechen. Auf der anderen Seite müssen Anwender jedoch auch ein gewisses Grundwissen über diese Technologien verfügen um mit ihnen umgehen zu können. Ein Ansatz um Menschen über die verschiedenen Fabrikationstechniken und deren Nutzen aufzuklären, ist die frühzeitige Integration in ihre Bildung. Kinder könnten bereits in ihrer Schulzeit in praktische Anwendungen mit den Fabrikationstechniken einbezogen werden und so erste Erfahrungen sammeln.

Diese Arbeit knüpft an diesem Punkt an und stellt eine eigenständige, einfach zu bedinende CNC Fräsmaschine vor, mit deren Hilfe beleuchtete Namensschilder aus Acrylglas von Kindern, für Kinder hergestellt werden können. Die Arbeit zeigt die Benutzerorientierte Entwicklung der vorgestellten Maschine und beinhaltet die mechanische und elektrotechnische Realisierung eines Grundgerüsts für die Fräsmaschine, das implementieren einer geeigneten Benutzerschnittstelle und die Eingliederung von beidem auf Hardware- als auch auf Softwareebene. Eine finale Evaluierung des entwickelten Systems beinhaltet eine informale Benutzerstudie, die auf dem Beobachten von Kindern, die das Gerät innerhalb eines Kinder-Workshops bedienten, beruht. Die Beobachtungen zeigen, dass das entwickelte Gerät über eine benutzerfreundliche Benutzerschnittstelle verfügt, die von Kindern eigenständig bedient werden kann. Das entwickelte Gerät weckte großes Interesse bei den Kindern und erwies sich als erfolgreicher Versuch unerfahrenen Benutzern die Möglichkeit zu bieten, frühe Erfahrung mit den Fabrikationstechnologien auf eine sichere und eigenständige Weise zu sammeln.

Acknowledgements

First of all, I would like to thank Prof. Dr. Jan Borchers for providing me the opportunity to write this bachelor thesis at the chair of the Media Computing Group and giving me access to the expensive equipment of the Fab Lab Aachen. Second, I would like to especially thank my supervisor Dipl.-Ing. Jan Thar for supporting me throughout this thesis. He did always respond immediately to any requests and taught me how to work with the different fabrication machines. I would also like to thank Dr. Nadine Bergner from InfoSphere, who enabled us to test the developed device within one of her kids workshops.

Furthermore, I would like to thank all members of the chair, in particular these, who were occasionally present in the Fab Lab and provided me with feedback during the development process. Finally, I want to say thanks to my friends and my family who offered me a comfortable environment during the time of writing this thesis.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

Definitions of technical terms or short excursus are set off in coloured boxes.

EXCURSUS:
Excursus are detailed discussions of a particular point in a book, usually in an appendix, or digressions in a written text.

Definition: *Excursus*

Source code and implementation symbols are written in typewriter-style text.

`myClass`

The whole thesis is written in American English.

Download links are set off in coloured boxes.

File: myFile[a]

[a] https://github.com/username/projectname/filenumber.file

Chapter 1

Introduction

"The transition from atoms (analog media) to bits (digital media) is the first half of a digital revolution. The second half involves the round trip back from bits to atoms to enable the creation of tangible materials based on digital designs."

—Glen Bull and Joe Garofalo, 2009

The advancement of the manufacturing technology during the industrial revolution has led to an era of mass production which endures until today. Nowadays, particularly computer-controlled factory machines – like laser cutters, die cutters, milling machines and others – produce a vast number of products of the same type. These products are designed and manufactured in order to satisfy the needs of the majority of customers in global markets. As a drawback, not all types of products can be produced this way being equally affordable and customized at the same time.

But since the digitalization, people are more connected with each other than ever before. Manufacturing and fabrication skills can be exchanged more easily. Online maker communities and internet platforms contribute to the process of sharing these information in form of Do-It-Yourself (DIY) instructions or free electronic blueprints. Moreover, the increasing trend of making open-source software available for everyone and high precision fabrication tools getting affordable for non-industrial institutions pave the way to personal fabrication.

1.1 Personal Fabrication

Personal fabrication can be seen as countermovement to the industrial massproduction. Digital fabricators (fabbers) allow people to realize their own, new ideas and enable them to fabricate customized products. Currently, 3D printing is said to be introducing a new industrial revolution (Barnatt [2013]). DIY desktop 3D printers are being available for less than 500 dollars providing individuals access to the new technology at their homes. They can be used to build almost any kind of structure from digital data and thus allow building quick prototypes, printing spare parts for broken devices or creating certain customized products on demand. Lipson and Kurman [2010] promise fabbers like 3D printers, laser cutters and milling machines soon to be part of every household bringing personal fabrication to our everyday life.

However, these affordable low cost devices are still very limited in their capability regarding power, size, precision and quality. Projects going beyond the desktop fabrication require different types of working tools which have to be more powerful and thus are too expensive for being purchased by single individuals. An opportunity to overcome this problem are institutions like open workshops which provide these kind of devices and working tools for free.

1.1.1 Fab Labs

Fabrication laboratories (fab labs) are open workshops which are accessible for everyone and enable individuals to work with more advanced machines being closer to industrially utilized ones. The first fab lab was initiated by Neil Gershenfeld at the Massachusetts Institute of Technology (MIT) in 2002. Since then, the idea of fab lab's has been spread all over the world. Usually every fab lab provides a common set of tools which can be found in any fab lab. Fabrication devices like laser cutters, 3D printers, CNC milling machines and printed circuit board (PCB) machines should allow users to "make almost anything" they want (Gershenfeld [2012]). Professionals as well as amateurs can make use of these workshops for personal fabrication and realizing their own projects. Several fab labs also offer educational workshops[1] and guidances for visitors to make people familiar with personal fabrication along with the provided manufacturing machines.

1.2 Fabrication in Education

As the trend of personal fabrication is becoming more popular and digital devices are becoming an integral part of our everyday life, an early education of fabrication technology and its practical usefulness appears to be more important than before. Today, children grow up with devices like smart-phones, tablets and personal computers (PCs). Most preschool children already have access to these devices and develop skills in using them at the early stage of their lives (Zevenbergen and Logan [2008]). Teaching the proper usage of these devices, as well as explaining how to exploit them for certain fields of applications can be beneficial to the education of younger generations of children. Maltese and Tai [2011] showed that early experiences in science, technology, engineering and mathematics (STEM) education have a significant impact on the future career of a child. Bull et al. [2014] argue that with the help of personal fabrication pupils and students could apply theoretical engineering concepts in reality and observe physical representations which give a better understanding of the underlying STEM concepts. In 2009, Bull and Garofalo already presented their approach of using a computer-controlled fabrication system to *"provide sets of physical manipulatives to teachers to faciliate math and science exploration"* (Bull and Garofalo [2009]).

[1] http://www.fablabeducation.org

1.3 Motivation

The Fab Lab Aachen periodically offers guided tours whereby visitors can explore the workshop and its provided fabrication technologies. Interested people, hobbyists, designers and engineers, but also school children belong to the typical group of attendees. While they are given an introduction to the different fabrication machines they also can observe the machines in action.

1.3.1 Illuminated Acrylic Name Tags

At the end of a tour each visitor is usually offered to make an individual illuminated acrylic name tag by using the laser cutter. The name tags (figure 1.1) enjoy rich popularity especially with the younger visitors. On one hand, they serve as personal souvenirs having the owners name and a custom illustration engraved on them. On the other hand, they are good-looking and also contain technological elements as they consist of acrylic glass and a small electronic circuit which is connecting the batteries with the light-emitting diodes (LEDs). By creating their own name tags using the laser cutter they gather first experiences with the fabrication technology due to a practical application.

1.3.2 Status Quo

By now, the manufacturing process of the name tags requires each person to select a graphic out of a predefined set of graphics. Then they have to provide their name which should also be engraved on the name tag. The names and graphics have to be modified and positioned correctly using an image-processing application. Using a computer-aided manufacturing (CAM) software the prepared vector graphic files are then sent to the laser cutter. After triggering the execution of the job by walking to the laser cutter and hitting the start button, the visitors can finally observe the machine during the cutting process. When the job execution has finished, the name tags can be removed from

Figure 1.1: Three examples of illuminated acrylic name tags which were created using the laser cutter.

the machine and the electrical circuit may be assembled on them.

The major amount of time during the manufacturing process is spent on the preparation of the name tags which does not involve the visitors directly. As the procedure requires prior knowledge in order to perform all necessary steps for preparing the job and executing it using different applications along with their individual user interfaces, it is difficult to engage every visitor in the whole manufacturing process. To provide the attendees and especially the children a more interesting experience, the manufacturing process should preferably involve a user during the entire fabrication procedure.

1.3.3 Objective

It is intended to develop a fabrication machine which allows to design and build the illuminated acrylic name tags in an easier way. The device should improve the prior manufacturing process by involving novice users from the very beginning and providing an user interface which allows them to perform all necessary steps on their own. This way the visitors from the Fab Lab Aachen and upcoming exhibitions should gather first experiences in a practical application. Especially children should be given the opportunity to get involved with the fabrication technology at an early stage of their life.

1.4 Thesis Overview

The thesis is split into four chapters and organized as follows: At first, some prior work about education in context of personal fabrication is introduced in chapter 2 — "Related work" (p. 7). Multiple design approaches of CNC machines are being discussed and several development tools are being presented. Chapter 3 — "Own work" (p. 25) starts by performing a short requirements analysis followed by the description of the development process and the implemented functionalities. This chapter constitutes the core of the thesis and is mainly split into a hardware and a software part. In chapter 4 — "Evaluation" (p. 71) the final prototype of the developed system is evaluated by conducting an informal user study with children and verifying the initially defined requirements from the previous chapter. Finally, the work is concluded by summarizing the most important aspects and results as well as discussing potential starting points for future work (5 — "Summary and Future Work" (p. 81)).

Chapter 2

Related work

This chapter is mainly divided into three different sections. While the first section (2.1) presents some related work which considers fabrication technology in context of educational applications, other approaches regarding different CNC machine constructions are discussed in section 2.2. Thereby, especially the mechanical designs along with their individual advantages and disadvantages will be emphasized. The third section (2.3) introduces several hardware and software solutions which are commonly used in the development process of the CNC machine and manufacturing applications.

2.1 Fabrication and Education

As the trend of personal fabrication has primarily been developed during the past decade, early educational applications were only being rarely studied so far. Nevertheless, there is some related work which lets assume that the integration of the fabrication technology into the educational process may be beneficial for the younger generations of children and could have a significant impact to their future career (Maltese and Tai [2011]).

2.1.1 Learning with CNC Routers

Aktan et al. [2016] developed a CNC router for educational purposes. Therefore, they designed a small dimensioned linear motion system with a mounted drilling tool and a simple graphical user interface (GUI) application which allows students to control the system using raw g-code (see 2.3.3). The authors state that students should be able to test theoretical concepts using the apparatus and get a better understanding of these by using the device for practical applications (figure 2.1). A final study showed that participants which were using the CNC router for practicing did perform 27.36 percent better regarding their grades than the ones, who were not using the machine. The mechanical design is also presented in section 2.2.1.

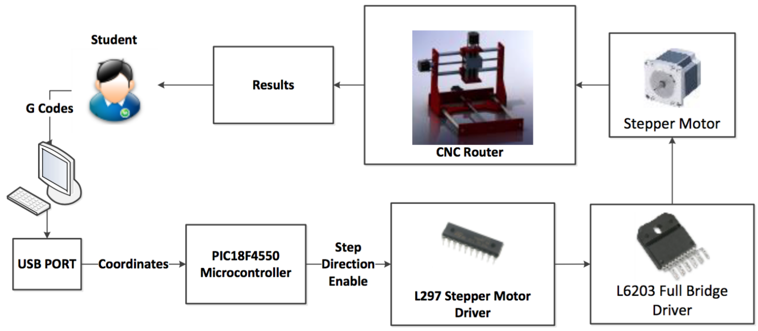

Figure 2.1: Educational interaction cycle with a CNC router by Aktan et al. [2016].

2.1.2 Study on Children Workshops

Posch and Fitzpatrick [2012] conducted a study on children workshops in a fab lab. They gave five groups of children the chance to explore their fab lab in two-day long workshops. During these two days the children were given an introduction to different design and fabrication methods using the devices provided by the fab lab: First programming skills were taught, motifs were cut out using a vinyl cutter and printed on t-shirts, 3D models were created with the help of a 3D printer and the participants came into touch with a simple assembly of an electronic circuit. While the children gave an overall positive feedback about the workshop, Posch and Fitzpatrick observed that the children especially preferred the fabrication tasks where the outcome had met their prior expectations at most. Furthermore, it is mentioned that the children had notably problems designing 3D models on the computer using the provided modeling software. Referring to this problem the authors claim that "more intuitive interfaces offering direct integration with digital fabrication technologies" are needed. In addition, they suggest more investigations on how children may be enabled to safely explore digital fabrication technologies on their own in a fab lab.

2.2 CNC Machines

CNC machines are commonly used to process different types of structures and materials. They usually offer a computer controlled linear motion system with a working tool attached to one axis. This way the workpiece can be processed in a predefined and very precise way. Especially two types of CNC machines are presented below: milling machines and laser cutters. The approaches show different designs and implementations of these types of machines, unveiling their individual strength and weaknesses.

2.2.1 Milling Machines and Routers

Milling machines and routers use a rotary drilling tool to engrave or cut a certain kind of material. Hereby, an electronic motor provides the rotational movement for the drilling tool and the workpiece is processed directly on top of its surface. As this technique is simple and the application of milling machines is widespread, there is a large range of different sized mills available, whereby small dimensioned ones can be obtained at low cost. Disadvantages of these types of machines are that they produce wastage of the removed material and tend to leave traces at lower speed of rotation. Furthermore, inner sharp edges or thin details cause problems because the attached tools diameter always limits the degree of precision. As the drilling tool has to be moved towards and from the workpiece, at least one axis is required to perform these movements.

CNC Router for Manufacturing Courses

Figure 2.2: Control and power supply box (left). CNC router structure (right).

Aktan et al. [2016] designed a small-sized 3-axis CNC router for educational purposes. The mechanical design of the linear motion system uses linear bearings to provide the desired motions along an axis. Stepper motors which are attached to leadscrews allow controlling the movements along an axis accurately. A hand held router is attached to the z-axis and manipulates a fixed workpiece below (figure 2.2 right). The power supply is assembled inside a control box (figure 2.2 left) which also consists of other electronic parts for controlling the stepper motors. Additional indicators display the current working tool position. The control box is connected via an universal serial bus (USB) cable to a desktop computer. With the help of a GUI and a keyboard, users can instruct the CNC router through sending g-code commands (see 2.3.3) to the machine. A PIC18F4550 microcontroller interprets these commands and controls L297 stepper motor drivers which ensure that the appropriated stepper motor movements are performed.

Low-cost CNC Milling Machine

Javed et al. [2015] propose a small low cost milling and drilling machine using open-source hardware and software (figure 2.3). They use an Arduino UNO with a GRBL-Shield as machine controller which can be connected to a computer and interprets g-code. The shield has got integrated stepper drivers and offers to connect and drive three independent bipolar stepper motors. The linear motion system consists of a solid metal structure, whereby the working tool moves along all three axis and processes a fixed workpiece. The whole construction is estimated to cost about 535 dollars. To send prepared jobs to the machine controller only the Serial Monitor of the Arduino IDE is mentioned to be used.

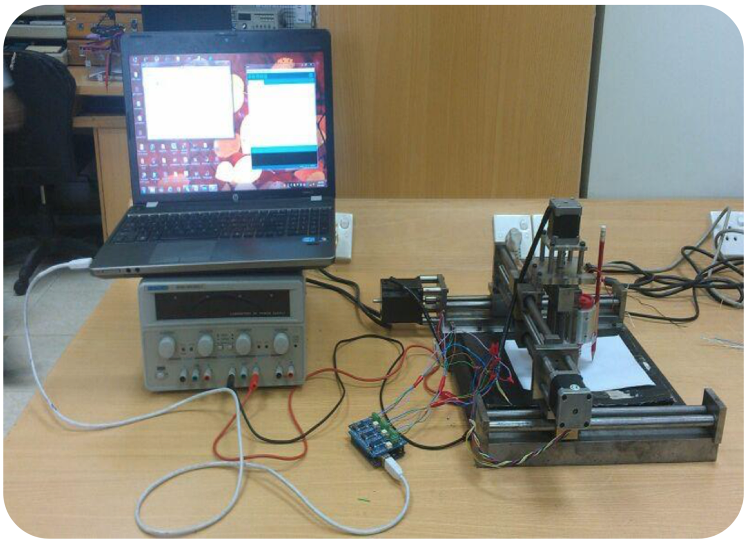

Figure 2.3: Small Low-cost CNC Milling Machine

2.2.2 Laser Cutters

Laser based fabrication machines make use of high-energy beams in order to cut or engrave different types of materials. The laser beam transfers its energy to the workpiece and heats up the surface until the material is molten and blown away. By collimating the laser beam using a lens, a very small waist radius can be achieved which allows precise manipulations on an object. Instead of milling machines, laser based CNC machines do not necessarily need a third axis to perform movements towards or from the workpiece away.

In this section, several approaches of DIY laser cutters are being reviewed with respect to their composition and assembly. In addition, prior findings on the cutting and engraving capabilities of different lasers will be presented in more detail.

Portable Mini 3-Axis CNC Laser Cutter

Al Habsi and Rameshkumar [2016] designed a portable mini 3-axis CNC laser cutter with a 500 milliwatt and 405 nanometer blue ray laser diode (figure 2.4). The device is based on a wooden structure and offers a working space of 130mm x 130mm. An Arduino UNO development board with an Atmega 328p microcontroller which runs the g-code interpreter GRBL controls three stepper motor drivers and takes care about the required movements of the 3-axis system. While the x- and y-axis afford two-dimensional (2D) movements on a horizontal plane above the workpiece, the z-axis offers vertical movements in order to automatically adjust the laser's focus. By connecting a PC with the Arduino via an USB-cable the laser cutter can be instructed over the serial interface to execute certain jobs which first need to be prepared by a CAM software in the form of g-code.

The authors mention to design the device being capable of cutting papers, engraving leather, wood and plastic cards. Some samples reveal the capability of cutting paper, but

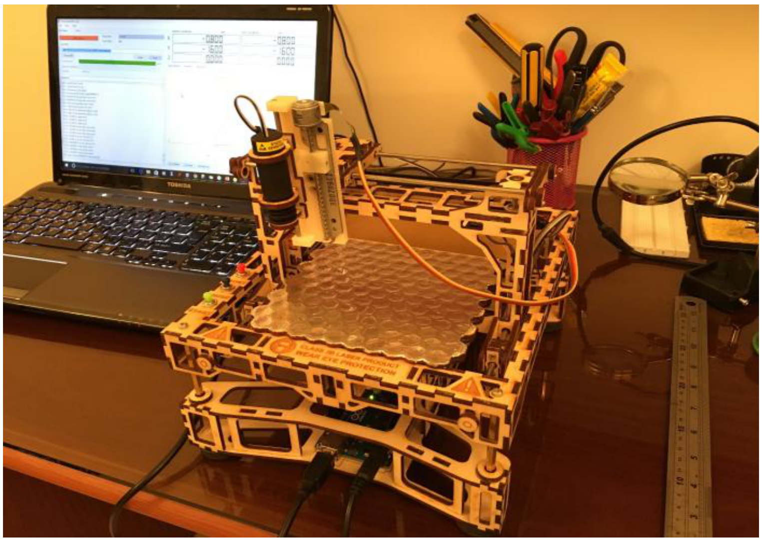

Figure 2.4: The assembled portable low-cost mini 3-axis CNC laser cutter.

other cutting or engraving capabilities regarding different kinds of material and thickness are neither apparent nor mentioned. Although, Al Habsi and Rameshkumar report achieving good results in respect of accuracy and repeatability using the developed system with a wooden structure. With a total price of about 150 omani rials - which is about 392 dollars at the current currency exchange rate - the portable system can be denoted as an affordable low-cost device. In order to improve portability it is suggested to use a Raspberry Pi with a touchscreen in future work.

3W Arduino based Laser Cutter

This approach waives the vertical z-axis and proposes a larger 42 x 42 inch construction of a laser cutter consisting of a wooden structure (FamousMods [2015]). The focus of the laser has to be adjusted manually at the focusable laser module. Instead of leadscrews the stepper motors are attached to timing belts in order control the movements on the axes. As these are mounted at the side of the machine for the y-axis, two timing belts and two stepper motors are

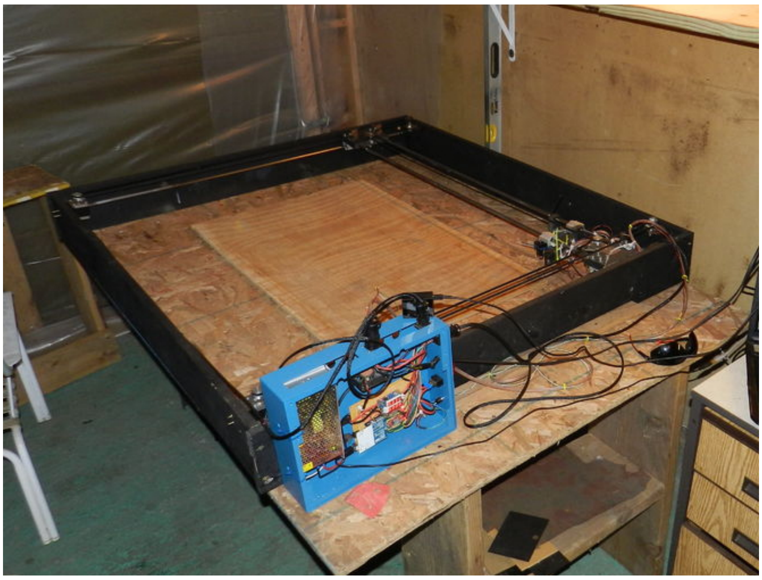

Figure 2.5: Blue electronic box in the front of the assembled linear motion system of the 3 watt laser cutter.

required to perform motions along the axis in a balanced way. However, only one stepper motor driver is needed for both motors of the y-axis. Therefore, three stepper motors and two stepper motor drivers are required for the linear motion system in total. As shown in the schematic of the electronic circuit (figure 2.6) an Arduino UNO development board is again used for controlling the stepper motor drivers. It runs the g-code interpreter GRBL and can be connected to a computer. A logic level metal-oxide-semiconductor field-effect transistor (MOSFET) allows to turn the power of the laser on and off. Moreover, four limit switches prevent the working tool from exceeding the machines bounds and afford calibrating the laser cutter by performing a homing-cycle.

The construction is said to be affordable for about 300 dollars not including steel round rods, screws, bolds, nuts and wood for the structure. Thin workpieces out of foam board, balsa wood, plastic, and cardboards are able to be cut using the device. Furthermore, it is mentioned that engraving may be possible on any surface. Although, it is questionable whether this is valid for acrylic glass. The author notes

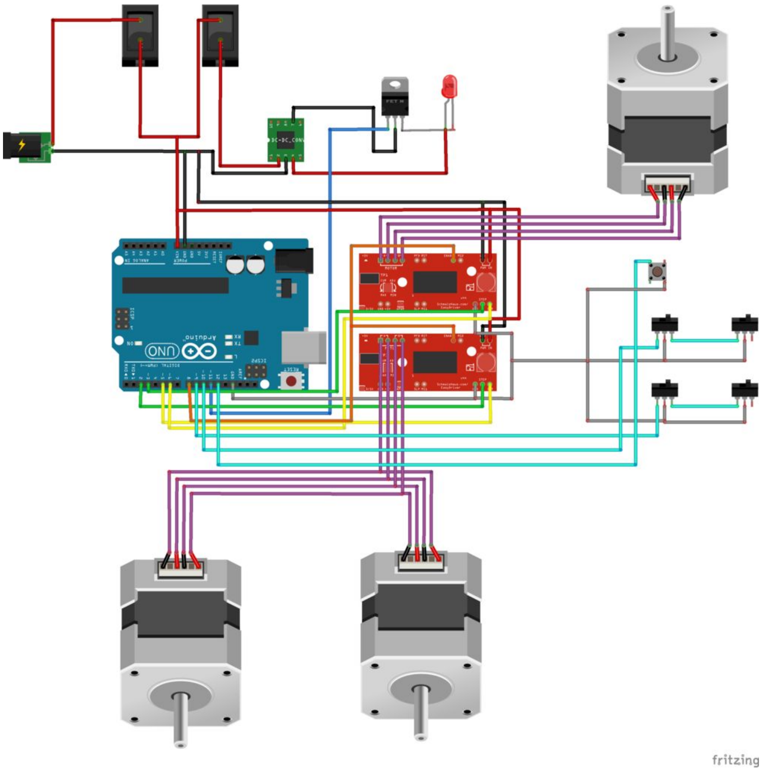

Figure 2.6: Schematic of the laser cutter's electronic circuit.

that a heat sink attached to the laser is not sufficient to prevent overheating when operating the device for a longer period of time. He recommends mounting an additional computer fan for cooling it down. Furthermore, it is explicitly stated that a safety glass has to be worn when operating a laser with the given power of three watts.

Laser Performance

There are different kinds of laser cutting devices which use different types of lasers. Most crucial for the performance and applicability of a laser is the afforded power and wavelength of the laser beam. These properties especially reveal how much energy may be absorbed by a certain kind of material and therefore define whether these materials can be cut or engraved by a laser in a given period of time.

Material	Cut	Engrave
Paper black	yes	-
Chocolate	yes	yes
Paper white	with masking	yes
Coloured fabric: silk, cotton	yes	-
Hard cardboard	no	yes
Balsa, plywood	no	yes

Source: odicforce.com[1]

Table 2.1: Laser Diode Performance: 250mW Red Laser

Material	Cut	Engrave
Paper black	yes	-
Chocolate	yes	yes
Paper white	yes	yes
Coloured fabric: silk, cotton	yes	yes
Hard cardboard	yes	yes
Balsa, plywood	no	yes
1.0mm balsa	yes	-

Source: odicforce.com[2]

Table 2.2: Laser Diode Performance: 500mW 405nm Blue Laser

Material	Cut	Engrave
1-2mm acrylic	2-3 passes	yes
0.125mm mylar sheet	yes	yes
Paper, white, brown	yes	yes
0.4mm hard card	slow	yes
3mm corrugated card	yes	yes
Balsa wood	slow	yes
Plywood	slow, 3-4 passes	yes
2mm leather	slow, 3-4 passes	yes
5mm foam board	slow, 2 passes	-
Anodised aluminium	(yes)	-
Brass, copper, aluminium	no	no
Glass	no	no

Source: odicforce.com[3]

Table 2.3: Laser Diode Performance: 2W 445nm Blue Laser

A Carbon Dioxide (CO2) laser belongs to the commonly used type of lasers in commercial cutting machines which are also affordable for smaller institutions. They usually emit light having a wavelength between 9.3 to 10.6 micrometers and a power from 20 to 500 watts. Several millimeters of various materials like wood, plastic and acrylic glass can be cut using these devices. However, a CO2 laser itself costs about a few hundred to multiple thousands of dollars. The laser tube which needs to be assembled is large and often requires a system which redirects the laser beam using mirrors. Furthermore, lasers of multiple watts can lead to eye injuries or accidentally cause a fire if no additional safety precautions are considered.

Cheaper laser diode modules provide laser beams with wavelengths between 400 and 700 nanometers and a power from 100 milliwatt to multiple watts. These can be found in laser pointers, in compact disc (CD) writers or Blu-ray players and may be purchased online for less than 100 dollars. There are several approaches which make use of diode lasers offering experimental experiences regarding the performance ability of these lasers. Most results unveil that blue and red laser diodes providing a power below one watt are only suitable for cutting thin and light materials like paper and cardboards (table 2.1 and 2.2). Stronger materials may only be engraved. Even more powerful lasers of about two watts seem not to be capable of cutting or engraving bare metal and glass (table 2.3).

2.3 Development Tools

The amount of available open-source software as well as open-source hardware has significantly increased over the past years. The members of different developer communities are working in collaboration and share their hardware and software projects under the General Public License (GNU) policy. Companies provide different development tools for these communities which are being widely used and supported by these communities. Hence, there are now being many open-source solutions available on the internet for various kinds of applications. Some of them which are commonly used and involved in manufacturing projects are presented below.

2.3.1 Development Boards

Several different development boards exist which are designed to provide beginners as well as professionals an easier starting point for their projects.

Arduino UNO

The Arduino UNO is a cheap microcontroller development board which can be purchased for less than 20 dollars (figure 2.7). It is based on the ATmega328 microcontroller with a preprogrammed bootloader and offers additional electronics such as a voltage regulator, an external clock, built-in LEDs and other parts which allow an easy integration into simple electronic projects. Using the USB-port the board can be connected to a computer and programmed with the help of the Arduino integrated development environment (IDE). As Arduino is quite popular and supported

Figure 2.7: Arduino UNO Developmentboard

by many maker communities there are many existing open-source projects which can be utilized for several applications. The development board is best suited for small embedded real time applications.

Raspberry Pi

Another popular developing board is the Raspberry Pi (figure 2.8). In contrast to the Arduino UNO the mini computer offers an ARM processor and other hardware capabilities which afford running different ARM based linux distributions. The newest model (Raspberry Pi 3 Model B) additionally offers a built-in bluetooth chip and a wireless lan module and costs about 40 dollars. Four USB-ports and a display port allow connecting typical computer accessories like a mouse, a keyboard and a monitor. In addition, multiple GPIO pins allow connecting it to other electronic circuits similar to the Arduino UNO.

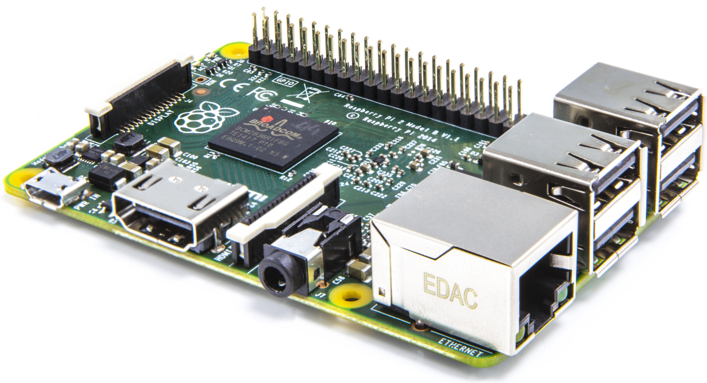

Figure 2.8: Raspberry Pi 2 Model B development board

2.3.2 FabScan-Shield

The FabScan-Shield[4] was originally developed by Engelmann [2011] for a 3D object laser scanner. The circuit board only costs 10 euros and can be mounted on top of an Arduino UNO. It allows one to easily plug-in four stepper motor drivers as well as connecting them to the corresponding stepper motors. The shield also offers additional sockets for connecting an LED, a laser diode and an external power supply (figure 2.9).

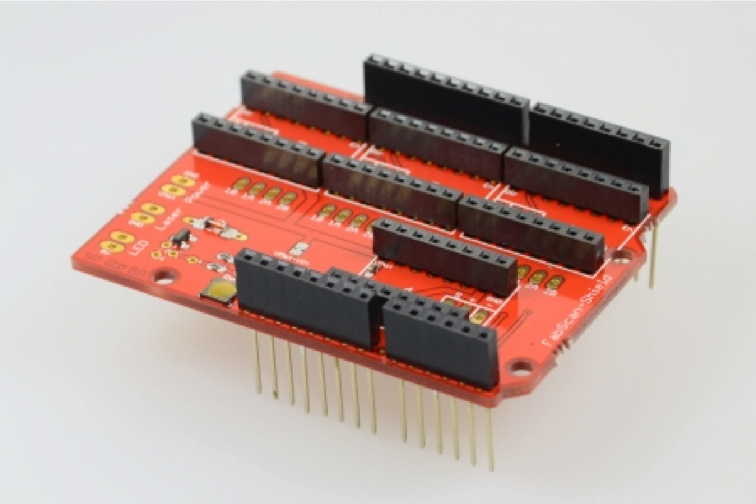

Figure 2.9: FabScan-Shield for the Arduino UNO development board.

2.3.3 G-Code

The 'G programming language' (g-code) was developed in order to control CNC machines and is supported by many fabrication machines. Using g-code commands the CNC machines can be instructed to perform certain movements of the work tool at a given speed, to control the spindle of a drilling tool or set specific machine operation modes. A major advantage is that this way the manufacturing jobs

[4] http://www.watterott.com/de/Arduino-FabScan-Shield

can be prepared by just considering the required movements in the machine's coordinate system. The motion commands are then interpreted and translated to the correct movements of the linear motion system. Nevertheless, there are different implementations of the G programming language and several machine controllers also interpret additional control codes for further functionalities.

Codes	**Description**
G38.3, G38.4, G38.5	Probing
G40	Cutter Radius Compensation Modes
G61	Path Control Modes
G91.1	Arc IJK Distance Modes
G38.2	Probing
G43.1, G49	Dynamic Tool Length Offsets
G0, G1	Linear Motions
G2, G3	Arc and Helical Motions
G4	Dwell
G10 L2, G10 L20	Set Work Coordinate Offsets
G17, G18, G19	Plane Selection
G20, G21	Units
G28, G30	Go to Pre-Defined Position
G28.1, G30.1	Set Pre-Defined Position
G53	Move in Absolute Coordinates
G54, G55, G56, G57, G58, G59	Work Coordinate Systems
G80	Motion Mode Cancel
G90, G91	Distance Modes
G92	Coordinate Offset
G92.1	Clear Coordinate System Offsets
G93, G94	Feedrate Modes
M0, M2, M30	Program Pause and End
M3, M4, M5	Spindle Control
M8, M9	Coolant Control

Table 2.4: Supported G-Codes in GRBL v0.9i

GRBL

GRBL[5] is an open-source g-code interpreter which is optimized for the Arduino UNO development board and its ATmega328p. It uses all features of the microcontroller to afford an accurate control of CNC machines and supports additional functionalities like an acceleration management or several safety features. The controller can be connected via a serial interface and receives g-code commands as well as other control commands. A list of the g-code commands supported by GRBL v0.9i can be seen in table 2.4.

2.3.4 CAM Software

Computer-aided manufacturing (CAM) software is usually used as interface between computer-aided design (CAD) software and the fabrication machine controllers. It allows importing CAD files and preparing the jobs for the machine controller. CAM applications normally offer a graphical user interface which allows to configure the settings of the job preparation process. Some applications also offer to simulate the manufacturing process. If the software supports a direct communication with the machine controller, the prepared jobs can also be send to the fabrication machine directly and further machine operations may be performed using the GUI.

Visicut

Visicut was developed by Oster [2011] to offer a platform independent user-friendly CAM software application. The application affords importing several types of CAD file formats and previewing the prepared job in an image view which is updated with a live recording from the machine's workspace. This way multiple jobs can be easily transformed and aligned in the machines workspace. The user interface allows to easily select presets for the target fabrication machine and a certain workpiece material. Finally,

[5] https://github.com/grbl/grbl

the job can be sent directly to the target machine, where the manufacturing process execution can be triggered.

Dxf2gcode

Another open-source CAM application is dxf2gcode[6]. It offers a GUI application which allows to prepare and configure DXF files for g-code jobs (figure 2.10). Moreover, a preview of the simulated manufacturing job can be displayed and the individual parameters of shapes and job entities can be adjusted. Additional postprocessor configuration files allow to adjust further settings for the job preparation. Finally, the job can be exported to a g-code file and has to be send to the fabrication machine manually.

[6]https://sourceforge.net/projects/dxf2gcode/

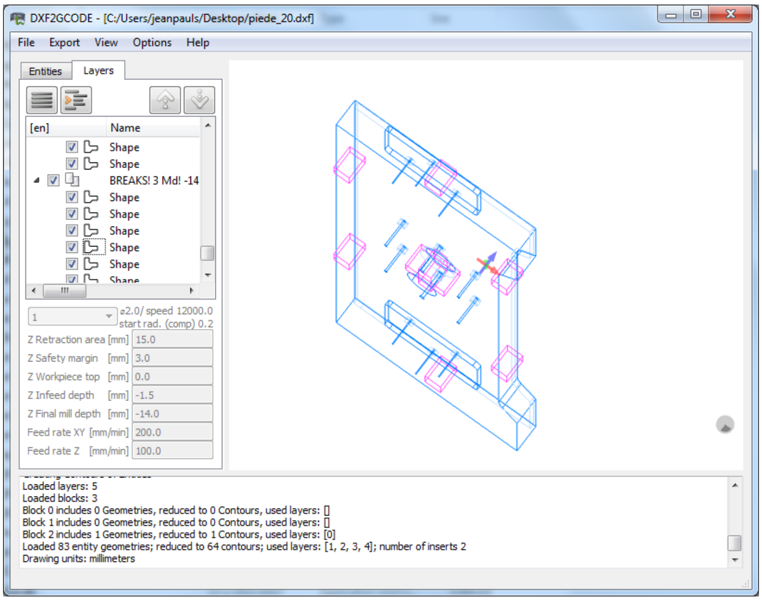

Figure 2.10: The graphical user interface of the dxf2gcode CAM application.

2.3.5 CAD Data Exchange Formats

Besides other CAD file formats which are commonly supported by CAM software, especially two formats are interesting for two-dimensional cutting or engraving jobs.

DXF Fileformat

The Drawing Interchange File Format (DXF) is an open-source file format from Autodesk which was developed for 2D drawing and 3D geometry data exchange. As its structure is well documented and easy to use, most CAD and CAM software support the file format today. Lines, points, curves, basic shapes, geometries and text can be saved in a DXF-file. However, a problem of the file format is that the unit of measurement is not intended to be specified by default. Although there are being different approaches of specifying the unit of measurement now, there is no universally accepted one so that there are DXF files with differing specifications.

SVG Fileformat

The Scalable Vector Graphics (SVG) file format was developed by the World Wide Web Consortium (W3C) which supports 2D drawings and is based on the Extensible Markup Language (XML). It was originally intended to replace pixel based image file formats like PNG, JPEG and BMP with a new graphic standard for websites. Even though it was first only partly accepted, most internet browsers and image processing programs are supporting the file format nowadays. Also many CAM and CAD software for cutting and engraving jobs support the file format. In contrast to the DXF file format SVGs support specifying the used unit of measurement - which is however not obligatory.

Chapter 3

Own work

In the following, the development process of the proposed device is presented along with its functionalities. An initial requirement analysis outlines which tasks need to be considered for the final device and which properties have to be focused on during the design process (3.1 — "Requirements Analysis"). The subsequent sections are split into a hardware and a software part. While section 3.2 — "Hardware" (p. 28) focuses on the prototyping process of the mechanical and electro technical design of the linear motion and milling system, section 3.3 — "Software" (p. 51) presents the implementation of the GUI application as well as the back-end motor control system. In addition, the communication and coordination will be explained in greater detail.

3.1 Requirements Analysis

With regard to section 2 — "Related work" and the set goal of enabling inexperienced users to operate the device and create illuminated acrylic name tags (1.3.3 — "Objective"), several requirements can be derived. The usability of the user-interface as well as the name tag creation process are being considered as main objective. The steps which would require a user to create CAD files and prepare the jobs using a CAM application should be simplified. The target user group mainly consists of children, but also other visitors of the Fab Lab Aachen and upcoming exhibitions. Therefore, the device has to be compact and afford being transported between different locations. Taking up the proposal of Posch and Fitzpatrick [2012], the machine should enable children to operate the machine in safe way and afford a self-directed exploration of the technology. To retain the concept of personal fabrication and reduce cost, the device should preferably be built with the equipment and tools located at the Fab Lab Aachen. It is intended to built a laser based CNC machine to engage the same manufacturing technology as used in the past name tag creation process.

The acquired requirements can be split into functional and non-functional requirements which are specified more concretely in the list below.

functional requirements:

- **Name tag creation** – Name tags should be engraved out of acrylic glass.
- **CNC machine** – A CNC machine needs to be developed.
  - **Linear motion system** – For the physical movements of the workspace and engraving tool a mechanical linear motion system has to be built.
  - **Motor control system** – A machine controller should drive the motors and provide an interface for front-end.
  - **Laser** – A laser should be implemented to engrave the workpiece.
- **GUI application** – A GUI has to be developed for the user interaction which should:
  - guide the user through the manufacturing process.
  - allow entering a name.

  - allow selecting a graphic.
  - afford to undo already provided input and cancel processes which do not involve the user.
  - prepare and execute the manufacturing job.

- **Communication** – A communication between the GUI application and the motor control system has to be realized.
- **Case** – A case which encapsulates the linear motion system and the user interface has to be developed.

non-functional requirements:

- **Process improvement** – The final result has to improve the prior process of making personalized badges. The device should involve a user during the whole manufacturing process and arouse the interest in the fabrication technology.
- **Do-It-Yourself (DIY)** – Building the device should be possible within a fab lab. The list of additionally required materials should be kept at minimum.
- **Affordability** – The construction has to be affordable and expensive materials should be preferably avoided.
- **Mobility** – To afford mobility the device should be designed compact and small-sized.
- **Usability** – The usability of the user interface (UI) has to be be considered notably. Novice users should preferably be able to operate the device without prior instructions.
- **Stability and Accuracy** – The construction has to be robust and resist emerging forces in order to operate steadily and accurate.
- **Safety** – Safety mechanisms have to be considered to prevent any accidental injuries.
- **Observability** – The manufacturing process should be observable.

3.2 Hardware

The development process covered many iterations of prototyping and followed the Design Implement Analyze (DIA) model (figure 3.1). The next sections will describe the main iteration steps, whereby each of them will be concluded with a short discussion about its advantages and disadvantages, leading to the following ones. As there were many short iteration steps involved in the whole process, these were summarized and assembled in more meaningful bigger ones.

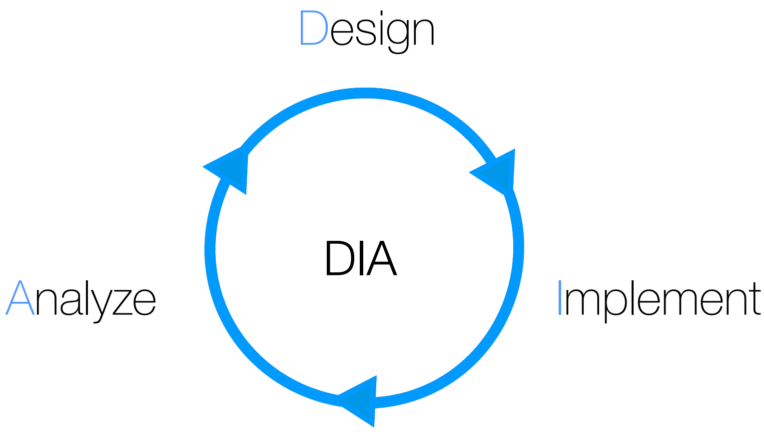

Figure 3.1: DIA Development Model

3.2.1 Hardware Prototype One

The first prototype iteration covered short drafts about the basic functionality of an engraving machine. As the machine would be used for a special purpose with a user-centered design and the requirements described in section 3.1 it appeared to be appropriate to build a customized CNC machine slightly differing from previous work (section 2.2).

First of all, the creation of personalized name tags primarily requires the device to engrave the user's name and a selected graphic onto a piece of acrylic glass. The idea was to

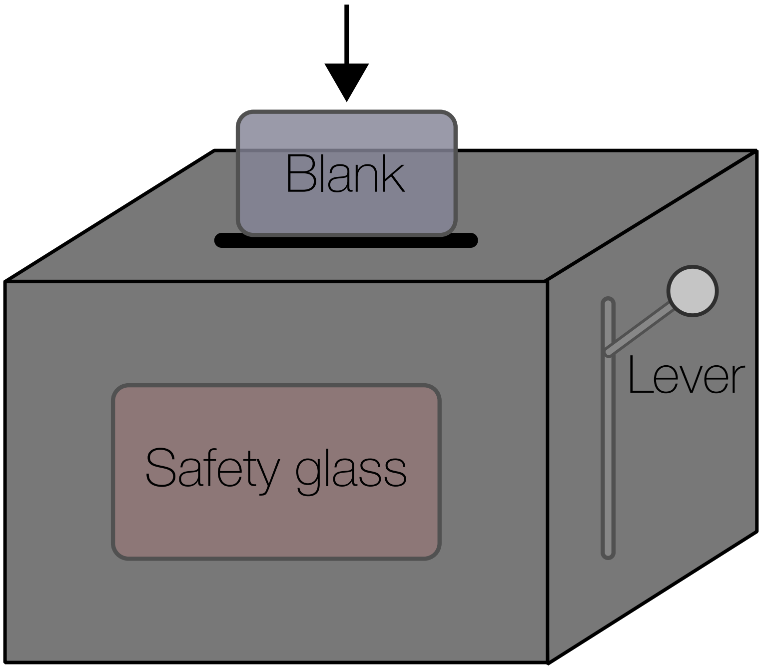

Figure 3.2: A card slot affords inserting a card as workpiece into the machine. The lever is used in order to lock the card. The safety glass allows observing the manufacturing process.

provide the user blanks of acrylic glass cards which would have to be inserted into the machine. This would allow to shrink the device's required workspace to a minimum and could result in a more user-friendly handling of the workpiece. Moreover, part of the processing time could be saved this way. The insertion and positioning of the workpiece were identified as one of the crucial tasks which should be considered within the design of the physical machine. A first approach suggested the user to insert the workpiece through a card slot which would be a common procedure known from usual cash machines (figure 3.2). After that, the card would have to be moved and get locked to a final position so that it could not move during the engraving process. In doing so, each time the same starting point would also be provided for the engraving procedure. For this task a lever mechanism, known from bread toasters, was considered to be used. It seemed to be suitable to place the card slot at the top for the insertion and engrave the

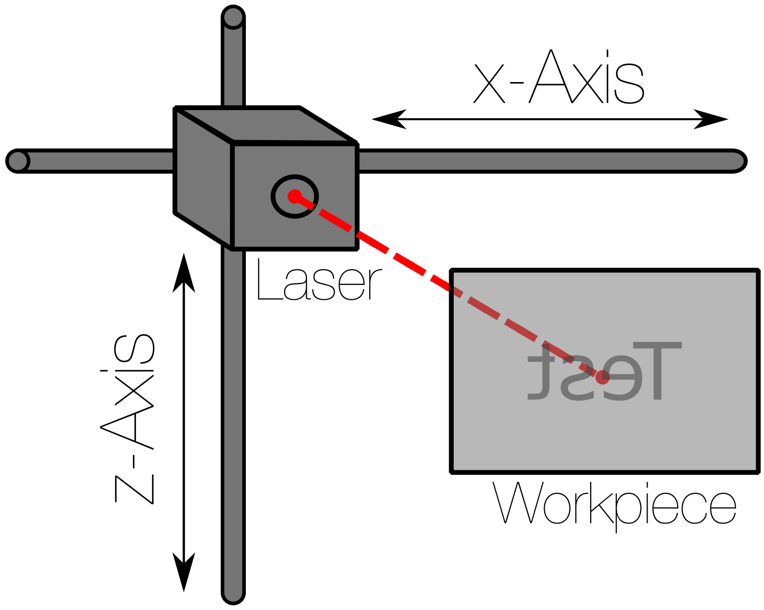

Figure 3.3: Sketch of a fixed workpiece (front) and a laser module attached to a 2-axis linear motion system (back).

workpiece from the side, providing an unobscured view to the translucent workpiece.

At this point still a laser was intended to be used for engraving the acrylic glass. As the workpiece would always have got the same thickness and the laser's focus would not require to be adjusted frequently a two-axis linear motion system was adjudged to be sufficient for the intended application – unlike to the apparatus proposed by Al Habsi and Rameshkumar [2016] (see 2.2.2). A first draft documented the idea of the mechanical system which is shown in figure 3.3. Hereby, the workpiece is fixed in front of the device and the laser is mounted at the linear motion system. While the x-axis performs horizontal movements, the z-axis is attached to the first one and performs vertical movements. In order to realize a low cost linear motion system with a laser attached to it, two CD drives were disassembled and examined. As CD drives consist of one linear axis controlled by a small stepper motor and a laser diode they provided all required mechanical parts.

Discussion

After disassembling the CD drives and performing some initial tests in driving them with the help of an Arduino UNO development board, the parts unveiled not to be suitable for the intended approach. Part of the stepper motors did not work anymore or seemed not being strong enough for a further usage as step losses were detected. With regard to the latter these might have been prevented by a more elaborative method in driving them using the Arduino. However, the linear rail system also seemed to be too small-dimensioned for the purposed workpiece which required a minimum workspace-size of about 85mm x 55mm.

In addition, the power of the laser-diode was too low in order to engrave acrylic glass. Further investigations uncovered that a laser based DIY approach might be inappropriate at all (see 2.2.2 — “Laser Performance”).

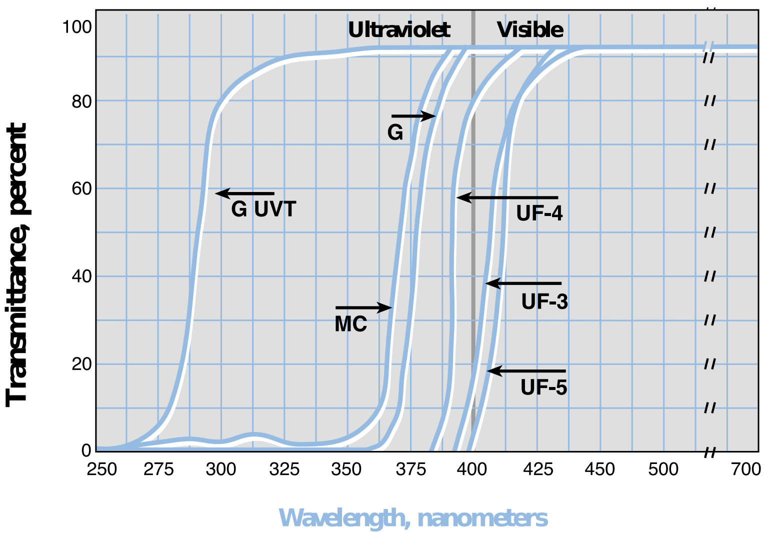

Figure 3.4: Visible and Ultraviolet Transmittance in Colorless PLEXIGLAS Sheet Group [2016]

LIGHT ABSORPTION OF PLEXIGLAS:
As this acrylic glass is nearly fully transparent and its total light transmission is 92 percent, it only provides a very small absorption spectrum. Typical cheap red laser diodes from CD and DVD drives offer lasers with a power between 200 and 300mW and wavelengths of about 650nm. Stronger Blu-Ray laser diodes operate with a wavelength of about 405nm. As figure 3.4 shows, these wavelength are barely absorbed by standard plexiglas (spectrophotometric curve G), making an engraving process almost impossible. Only the more expensive plexiglass sheets with a UV filter (UF-5) may absorb 10 to 20 percent of a 405nm lasers. Ultraviolet laser diodes below 400nm are only used for medical or specific scientific applications. The cheapest one, operating at 375nm and 70mW, which could be found costs 1.608 dollars.

Definition: *Light Absorption of Plexiglas*

By choosing more powerful lasers which would be able to engrave acrylic glass within a satisfying period of time, safety would have to be considered extensively and the costs would also increase dramatically. High power laser modules like CO2 laser modules are expensive and increase in size with the consequence that a redirection of the laser beam with the help of mirrors need to be considered. A self built laser would still require one to take care about the single components mainly consisting of a laser, lens, power supply and a cooling system which prevents the laser from overheating. Furthermore, lasers with a power of multiple watts are usually classified by the laser safety class four. As even the reflected diffuse light can harm surfaces of the environment and cause eye injuries this would require more expensive surfaces of the inner device which resist the laser beam. In addition, safety glass would be needed in order to make the manufacturing process observable for users – which is highly expensive.

A laser of the laser safety class 4 is highly dangerous and can burn skin or cause eye damage through reflected, diffuse light.

Because of the increasing costs, complexity, size and safety risks it was finally decided to resign using a laser in order to engrave acrylic glass. Hence, an alternative tool had to be considered for the next prototype iteration. The card slot system still appeared to be a good idea providing an intuitive way of interaction.

3.2.2 Hardware Prototype Two

In the next iteration a rotary milling tool was suggested to be used in order to engrave the acrylic glass cards and a first linear motion system was designed and tested. The linear motion system required some adjustments: As a mill processes a workpiece using its rotary tool with direct contact to the workpiece's surface, a third axis needed to be attached to the second axis. The third axis would hold the milling tool and allow to perform movements towards or back from the workpiece.

To achieve controlled movements along the different axes a linear motion system was developed similar to the one proposed by Aktan et al. [2016] (see 2.2.1). For each axis a leadscrew was mounted between two aluminum rods (figure 3.5). A platform could slide along these two rods with a fixed orientation by using sleeve bearings which provide less friction. Simple nuts in combination with the leadscrews were used to translate the turning motion of a Nema 11 stepper motor into linear motion. The placement of the leadscrew right in the middle of the rods also ensured

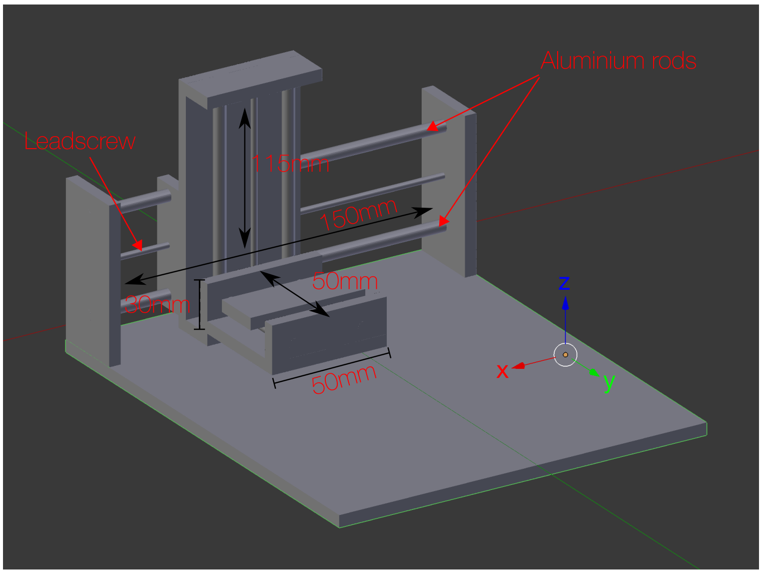

Figure 3.5: Rough sketch of the new the linear motion system modeled in Blender.

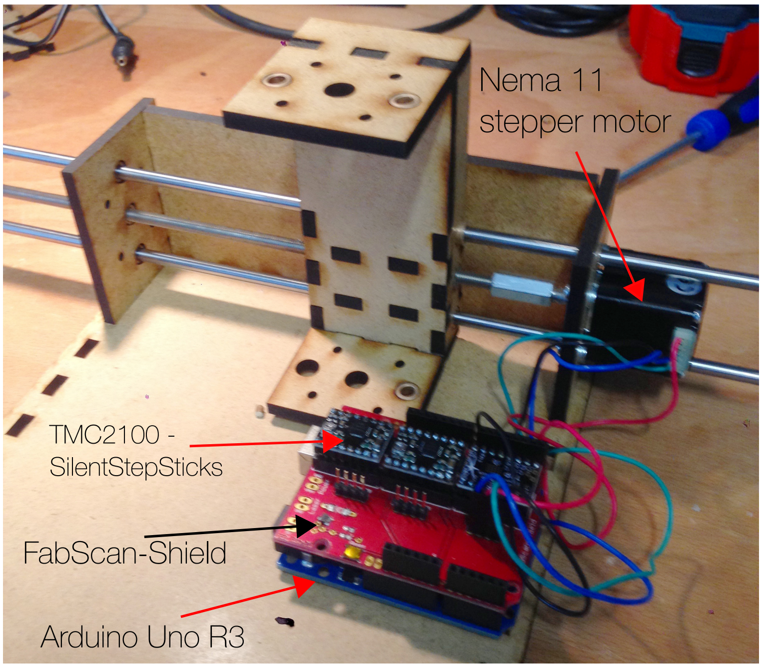

Figure 3.6: First implementation of the x-axis system. An Arduino Uno R3 with a FabScan-Shield and three TMC2100 SilentStepSticks are used in order to drive the Nema 11 stepper motor.

that an evenly distributed pressure would be applied to the sleeve bearings.

The whole construction was built out of 5 millimeters thick medium-density fibreboard (MDF), a solid and affordable material which can be customized by cutting it with a laser cutter. Therefore, vector graphic files were prepared with Inkscape[1] (an image-processing application). The MDF sheets were then cut using the Epilog Zing CO2 laser cutter from the fab lab. The individual parts were assembled using a interwoven construction design and glue (see figure 3.6) . With respect to the width of the different axes components and a little scope for unintentionally required space the effective length of the leadscrews and aluminum rods were estimated to be 150 millimeters for the x-axis, 50 millimeters for the y-axis and 115 millimeters for the z-axis.

[1]https://inkscape.org/

An Arduino Uno R3 and the FabScan-Shield, which can be mounted on top of the Arduino UNO, were used to drive the stepper motors and formed the motor control system. Hereby, TMC2100 SilentStepSticks were used as stepper motor drivers which are similar to the commonly known Pololu A4988 drivers. The differences between these two types of motor drivers are mainly that the SilentStepSticks provide a larger range for the motor voltage supply, are being less noisy and have got a low power drain.

Discussion

First tests of driving the stepper motors with the developed system showed that linear movements along the x-axis could be performed successfully and the general concept of the axis system worked. The theoretical precision which could be achieved using the proposed linear motion system unveiled to be sufficient for the intended application (discussed in section 3.2.7 — "Precision"). Nevertheless, step losses occurred during the tests and a lot of force had to be applied to the leadscrew for the movements. It turned out that the edges of the construction were not cut straight. Because of this, the sleeve bearings were also mounted in a skew way which led to high friction. As this problem was identified as a laser cutter issue which could not be resolved immediately, it was suggested to provide some tolerance for the sleeve bearings the next time. It was also noticed that bounds for the aluminum rods were required in order to prevent the rods from moving. Furthermore, limit switches had to be taken into account in the next iteration step. These would allow calibrating the linear motion system as described in the following iteration.

3.2.3 Hardware Prototype Three

This time the holes for the sleeve bearings were designed slightly bigger than before. The aluminum rods and sleeve bearings were assembled at once so that the sleeve bearings would have an optimal orientation when the glue cured. It was also decided to adjust the whole design of the components to provide bounds for the rods (figure 3.7). The bounds were kept removable so that other parts could be disassembled if further improvements had to be done. Moreover, a lighter basis platform was designed offering additional space for future extensions. Micro switches were now considered to be placed at one end of each axis system. In doing so the device would be able to determine a homing point by performing a homing cycle.

Definition: *Homing Cycle*

HOMING CYCLE:
As the working tool's position may not necessary be known by the motor control system at startup, CNC machines usually perform an initial homing cycle. During the homing cycle the workpiece is moved towards a configured direction along each axis. By the use of limit switches the motor control system is able to detect whether the workpiece reached a bound of an axis system. If the workpiece reached one bound of each axis system the homing point is determined. After that all further movements can be performed with reference to this point.

Further limit switches at the opposites were not suggested to be implemented because the device's dimensions would be known by the motor control system and safety mechanisms were planned to be realized on the software side. A Proxxon MicroMOT 50 seemed to be suitable to be used as a rotary milling tool. The specifications of the hand-held device stated that it would be capable of processing glass and its round shape allowed to fix it without much effort. For this purpose the y-axis system was adjusted in order to carry the machine.

Discussion

Before mounting the Proxxon MicroMOT 50 to the y-axis platform, different grinding and drilling heads were tested with the machine in order to determine the most suited one for processing acrylic glass. Cutting still showed to be problematical using the hand-held milling tool. How-

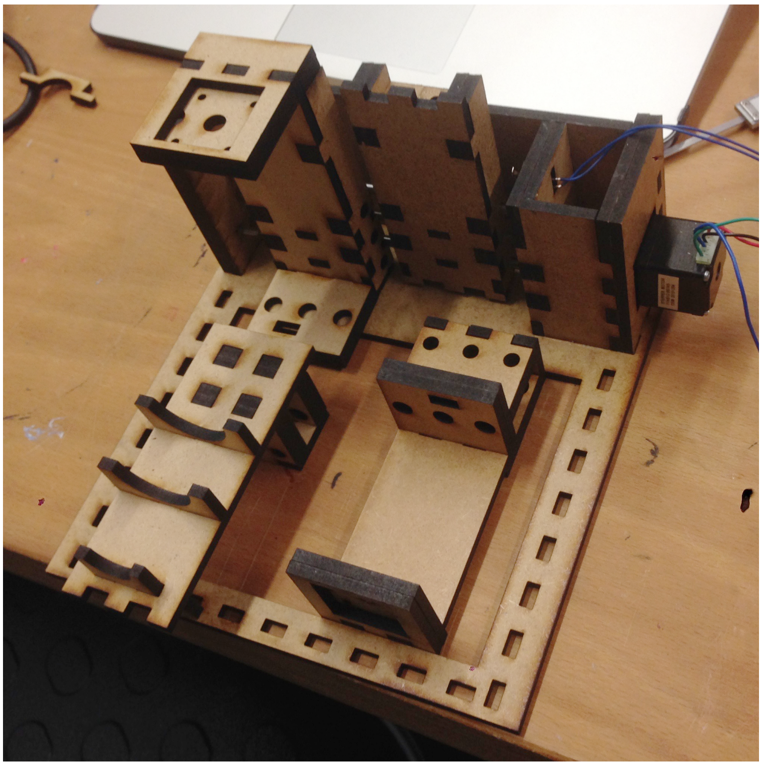

Figure 3.7: Components of the adjusted linear motion system with three axes.

ever, the tests unveiled that the device would be at least sufficient for the intended engraving process. The drilling heads achieved the best results as deeper notches could be achieved more easily.

Movements along the different axis systems turned out to be much smoother with the new prototype. In addition, a first homing cycle was successfully performed with the new limit switches. A significant problem was realized when the Proxxon MicroMOT 50 was mounted on the platform of the y-axis system. The construction was not stable enough to withstand the weight of the rotary tool and the designed y-axis system, which lead to an oblique bending of the structure. This was mainly explained to be caused by the center of gravity which was shifted too far away from the bearing x-axis system. It was finally decided to develop a new design for y-axis of the linear motion system.

3.2.4 Hardware Prototype Four

Instead of developing an entirely new linear motion system the y-axis system which carried the milling tool was placed at the opposite (figure 3.8). Therefore a platform had to be designed which ensured that the drilling head would operate at an appropriate height. The carrier of the Proxxon MicroMOT 50 did now afford fixing the tool with the help of a hose clamp. Furthermore, a card holder was mounted at the z-axis system so that the workpiece could be moved on the vertical XZ-plane.

At this stage of development it was decided to use GRBL

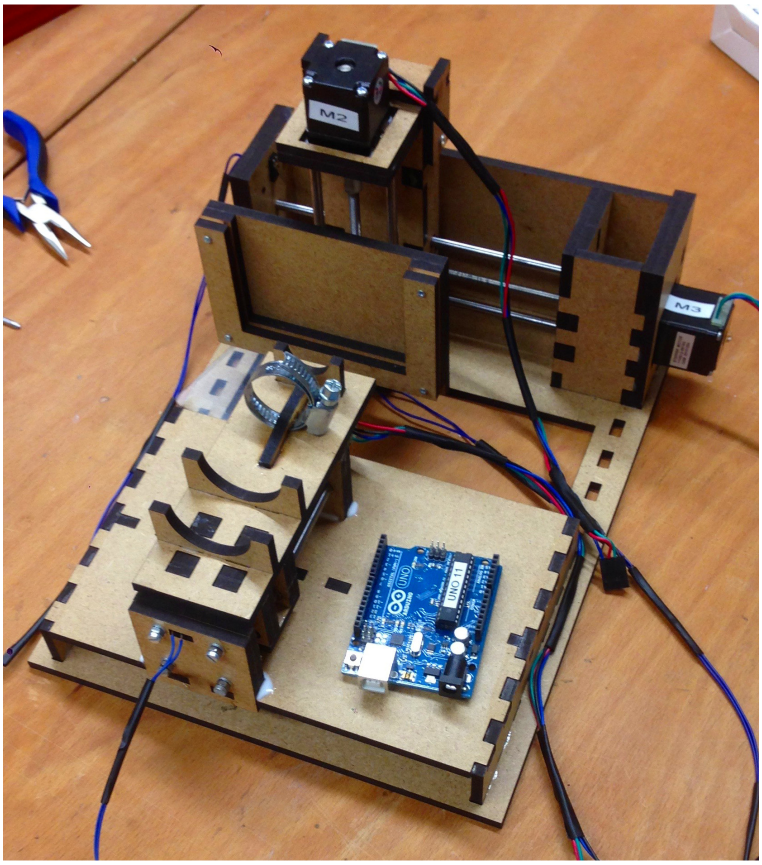

Figure 3.8: New linear motion system with the y-axis system placed at the opposite and a movable card holder.

as back-end solution for the motor control system. The g-code interpreter was designed to run on the ATMEGA328P microcontroller of the Arduino UNO development board and could be instructed by using a serial connection (see 2.3.3 — "GRBL" and 3.3.6 — "GRBL Interface"). Taking up the proposal from Al Habsi and Rameshkumar [2016] (2.2.2 — "Portable Mini 3-Axis CNC Laser Cutter") a Raspberry Pi 3 was intended to be used as front-end device. The mini computer offered serial ports to communicate with the Arduino and allowed to drive a display device for the suggested GUI application. For this purpose a Waveshare 3.2inch RPi LCD shield with a touchscreen interface was mounted on top of the Raspberry Pi.

To turn on and off the rotary tool the Proxxon MicroMOT 50 was disassembled and a MOSFET IRF540N was used to drive the direct current (DC) motor. The MicroMOT 50 was connected to the same power supply the stepper motor drivers were connected to.

Discussion

The milling tool could be mounted on the y-axis system easily and the new construction showed to be much more stable than before. However, the y-axis system was now obscuring the workpiece at the front view. In addition, the insertion or removal of the workpiece would now require the card holder to move to an adequate position beforehand.

During some engraving tests it was observed that the rotary tool's number of revolutions decreased significantly when the stepper motors were driven at the same time. After verifying that sufficient current was provided by the power supply and the problem could not being resolved it was considered to use separate power supplies for the stepper motors and the MicroMOT 50. Furthermore, there were still step losses detected and the stepper motors did make loud noises. An inspection of the FabScan-Shield's electronic circuit unveiled that the configuration pins were set wrong for the TMC2100 stepper drivers. Although the Pololu A4988 is said to be compatible with the TMC2100, this is only true in respect of the pin layout. The signal level of the configuration pins are interpreted in a different way. The most appropriate pin configuration for the TMC2100 SilentStepSticks was found to be: CFG1=low, CFG2=open and CFG3=open. The circuit was tested using a breadboard. It also turned out that the FabScan shield is not compatible with the pin mapping of GRBL. As GRBL takes advantage of certain pin features, the mapping could not simply being altered on software side.

The 3.2inch touchscreen showed to be insufficient for the purposed user interaction. On the one hand, the resistive touch was perceived to be less user-friendly as much pressure had to be applied for triggering touch events. On the other hand, the screen was too small dimensioned to display an intuitive GUI with images, labels and buttons. Especially tapping on small buttons with a finger appeared to be hard as the touchscreen was too inaccurate. A different touchscreen was suggested to be used for the next prototype.

3.2.5 Hardware Prototype Five

The next prototype covered several major improvements. A Waveshare 7inch capacitive touchscreen display with a resolution of 1024x600 pixels replaced the old device providing better touch sensitivity and enough space for a user-friendly GUI with a 'one-to-one' preview. The display could be connected to the Raspberry Pi via an USB and HDMI port. Four screw holes afforded an easy installment on top of the device. In addition, a customized Arduino shield (figure 3.9) was developed which was now being used instead of the FabScan-Shield. The Arduino Shield was designed using the PCB design software EAGLE (appendix A — "Arduino Shield – Schematic and Board Layouts"). Besides offering a proper configuration for the SilentStepSticks the new shield provided a better interface for connecting the limit switches, sperated power supplies and serial connectors to the Raspberry Pi. As the Raspberry Pi's GPIOs operate at 3.3V and the Arduino at 5V the power levels had to be adjusted. Furthermore, the pin mapping

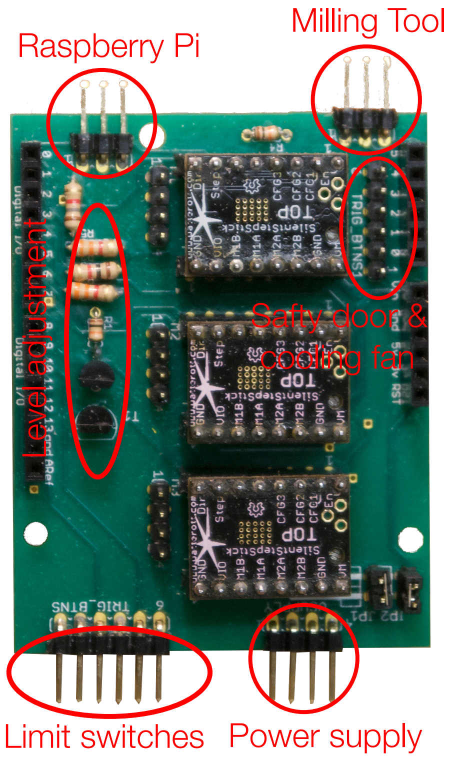

Figure 3.9: The new Arduino UNO Shield providing additional pin headers and a power level adjustment.

was now compatible to the GRBL controller software.

A case was designed which encapsulated the milling system. The previous developed linear motion system could be mounted onto two mounts which are shown in figure 3.10. Moreover, a keyboard was intended to be used for entering the name and could be plugged in a USB port which was placed at the outside. A cooling fan should ensure to have some air circulation in the case and a removable waste container was considered to collect waste below the card holder. In addition, an openable safety door provided access to the interior system for inserting or removing the workpiece . Four windows consisting of Plexiglas afforded the observation of the milling process. A simple switch triggering mechanism allowed to inform the backend and front-end devices about a state change when the door was opened or closed. Also two short WS2812 LED

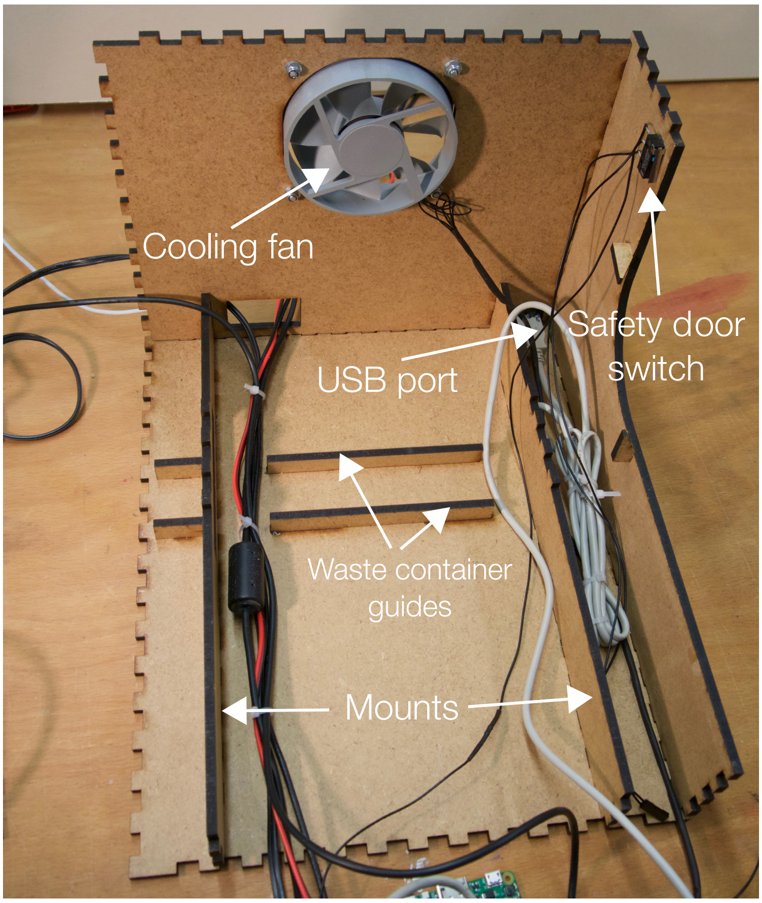

Figure 3.10: Interior view of the case and its providing features without the linear motion system.

stripes were mounted at the inner ceiling of the device to illuminate the interior milling process. The slant of the case afforded an optimal angle of about 15 degrees for the touchscreen (Alan Dix [2004], p.76). The case furthermore provided enough space for hosting the Raspberry Pi, a power supply and all the wiring.

Discussion

Because of the new circuit board the stepper motors were being less noisy and performed much better than before.

Figure 3.11: A unicorn engraved by the milling machine.

No step losses were detected anymore. As GRBL supports g-code instructions to control the cooling fan and safety door mechanisms, the fan could automatically be turned on during the milling process and opening the safety door would cause the machine to halt. A more complex engraving test of a detailed graphic delivered satisfying results (figure 3.11). But the milling time took about five minutes which needed to be improved. Increasing the speed of the motors and splitting the milling job into two layers of a different depth level resulted in a speedup. Moreover, this way a card could be inserted into the card holder without an additional locking system. As the cardboard was clamped between the two pieces of MDF, there was sufficient friction to keep the card fixed during the engraving process.

Although, it was detected that the paths of the second layer did have slight deviations from the ones of the first layer. The head of the y-axis system's platform showed to be slightly turning to the sides, being affected by movements along the x-axis due to the friction of the workpiece. In addition, sometimes the touchscreen stopped recognizing touch gestures and slight flickering was observed which

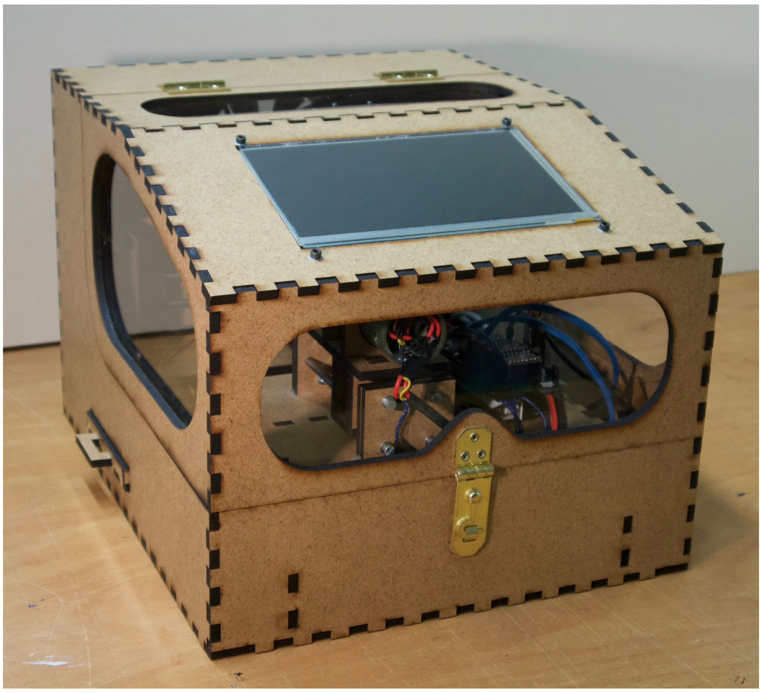

Figure 3.12: Exterior view of the assembled device with a case encapsulating the interior milling system.

lead to the assumption that there was not enough current provided by the Raspberry Pi's USB ports. Tests regarding the GUI interaction showed that the application (see 3.3.2 — "GUI Application") was sometimes lagging behind when a button was pressed. This could lead to a wrong perception of the user who might think his touch gesture had not been recognized.

All in all, the prototype did offer a compromise between several different usability factors. On the one hand, the touchscreen was easily accessible at the front of the device and large enough to provide a user-friendly interface. On the other hand, it obscured a greater part of the interior system (figure 3.12). As the remaining space was considered to be used for translucent windows which should improve the observability, the cooling fan could only be mounted at the back of the device which was not an optimal position because the z-axis system would be always operating in front of the cooler. Furthermore, the case was now providing a compact system which protected the encapsulated mechanical construction and electronic parts and afforded some safety mechanisms. However, in order to insert or remove a card the user would have to lift the safety door which was not as comfortable as it was initially intended. This process required two hands, one which was opening and holding the safety door, and one which inserted or removed the card. As the card holder was not fixed and a physical gap between the card holder slot and the ceiling existed, a mechanism which would not require opening the safety door unveiled to be hard to implement. Hence, a blank card had to be manually pushed down to the correct position.

3.2.6 Hardware Prototype Six

The last prototyping iteration covered multiple minor modifications which are shown in figure 3.13. To stabilize the working tool two brackets were attached at the sides of

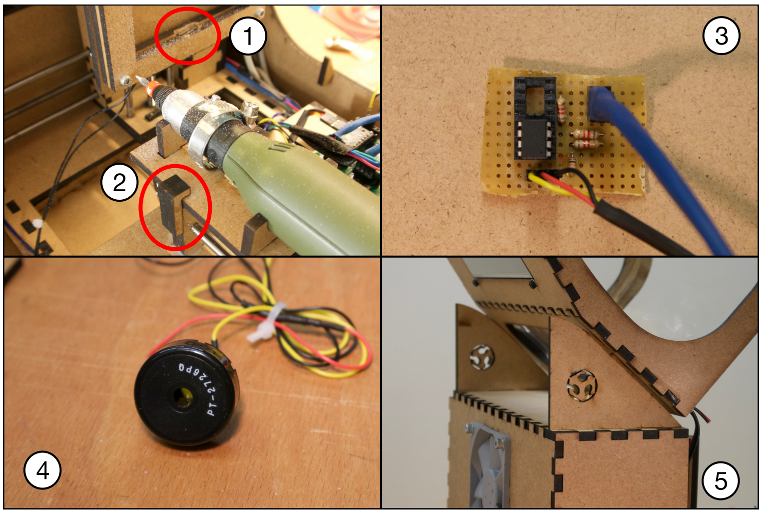

Figure 3.13: (1) A mircoswitch which detects a correctly inserted card. (2) One of the brackets which stabilize the working tool. (3) The ATtiny85 circuit board which drives the WS2812 LED stripes. (4) The beeper connected to the Raspberry Pi. (5) The stand for the safety door.

the front of the y-axis system, preventing any movements along the x-axis or z-axis. A stand was mounted on top of the case so that the safety door could lean against it when the device would be opened. The Raspberry Pi could now provide acoustic feedback to the user by using a beeper which was connected to it. An ATtiny85 microcontroller was used to drive the WS2812 LED stripes independently. The Raspberry Pi could control the light and offer some additional visual feedback inside the device. As the correct insertion of a blank card was identified as crucial task another micro switch was installed at the bottom of the card holder. Moreover, the touchscreen was connected to an active USB-Hub which provided enough power for the display.

Discussion

The modifications improved the quality of the engraved name tags. A comparison of two name tags is shown in figure 3.14. Obviously, the deviations which occured previously along the x-axis could be reduced and the shapes were engraved in a more accurate way. With help of the USB-Hub no problems of the touch screen occurred anymore and opening the safety door was now much more comfortable. In addition, the new switch and feedback devices allowed to check whether the card had reached the correct position and the user could be informed about an accepted card position without the need of the touchscreen display. The final device can be seen in figure 3.15. More information about the wiring of the final prototype is given in section 3.2.8.

Figure 3.14: Name tag engraved by the old prototype (left). Name tag engraved by the new prototype (right).

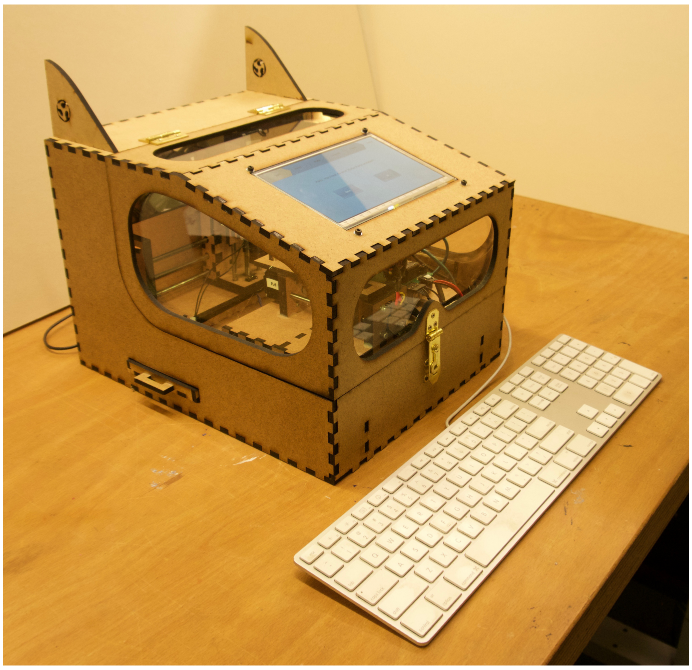

Figure 3.15: Final prototype with the applied modifications and a keyboard connected to the device.

3.2.7 Precision

Definition: *Linear Movement Precision*

LINEAR MOVEMENT PRECISION:
The theoretical precision of the linear movements along an axis is limited by the *step angle* α (in degrees) of the stepper motor and the *leadscrew pitch* p (in millimeters). The step angle describes the rotation which is performed within one step. The *leadscrew pitch* defines the distance moved within one complete revolution. With the help of these values the precision, more specifically the *distance per step*, can be calculated:

$$D_p = \frac{\alpha}{360^\circ} * p$$

Nema 11 stepper motors provide a *step angle* of 1.8°. As the the TMC2100 stepper motor drivers support a microstepping technique which allows to perform up to 16 micro steps per full step, a *step angle* of

$$\alpha = \frac{1.8^\circ}{16} = 0.1125^\circ$$

may be achived. With a *leadscrew pitch* of $p = 0.8mm$ a theoretical precision of

$$D_p = \frac{0.1125^\circ}{360^\circ} * 0.8mm = 0.00025mm$$

per step could be attained this way.

The effective precision however depends on the physical stability and reliability of the system, the computing precision due to architecture related limitations and the proper control of the stepper motors. Regarding the latter one a common problem are steps losses.

Definition: *Step Loss*

STEP LOSS:
Step losses occur when the motor control system expects a stepper motor to perform a step which is then not being realized by the stepper motor. Usually this occurs when the stepper motor does not provide enough torque to perform the step. Because the motor control system acts as if the step was performed the step ‘gets lost’.

More about the proper control of stepper motors is described in the software section 3.3.1. Another parameter which influences the level of detail, which can be achieved with a milling machine, is the *working tool diameter*. The *working tool diameter* especially defines how good sharp corners may be drilled.

3.2.8 Wiring

The complete electronic wiring without the Arduino Shield is shown in figure 3.16. The touchscreen and the keyboard are connected via the HDMI port and the USB ports to the Raspberry Pi development board (front-end device). The front-end also monitors the card holder's switch and the safety door's switch states, which are connected to the GPIO pins. Internal pull-up resistors are set on software side. Using the GPIOs the Pi also controls the auditory feedback of the beeper. The ATtiny85 functions as driver for the WS2812 LED stripe which can be set via its analog input pins (A1-A3).

The Arduino UNO (back-end device) controls the stepper motors, the rotary milling tool of the Proxxon MicroMOT 50 and the cooling fan. In addition, the limit switches as well as the safety door switch are connected to interrupt pins of the Arduino. Through the UART pins the back-end and front-end devices are able to communicate with each other. As the Arduino operates at 5 volts and the Raspberry Pi at 3.3 volts, the level adjustment circuit is used to ensure that the serial pins of the Pi receive a 3.3V signal and the Arduino UNO pins a 5V signal.

The developed Arduino UNO Shield implements the level adjustment circuit and replaces a lot of the required wirings. The schematic and board layouts of the GRBL compatible shield can also be found in the appendix A — "Arduino Shield – Schematic and Board Layouts". The control of the different devices is explained in the software section 3.3.6 — "Communication" (p. 62).

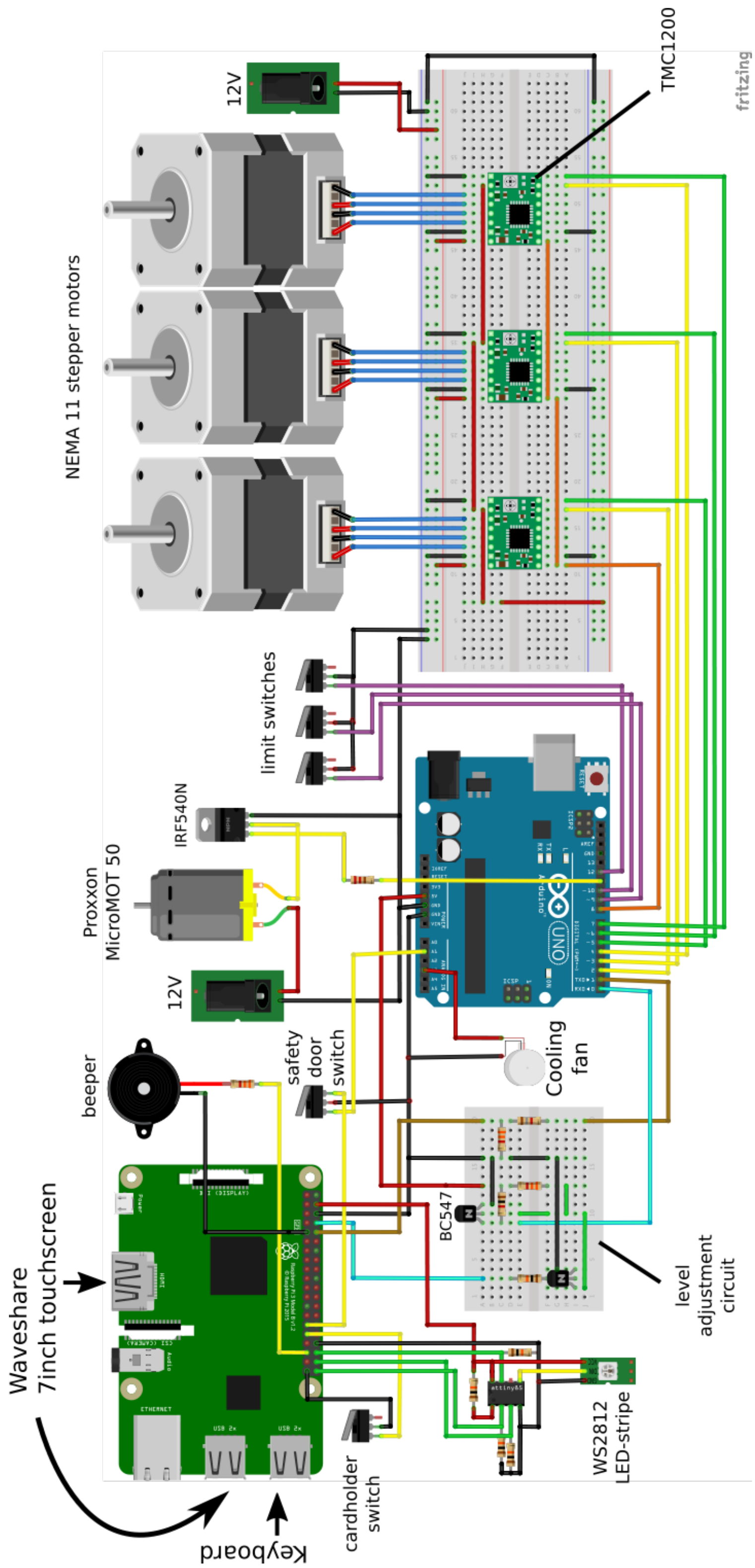

Figure 3.16: Electronic wiring without Arduino Shield

3.3 Software

In this section the different software implementations for the front-end and back-end devices are explained. At first, the requirements and implementations of the motor control system (back-end) are outlined, followed by a description of the developing process of the GUI application (front-end). While the GUI development focuses on the functionality and usability with respect to the user interaction, the communication and further implementations are discussed later on.

3.3.1 Motor Control System

The motor control system serves as back-end which is responsible for controlling the stepper motors and offering an interface for the front-end application. A separation between front-end and back-end device ensures an independent and accurate control of the movements on the linear motion system.

For this purpose the ATmega328P microcontroller of an Arduino UNO development can be used, which operates at 5 volts. As stepper motors usually require higher voltages to provide enough torque, stepper motor drivers are used to drive the motors independently. A stepper driver handles the proper control of the motor's phases to achieve a certain amount of rotational movement and also provides a way to limit their current draw. A rising edge at the step input pin of the driver causes a step of rotational movement in the direction being defined at another input pin. Therefore, a controller software was needed which runs on the ATmega328P and controls the stepper drivers to perform movements on the linear motion system.

As long as a movement only requires one motor to perform rotational steps, no accurate timing is strictly necessary. But as soon as more than one stepper motor is involved – for example to perform a movement on the XZ-plane – very precise timing is needed to accomplish a straight movement. To achieve real parallelism the counters, timers and prescalers of the ATmega328P were utilized to perform timed pulse-width modulation (PWM) signals for all three stepper motors. For this purpose, the PlatformIO IDE of the Atom editor was used. It offers a better project management and supports several microcontroller boards. This way simple linear movements could be accurately performed with the 3-axis of the linear motion system. However, when starting to perform high speed movements from a standing position the stepper motors require a higher torque which may not be provided. To overcome this problem, a common solution is to start at slow speed and accelerate to the high speed. This required a more complex acceleration management of the motor control software. Also many other functionalities would have to be focused on.

GRBL Configuration

GRBL, which is especially designed for the Arduino UNO board with the ATmega328p, implements the acceleration feature besides many other features for controlling a linear motion system. It takes advantage of timers and counters for accurate movements, uses external interrupts for the limit switches and offers a good configuration of all relevant parameters. Moreover, it offers an interface for the front-end device via a serial connection and interprets g-code commands. For further control of the linear motion system the the Arduino UNO was flashed with GRBL v0.9i (2.3.3 — "GRBL"). The safety door feature was enabled by defining the `ENABLE_SAFETY_DOOR_INPUT_PIN` constant in the configuration file.

Parameter	Description
$0=10	(step pulse, usec)
$1=25	(step idle delay, msec)
$2=0	(step port invert mask:00000000)
$3=0	(dir port invert mask:00000000)
$4=0	(step enable invert, bool)
$5=0	(limit pins invert, bool)
$6=0	(probe pin invert, bool)
$10=3	(status report mask:00000011)
$11=0.010	(junction deviation, mm)
$12=0.002	(arc tolerance, mm)
$13=0	(report inches, bool)
$20=1	(soft limits, bool)
$21=0	(hard limits, bool)
$22=1	(homing cycle, bool)
$23=7	(homing dir invert mask:00000111)
$24=250.000	(homing feed, mm/min)
$25=400.000	(homing seek, mm/min)
$26=250	(homing debounce, msec)
$27=1.000	(homing pull—off, mm)
$100=4000.000	(x, step/mm)
$101=4000.000	(y, step/mm)
$102=4000.000	(z, step/mm)
$110=500.000	(x max rate, mm/min)
$111=500.000	(y max rate, mm/min)
$112=500.000	(z max rate, mm/min)
$120=15.000	(x accel, mm/sec^2)
$121=15.000	(y accel, mm/sec^2)
$122=15.000	(z accel, mm/sec^2)
$130=90.000	(x max travel, mm)
$131=58.000	(y max travel, mm)
$132=20.000	(z max travel, mm)

Table 3.1: GRBL Configuration

In order to make GRBL work properly with the developed system, several parameters had to be adjusted using a serial connection. A list with the set parameters can be seen in table 3.1. Most crucial for a precise control of the linear motion system is the correct configuration of the 'step per millimeter' parameter. As mentioned earlier (see 3.2.7 — "Precision") a theoretical precision of

$$D_p = \frac{0.1125°}{360°} * 0.8mm = 0.00025mm$$

per step can be achieved with the built construction. Hence a value of

$$\frac{1.0mm}{0.00025mm/step} = 4000steps$$

per millimeter can be deduced for the configuration. The maximal feed rate of 500mm/min was roughly determined by testing different feed rates at which no step losses were detected. Furthermore, the `homing direction invert mask` was adjusted so that the movements were performed towards the limit switches and a successful homing cycle could be accomplished. With respect to the hardware no additional limit switches were intended to be used. Instead, the soft limits feature was enabled to prevent accidental overshooting of the axis limitations. In doing so GRBL would not exceed the bounds set by the `max travel` parameters.

3.3.2 GUI Application

The development process of the graphical user interface (GUI) ties in the fourth and fifth iteration of the hardware prototyping process (section 3.2.4). Main part of the user interaction was planned to be realized via the touchscreen and a keyboard. Therefore, an application had to be developed on software side which provided a user-friendly interface for the user-driven tasks.

In the following sections state charts are utilized to illustrate the functionality of the developed GUI application in a simplified form. Analogous to the hardware prototyping process the development followed the DIA cycle model by first collecting some requirements and then presenting the individual prototyping iterations as well as discussing their strength and weaknesses.

Requirements

Referring to the previous identified requirements in section 3.1 the *input of a name*, the *selection of a graphic* and *starting the engraving process* belonged to the essential functional requirements of the GUI application. A further suggestion was that the user should be able to undo any action or cancel non involving operations like the milling process. A very basic concept which would fulfill these minimal requirements was defined at an early stage and served as a starting point for the following GUI prototypes (figure 3.17).

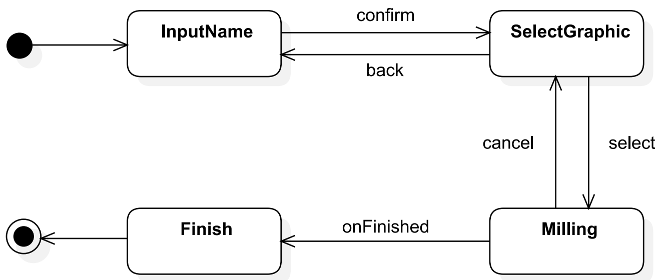

Figure 3.17: State chart of the minimal GUI functionality.

3.3.3 GUI Prototype One

The application was developed using the Java programming language and the NetBeans IDE. One advantage of the NetBeans IDE is the provided GUI editor which can be utilized to create GUI prototypes with little effort. This way the 'look and feel' of an user interface (UI) can be tested at an early stage of development with respect to the usability.

As a user should be guided through the manufacturing process step by step it was decided to prepare different views for each step consisting of their own UI elements. Java provides the GUI widget toolkit *Swing* which also offers a layout manager for organizing a container's components. By using a `CardLayout` the different views could be pre-

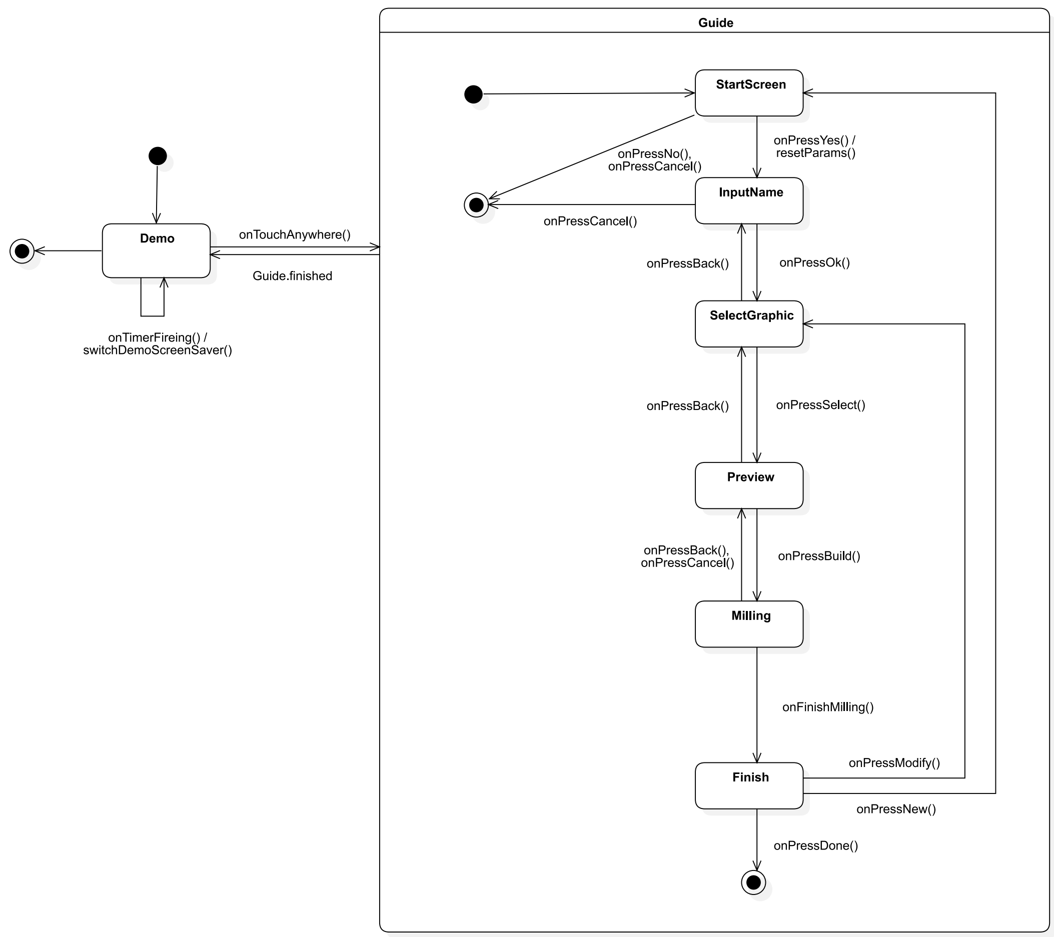

Figure 3.18: State chart of the initial GUI functionalities relevant for the user interaction.

pared with the help of `JPanel` objects. In doing so the `CardLayout` would afford switching between the different views, more specifically the panels which are acting in place of the 'cards', by using its providing methods.

For the first prototype it was considered that the device may be located in a fab lab or at an exhibition where it should also arouse the interest of visitors when not being in use. During this time a demo preview would inform the visitors about what they can do and how they can operate the device (figure 3.18). As multiple users should be able to operate the device one by one, the application would have to run in a loop which resets all settings at the beginning of each iteration. In order to provide the user with consistent feedback about her progress a top bar was implemented which shows all steps required to complete the manufacturing process and an indication of the currently active one. In addition, a preview was shown to the user before the milling process had begun. Only after a confirmation the machine would start engraving the workpiece. The user's name could be entered in a text field using the keyboard and afterwards hitting the return key or pressing an 'Ok' button on the touchscreen. In the graphic selection view a preview image of the current preselected graphic was shown and could be selected by pressing the 'Select' button on the touchscreen. Using two additional buttons the user was able to navigate through the set of predefined graphics.

Scalable Vector Graphics (SVG) files were preferred to be used for the intended application as the format is a common image format and provides a good basis to prepare 2D images for the intended milling job (see 2.3.5). Although it was decided to provide the user a fixed set of graphics, the implementation was intended to be designed flexible and extensible. The Apache™ Batik Project[2] offers a SVG toolkit which was used to extend native Java UI component and container classes like the `JPanel` class with the capability of displaying SVGs. Although the toolkit supports parsers and generators which simplify loading SVGs or generating fully new ones, image manipulation methods were not offered and the provided document object model (DOM) document object could not be modified directly. Therefore, a workaround had to be realized to afford the manipulation and export of SVGs. Helper classes were implemented which extended the batik `JSVGCanvas` class with common transformations like scaling, rotating and translating the image. A DOM document was loaded and the modified version was then manually written to a new file when using the new export method.

To engrave the selected graphic and the user's name on the workpiece both had to be embedded in a suitable layout, exported and converted to g-code (see 3.3.7 — "Milling Job Preparation") before it could finally be forwarded GRBL.

[2] https://xmlgraphics.apache.org/batik/

Discussion

The basic concept seemed to be good and simple to use. A user could provide all required input, undo prior decisions or cancel the interaction cycle. While the selection of a graphic was limited to the predefined set of SVG files, the name's textfield still allowed any input. As entering no name could cause a Division-by-Zero exception during the layout adjustment and the limited size of the workpiece would not allow long names, the name insertion had to be restricted. Although the prototype afforded canceling the milling process, this would only prevent the front-end application from sending further g-code instructions to the Arduino UNO. Because GRBL uses a look-ahead planner input buffer which stores multiple instructions the milling machine could still continue operating until all instructions were processed. A better solution could make use of special control commands or the safety door feature.

The implementation of SVG canvas components resulted in greater latencies when the UI appearance changed because the files were loaded and painted dynamically during the user interaction. Also other system internal operations like exporting and converting the layout were still bound to the UI thread leading to a bad responsiveness of the GUI during the interaction. Moreover, there was no feedback provided during the milling process which informed the user about the progress. This was also considered to be added in the next prototype.

3.3.4 GUI Prototype Two

The second software prototype made use of additional worker threads which would no longer block the UI thread during the milling job preparation or the milling process. Furthermore, all SVGs were now being loaded and painted beforehand. A loading screen was displayed during this process until the main loop could be entered. A whitelist was implemented in order to prevent unintended escape characters or special characters. Only words of a length between one and twenty consisting of letters and numbers

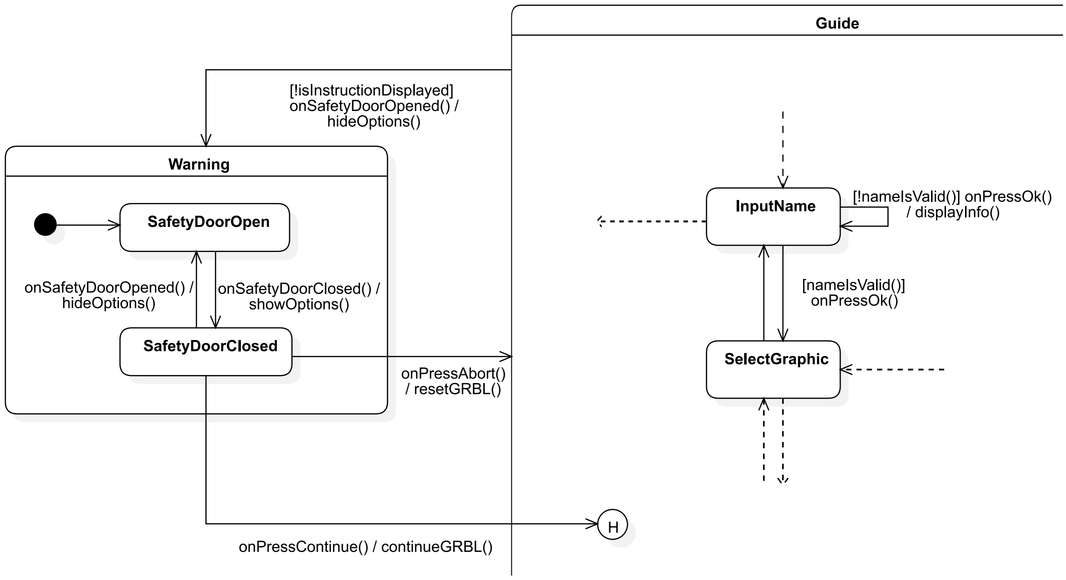

Figure 3.19: Incomplete state chart of the relevant GUI changes for the user interaction. Coordination of safety door opening and closing events (left). Name input validation check (right).

were allowed. The user could only proceed when a valid name was entered. An invalid name would cause a red info text to appear which informs the user about the restrictions of the name input. Moreover, a progress bar was implemented indicating the current milling progress.

At this point the hardware prototype provided an additional switch which simultaneously informed the front-end and the back-end device about the current safety door status. The internal handling and coordination of an safety-door-opened or safety-door-closed event is explained in greater detail the communication section 3.3.6. The user relevant changes of the GUI are shown in figure 3.19. The safety door would now interrupt the engraving process and halt the milling machine. A view then asks the user to close the door to proceed. After closing the door the user could decide whether he would like to continue or cancel the manufacturing process.

Figure 3.20: GUI screenshot of the initial question view.

Discussion

To get an impression about the 'look' of the GUI a screenshot can be seen in figure 3.20. The responsiveness of the GUI had been significantly improved and the safety door did now allow to interrupt the milling process immediately. This ensured that no user could get injured if the case had been opened. In addition, the machine could be stopped when any unexpected behavior occurred. As the progress bar indicator value was only set to the current instruction number in relation to the total number of all g-code instructions, a user could not estimate the remaining time with the aid of the progress bar. An improved version could consider the traveling time of the workpiece.

The insertion of a workpiece unveiled to be another problem. It was not clear when and how a blank card should be inserted. In particular, the card had to be pushed to the bottom of the card holder as it may otherwise move during the milling process. A test user did also mention that the modify option in the final view might not be that intuitive to understand because there was no information indicating what would be modified.

3.3.5 GUI Prototype Three

It was decided to completely remove the 'modify' option in the final view as only a little amount of information had to be provided by the user at all and the user could simply create a new card instead. The progress bar itself was not modified, but a label was now indicating the remaining time above the progress bar. The remaining time was roughly estimated beforehand as described in section 3.3.8. In order to resolve the card positioning problem the application did now check whether a card was inserted correctly before and removed after the milling process. This was realized using the switch placed at the bottom of the card holder (see 3.2.6). The user could not proceed until he had followed the instructions which were also displayed in the GUI (figure 3.21). As the touchscreen was mounted on top of the safety door which would be lifted during the insertion, it was not possible to provide the user immediate feedback when the correct card position was reached using the display device. Therefore, a beep should inform the user about the correct card insertion. As the color of the implemented led stripes could be easily controlled, it was also considered to provide the user additional feedback by a color change from yellow to white. Furthermore, red light was shown during the milling process which should not be disturbed and green light indicated the finished milling process. Also each button press event of the GUI did now trigger an auditory beep. More information about the visual and auditory control is given in section 3.3.6.

Discussion

The final prototype offered a less error-prone guide for the user interaction. The workpiece insertion worked without any problems and the auditory and visual feedback fulfilled its purpose. Screenshots of the different GUI can be found in the appendix D — "GUI Screenshots". An informal user study was conducted with children (see 4.1 — "User Study") which was considered for the final evaluation.

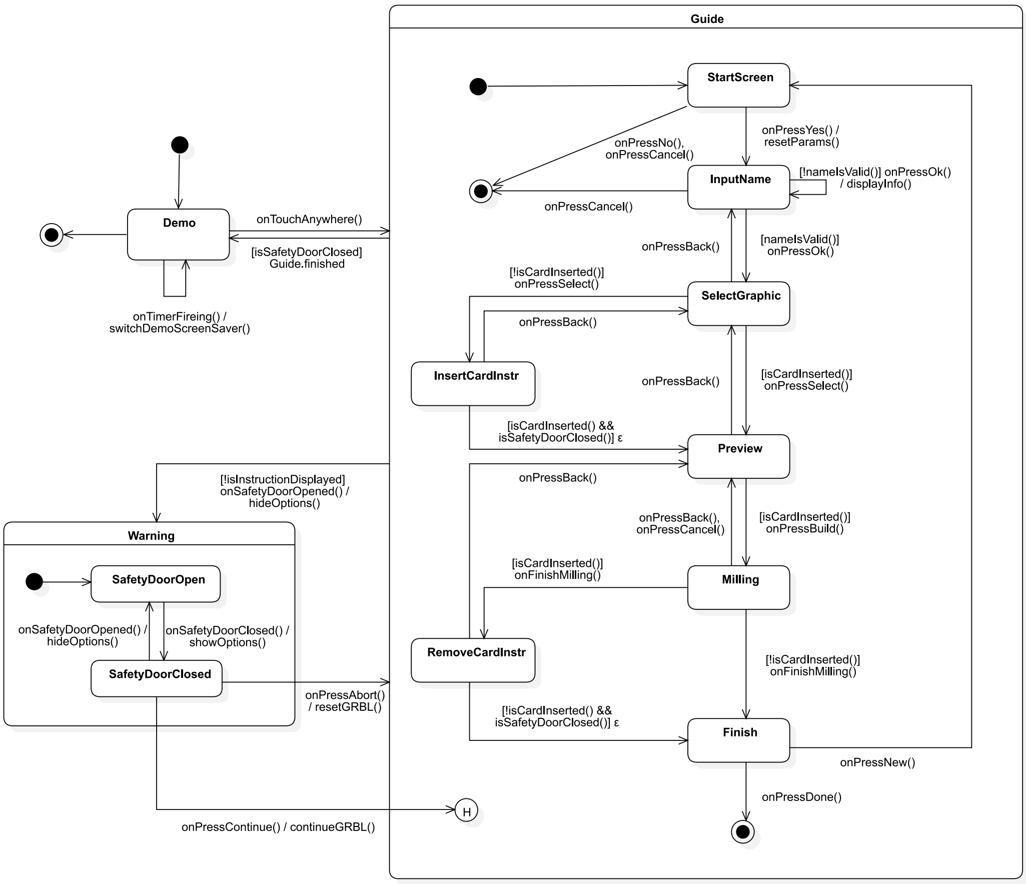

Figure 3.21: State chart of the final GUI functionality. The user is now forced to insert and remove the workpiece correctly.

3.3.6 Communication

The Raspberry Pi acts as central control device which offers a user interface on the one side, but also communicates with other devices connected to its GPIO pins. It monitors the current states of the safety door and card holder switches, controls additional feedback devices, such as the beeper and inner lighting and sends the milling jobs to the back-end device. In the following, their implementation into the java application is described by looking at their different software interfaces.

GRBL Interface

Two classes are responsible for realizing the communication with GRBL and controlling the milling system. The `GRBLSerialComm` class and the `GRBLController` class.

The `GRBLSerialComm` class establishes a serial connection between the Raspberry Pi and the Arduino UNO by using the jSSC-2.7.0 library[3]. The library provides a `SerialPort` object which offers basic methods to open a serial port and read or write to it. Using these methods the `GRBLSerialComm` class forwards G-code commands to the serial port and handles its receiving respond messages from GRBL. A G-code command is sent using the `sendGCode(String command, boolean blocking)` which returns a respond status for the sent message in form of an `enum` constant. The respond status may be either `RESPOND_MSG_OK`, `RESPOND_MSG_ERROR`, `RESPOND_MSG_ALARM`, `RESPOND_MSG_UNDEFINED` or `RESPOND_MSG_AWAITING`. The second argument defines whether it should be waited for a respond message (blocking) or not. For the latter case the `getLastRespondStatus()` can be used to retrieve the last respond status. If a `RESPOND_MSG_AWAITING` is retrieved no messages was received yet. A `RESPOND_MSG_OK` confirms an successfully interpreted command by GRBL. All other respond statuses indicate that a problem has occurred. In this case the last respond message can be retrieved by using the `getLastRespondMsg()` function.

The connection to the back-end device is established at the serial port (`/dev/ttyS0`) of the Raspberry Pi with a symbol rate of 115200 baud. After that a `GRBLController` can communicate with GRBL using the functions of the `GRBLSerialComm` class. An instance of the `GRBLController` class mainly prepares the mill, sends G-code jobs to the back-end and reports the current machine status. At start up, the milling machine is prepared using the `prepareMill()` method of an `GRBLController` instance. During the preparation,

[3]https://code.google.com/archive/p/java-simple-serial-connector/

GRBL is first instructed to perform a reset by sending the reset control code `ctl-X (0x18)`. Then a homing-cycle is performed using the homing command `$H`. After a successful homing-cycle a predefined sequence is send to GRBL in order to set several machine modes which ensure that GRBL processes future milling job commands correctly:

```
S1000
G17 G21 G91 G94
G0 X85 Y55
```

The first command simply advices the machine to operate the spindle at its maximum speed. Usually the `S` command is used to set the revolutions per minute (RPM) for the milling tool. As the spindle is only intended to be turned on or off and the default maximum rpm value is defined to be 1000 it is set to its maximum. The command sequence of the second line first selects the XY-plane for circular interpolations (`G17`). Because the milling job paths are prepared in millimeters using relative movements the machine has to be informed about this using the `G21` and `G91` commands. By using the `G94` command GRBL is instructed to interpret all received feed rate values in 'feedrate per minute'. Finally, the working tool is moved to an initial position from which the milling jobs should start using the rapid positioning command `G0`. As the milling jobs always start at the bottom left corner of the workpiece this allows to save some time.

Using the `addToJobList(SVGFile pathname)` method, SVG files can be added to the job list of a `GRBLController` instance. The SVG files are then converted to processable G-code as described in 3.3.7. After invoking the `startMilling()` method the prepared G-code instructions of the job file list are sent to the back-end.

Lighting

The lighting and all other devices, which are connected to the GPIO pins, are controlled by using the Pi4J library[4]. Pi4J offers an application programming interface (API) to easily control the GPIO pins of the Raspberry Pi in Java. For the lighting control the GPIO pins 27 to 29 (WiringPi pin number scheme[5]) are used as digital outputs in order to set the light mode at the ATtiny85. The ATtiny drives the WS2812 led stripe using the Adafruit NeoPixel library[6] and polls the state of pin A1 to A3 (Arduino pin numbering). This way a three bit information with eight possible states can be received. The mapping is defined as listed in the following:

```
#define MODE_DEMO           0b00000000
#define MODE_GREEN          0b00000010
#define MODE_YELLOW         0b00000100
#define MODE_RED            0b00000110
#define MODE_WHITE          0b00000001
#define MODE_BRIGHT_LOW     0b00000011
#define MODE_BRIGHT_MID     0b00000101
#define MODE_BRIGHT_HIGH    0b00000111
```

When the demo mode is activated the leds are fading between different colors. The next four modes can be used to set a fixed color of the led stripes. With the last three modes it is also possible to switch between three different brightness levels. The source code for the WS2812 driver is also linked in appendix E — "Source Code – WS2812 Driver".

Beeper

The beeper is connected to the GPIO 24 pin of the Raspberry Pi. As it is an analog beeper device the beep is generated by switching the beeper on and off with a certain frequency. For this purpose a PWM signal is used at the GPIO pin to generate a waveform with a desired frequency. In doing this, the beep signal generation also does not block

[4]http://pi4j.com/index.html
[5]http://pi4j.com/pins/model-3b-rev1.html
[6]https://github.com/adafruit/Adafruit_NeoPixel

the main thread of the application. After enabling the PWM signal a timer instance is created which disables the PWM signal after a desired beeping time.

Safety Door

Since GRBL v0.9i was released, a safety door feature is supported which automatically halts the machine as soon as the safety door input pin is 'pulled' to a low level. An internal pull-up resistor ensures that the pin is set to a high level by default. As soon as the safety door is opened, the safety door switch is released and the input pin is pulled down. This way GRBL detects an safety door opened event, halts the milling machine and enters the safety door alert mode. The working process is then only continued if the safety door was closed again and GRBL receives a ~`(0x7E)` over the serial connection. Therefore, the GUI application needs to be notified about the opening and closing events and has to instruct GRBL to continue the milling process. Instead of polling the GRBL status via the serial connection it was decided to connect the safety door switch to the Raspberry Pi, too. This way the Pi also detects the safety door events. If the door was closed again and the user wishes to continue the Raspberry Pi sends the corresponding control code to GRBL. Otherwise, GRBL will be reset and the mill will be prepared again.

3.3.7 Milling Job Preparation

In order to engrave the acrylic name tag a job has to be prepared in form of g-code which is then forwarded to the back-end and interpreted by GRBL.

Layout and Export

At first the name and the selected graphic need to be scaled and arranged to fit the card layout. As normal SVG text

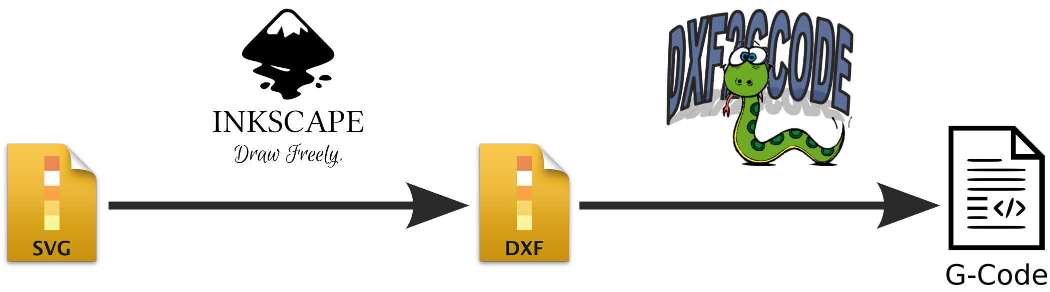

Figure 3.22: Conversion from SVG to DXF to G-Code using Inkscape and dxf2gcode python scripts.

elements do not contain any path information which is required for the milling process, the name has to be transformed into a set of paths. Inkscape[7] is an open-source image processing application which allows doing this by using the command line options `--export-text-to-path -D --export-plain-svg`. After transforming the text to path both files need to be merged and arranged correctly. Therefore, a new SVG document is created with a prepared skeleton of the card layout. The path elements of the graphic and text files are each embedded into a group object and added to the SVG content. By setting the `transform` attribute of the group element the text and graphic are scaled and translated properly. Finally, the prepared SVG document is exported and ready to be converted to g-code.

Conversion

While many CAM-Software applications support the DXF file format and offer open-source solutions to convert DXF files to g-code, SVG files are not widely supported. An existing solution of an open-source project 'svg2gcode' which offers converting SVG files to g-code was tested but during the conversion of several test files errors were occurring. Because of this it was decided to write a short bash script which would offer a workaround by first converting the SVG file to DXF and then from DXF to g-code (figure 3.22).

[7] https://inkscape.org/en/doc/inkscape-man.html

The conversion from SVG to DXF is realized by using the python export script from Inkscape (GPLv2). To convert the resulting DXF file to interpretable g-code, the dxf2gcode CAM-Software (GPLv3) is utilized which usually provides an additional GUI. The application also offers several export-options to configure the final g-code job. Most important configurations which had to be done were setting the appropriate feed rate for movements during the milling process and setting the depth at which the milling process should begin. By defining a starting depth, an end depth as well as a slice depth, the job can be split into multiple layers with an increasing depth. This is especially useful for engraving and cutting more robust materials which require multiple iterations of processing.

3.3.8 Time Calculation

The implemented time calculation is very basic and simple. Before each engraving process the G-code file is analyzed and scanned for explicit motion instructions like rapid positioning `G0` or interpolated movements `G1, G2, G3`. While the rapid positioning feed rate is known previously and passed to the time calculation function, the interpolation feed rate may be set during the milling process and needs to be tracked by scanning for `F` commands. Currently, circular interpolations of `G2 (clockwise)` and `G3 (counterclockwise)` motion commands are treated like linear interpolations commands `G1`. This may lead to quite inaccurate time predictions in some cases, but is at least sufficient to roughly estimate the required milling time. For each motion command the relative distance to the target position is calculated by using the Pythagorean theorem. By dividing the distance by the corresponding feed rate the time which is needed for the linear movement can be obtained. The sum of all individual required times finally returns the total amount of time needed for the whole milling job.

3.3.9 Language

As the device is intended to be used at different locations, including exhibitions where the users may prefer a different language for the user interface, the text of all UI elements is set dynamically at the beginning of the GUI application. The language which is loaded from the `resources/lang` resource bundle is defined by the default locale of the current JVM. The locale can also be set by using the `-Duser.country` and `-Duser.language` parameters when executing the application. This way the language can be easily adjusted or new languages can be added dynamically without altering the source code.

Chapter 4

Evaluation

This chapter covers an informal user study which was conducted in order to verify the effective usability of the developed system from the last chapter. Finally, it is discussed whether and to what extent the initially defined requirements from 3.1 — "Requirements Analysis" (p. 25) are met by the final prototype.

4.1 User Study

In order to evaluate the final design an informal user study was conducted within a children workshop. Part of the workshop was a short excursion to the Fab Lab Aachen where the children were able to explore the laboratory and its providing fabrication technologies. This was an opportunity to test the developed device under natural conditions in one of its purposed environments. The target group consisted of school children at the age of 8 to 11. The evaluation was based on the observation of the users which were operating the device. Questionnaires were prepared previously, but because the children were very low aged and the visitors only had a limited amount of time to explore the fab lab it was decided to keep the evaluation informal and at a verbal level.

In total 23 children, divided into three groups, were guided to the fab lab one by one. During their exploration they were asked to try out the developed device in order to create their individual illuminated name tags. They were told not to blame themselves for any mistakes and to try to operate the device on their own without any help. Help was only provided when problems occurred or questions arose. Because of the limited amount of time it was decided to make additional name tags using the laser cutter. The laser cutter afforded to make multiple name tags at the same time and ensured that every child could have one at the end of the excursion. While the children were allowed to take home the name tags produced by the laser cutter, the ones produced by the developed CNC milling machine had to be left back in the fab lab for fairness reasons. Moreover, each card produced by the laser cutter did have the same graphic and only the names of the children were used to personalize the tags. During the children's exploration time, nine name tags were created using the machine whereof one was faulty because a physically wrong dimensioned card had been offered to the children. To the main tasks of operating the developed CNC machine belonged the following:

- Navigating through the guided application. (touchscreen)
- Enter a name. (keyboard)
- Select a graphic out of a set of 26 different graphics. (touchscreen)
- Insert a card. (involves opening/closing the case)
- Confirm and trigger the execution. (touchscreen)
- Removing the card. (involves opening/closing the case)

Assembling the electronic circuit on the name tags did not belong to the observation process.

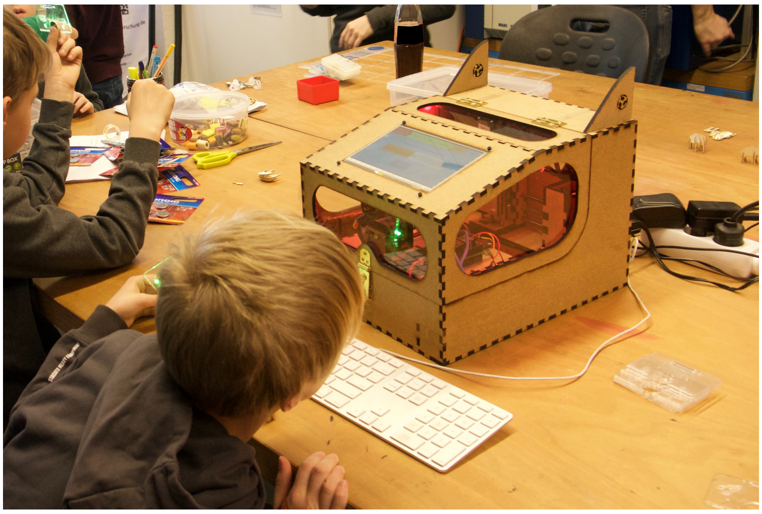

Figure 4.1: A child watching a name tag being fabricated.

4.1.1 Observations

Overall, the children did have great success operating the device and seemed to be very interested. Even though they were told that they were not allowed to take the name tags at home and that not enough time was left to let everyone operate the machine, they did ask for creating one with the help of the developed device. Most children also watched attentively how their name tags were manufactured by the mill (Figure 4.1). In addition, they showed to be very excited about the results. Asking a child about how satisfied she is regarding the final outcome compared to the intended outcome was answered by 'Very. This is really awesome!'. Children which observed other ones using the device did operate the device more confidently afterwards because they could define their goals more clearly beforehand. Observing the behavior of the first children of a group therefore was important as the following participants could adapt their behavior. While the first child in the first group was very shy and needed some initial explanation, the first children of the second and third group were able to create their name tags without any prior help or instructions.

During the observation of all three groups a few problems were still noticed. Some of those can be reduced to design issues, others may be related to the low age of the children or their differing intentions. With regard to the latter especially two children did not seem to be reading the labels and instructions displayed on the touchscreen. They simply aimed for buttons in order to go on and skip inserting their names or selecting an individual graphic. This lead to the assumption that they did only want to observe the mill working on the card. As entering no name at all prompted an info message to appear which explained why one could not proceed, they adapted and inserted a name. However, concerning the selection of a graphic a preselected one was initially offered to the user which could be confirmed without looking at further graphics. A girl who was asked why she did not have a look at other graphics answered that she did just want exactly that graphic she had seen before on a name tag laying next to the mill. At the beginning, one child did not notice that the touchscreen had to be used in order to perform actions with the GUI. An indicator for the touchscreen was considered in the demo views, but as the children's starting point was the initial question view there were no indications to use a touchscreen. Another one inserted his card upside down into the card-holder. Again this was not necessarily a fault by the child; there were no concrete instructions or physical constrains which offered information about how the card should be inserted with regard to this. Nevertheless, all of the other children inserted the card the right way. One participant was not sure about whether and how she should open the case for inserting a card. She did already have the right idea but preferred to ask whether the idea might be right before going ahead.

Unlike prior apprehensions that the children might have problems inserting the card and moving it to the correct position all children quickly figured out what the right position was. Only one child did have to correct the position before the application allowed her to proceed. Obviously the instructions were clear enough and the auditory feedback of the beeper combined with the visual color change of the lighting was intuitively perceived as a confirmation for the correct positioning by the children. The lighting also showed to be a great indicator for indicating

Figure 4.2: Four name tags manufactured by the children.

the completion of the milling process. Observing the communication between the children unveiled that some children did not want to wait for the mill getting back in the starting position after successfully engraving the name and the graphic. The red light however seemed to be a good 'work in progress' indication so that they preferred to keep waiting for a feedback of the device. The final color change to green was again intuitively interpreted as a confirmation of the finished working process and that they were now allowed to take out their name tag.

4.1.2 Results

The study has proven that the developed device can be successfully operated by novice users like children in a safe and self-directed way. The design also showed to be sufficient enough in order to produce satisfying results. Some of them can be seen in figure 4.2. Nevertheless, the observations also unveiled some problems from which several possible minor design improvements may be derived. These are also discussed in 5.2 — "Future Work" among other things. A general drawback showed to be that only one child could operate the device at once and this way only one name tag could be manufactured at the same time.

4.2 Requirements Verification

The initial goal of developing a laser cutter device was rejected and a milling machine was built instead. In order to estimate the quality of the complete system, the non-functional requirements, which were collected in 3.1 — "Requirements Analysis" (p. 25), are evaluated with respect to the devices functionalities.

4.2.1 Process improvement

Regarding the raw fabrication time and throughput, the 40W laser cutter from the 'Fab Lab Aachen' still performs better. However, the user study showed that the developed device clearly more attracts children and arouses greater interest of the visitors than the prior process involving the laser cutter. Particularly this appears to be accredited to the fact that users can perform all required actions on their own, leading to a greater involvement of the individual user.

4.2.2 Usability

The user study showed that the developed device offers an overall *intuitive* and *user-friendly* user interface as most children were able to operate the device without further help. The user interaction, which was designed to guide the user through all necessary steps, and the implemented constraints showed to be beneficial to the usability. However, it was noticed that more specific instructions or constrains could be used to prevent inserting a blank card upside down. Also explicit signifiers could inform the user about how and when to open the safety door. The implemented *feedback* unveils to be helpful and not to be annoying for the user. Especially the visual and auditory feedback showed to be beneficial for the card insertion task during the user study. The progress bar and top bar offer a consistent feedback about the current progress. Furthermore, they increase the *predictability* of the system. It was recognized that the 'back' and 'cancel' button which is placed at the top-left in the top bar introduces some lack of *consistency*, as all other interactive UI elements are placed in the panel below. As most internal operations which require longer time are performed in worker threads which are separated from the main UI-thread, a good *responsiveness* of the GUI application is ensured during the entire interaction. Nevertheless, it was observed that the delay between action and response sometimes varies and can exceed the limit of 100 milliseconds which may lead to a causality breakdown between action and response. This may be related to the limited resources of the Raspberry Pi and running the GUI in the Java Runtime Environment (JRE). Ensuring to meet the reaction time of 100 milliseconds could further improve the responsiveness and create a smoother perception of the interaction.

4.2.3 Safety

The developed milling machine is adjusted to engrave acrylic name tags and the ensuing torques are therefore much lower as the ones used in traditional milling machines. As the mechanical milling process is encapsulated in a case and the implemented safety features prevent the user from touching the mechanical milling system during the working process, the device unveils to be quite safe. No safety concerns arose during the whole user study.

4.2.4 Stability and Accuracy

The engraved results show that the machine can perform sufficient accurate results for the intended application using the final prototype. Although, some minor deviations are visible on the engraved name tags (figure 4.2). Especially negative movements of the z-axis appear to cause these very slight deviations. Using a more steady and robust construction could prevent these from occurring. However, in general the construction seems to be strong enough to withstand multiple operations and it could not be detected that the quality of the engraved name tags did change over time.

4.2.5 Observability

The translucent windows allow observing the milling process from different perspectives and the lighting offers a better visual perception of the device's inner operation. However, the front view is partly obscured by the milling tool and the touchscreen covers a larger area of the case which might provide a more appropriate view of the engraving process instead.

4.2.6 Mobility

Being a light-weight and compact stand-alone device with an outer dimension of 230 (height) x 275 (width) x 330 (length) millimeters, the apparatus is portable and can be deployed at different places of use. The safety door can be locked and the case protects the inner components during the transportation. Moreover, the safety-door stands on top of the case are easily unmountable. Nevertheless, no handles were designed which could afford carrying the device more easily.

4.2.7 Do-It-Yourself

The device was built in the Fab Lab Aachen and should also be buildable in any other fab lab. Besides a soldering nozzle mainly the laser cutter and the PCB machine were used as fabrication machines. In addition, most materials which are required for building the device can be found inside a fab lab. The parts which had to be purchased are listed in the table 4.1 below. The Arduino Shield schematics, the CAD files and software can also be found in the appendix.

4.2.8 Affordability

Many parts required for building the device can be found in a fab lab. Screws, nuts, wires as well as the beeper, the ATtiny85 and other parts were taken from the equipment provided by the Fab Lab Aachen. The price resulting from the parts which had to be purchased externally is about $260 as shown in table 4.1. Not included are the material costs for the MDF and Plexiglas sheets, the keyboard, beeper, ATtiny85 and the WS2812 led stripes. Also the power supplies which were disassembled from unused devices are not considered. While some pieces of hardware like the 7inch touchscreen are quite expensive and may be replaced by less cost intensive parts, the linear motion system consisting of leadscrews, metal rods, sleeve bearings and the stepper motors unveils to be quite cheap.

Material	**Price**
1x Raspberry Pi 3 Model B	$40.13
1x Arduino UNO R3	$21.35
1x Waveshare 7inch Touchscreen	$68.99
3x Nema 11 Bipolar Stepper Motors	$36.18
3x SilentStepStick drivers	$42.48
1x Proxxon MicroMOT 50	$24.56
Leadscrews, metal rods, bearings	$25.00
Total	**$258.69**

Table 4.1: Cost Calculation

As the device is adjusted for the creation of name tags and offers a front-end with a graphical user interface, it is hardly comparable to the devices presented from related work with regard to the affordability. However, as its cost level is close to one of the 'Portable Mini 3-Axis CNC Laser Cutter' from Al Habsi and Rameshkumar [2016] (~$392) and the '3W Arduino based Laser Cutter' from FamousMods [2015] (~$300) it may be classified as an affordable low-cost device.

Chapter 5

Summary and Future Work

The thesis is concluded by reviewing the most important aspects and results from the previous chapters. In respect of these, some potential extensions and improvements of the developed system, as well as other possible investigations by future work are discussed.

5.1 Summary and Contributions

In this work, an easy-to-use stand-alone CNC milling machine was developed to enable novice users to design and built illuminated acrylic name tags. The motivation was to improve the prior process of the name tag creation at the Fab Lab Aachen and offer a user interaction which involves a user in the whole manufacturing process. In doing so, the interest of children and visitors should be aroused with regard to the personal fabrication technology. The development covered the design and implementation of a linear motion system, a back-end system to control the milling system and a user friendly GUI application. The initial goal of building a small laser engraving machine was discarded because of safety reasons and potentially high expenditures. Instead, a rotary drilling tool was decided to be used. The coordination of the back-end milling system was realized by using the free g-code interpreter GRBL running on an Arduino UNO development board. As front-end device a Raspberry Pi 3 Model B was integrated which runs the developed Java GUI application and offers an interface for several input and output devices, affording a more enhanced user interaction. The final evaluation which included an informal user study unveiled that the proposed device offers a quite intuitive user interface and can be operated by young aged children without prior instructions or help. Nevertheless, not all participants did operate the device without any problems and some potential design improvements were identified.

This work makes a proposal for an affordable DIY milling system which can be built in a fab lab and offers a user interface which allows novice users to get in touch with the personal fabrication technology by involving them in a practical application. The results of the user study show that this way children could gather first experiences with digital fabricators and their beneficial utilization, in a safe and self-directed way. The observations let assume that the integration of such personal fabrication devices into the educational process can be beneficial to younger generations of children. Practical applications show to offer a good opportunity to gather first experiences and arouse the interest of the children in this technology.

5.2 Future Work

The evaluation showed great interest by the children. To deepen the study about possible applications of personal fabrication in context of education, further investigations should be carried out. With respect to the developed device, several starting points for future work can be specified.

5.2.1 Structure

To improve the stability of the structure a more robust material than MDF could be used in future. In addition, the metal rods and leadscrew of the x-axis system may be placed at a higher position to afford more stability of the carrying z-axis component.

5.2.2 Observability

Further investigations could check whether the observability can be improved through using a different arrangement of the user interface or increasing the size of translucent surfaces.

5.2.3 Power Supply

Currently several different power supplies are being used. A better solution could make use of a single compact power supply inside the device which provides enough current to power all electronic components.

5.2.4 Raspberry Pi Shield

The wiring between the Raspberry Pi and the Arduino UNO could be replaced by using a Raspberry Pi shield which undertakes the task of the Arduino UNO. The RPi-FabScan-HAT[1] which was developed from Watterott for the new FabScan Pi (Lukas [2015]) offers a new shield which can be mounted on top of an Raspberry Pi. A similar shield may be developed which is compatible to the pin mapping of GRBL.

[1] https://github.com/watterott/RPi-FabScan-HAT

5.2.5 GUI Application

To improve the responsiveness of the GUI, the reaction time could be improved so that a response meets the 100 milliseconds limit of the human perception. From the evaluation of the user study several minor design improvements may be considered in future. For a better understanding of the possible ways of interaction an indicator could be integrated into the first question view which informs a user to use the touchscreen as input device. Furthermore, the user needs to be informed more precisely about how to insert a card so that the card can not be inserted upside down anymore. A physical constrain could additionally force the user to insert the card only in the correct way. Another indicator should inform the user how and when she has to open the case. A more intuitive signifier could also be utilized at the physical device.

5.2.6 Free Graphical Design

To provide users with more freedom regarding the graphical design of the name tags, a drawing tool could be implemented into the GUI application. Another attempt could offer an interface with which custom graphic files may be imported and implemented in an easy way.

5.2.7 Scalability

A general drawback unveiled to be the limited throughput. To ensure that more name tags can be created in a shorter period of time, different approaches may be considered. On one hand, the preparation and milling time could be reduced through an improved conversion method and a stronger working tool. On the other hand, more devices could be built which would afford multiple users designing a name tag at the same time. Instead of just building multiple individual devices as indicated in figure 5.1 (left), another solution may split up the design- and build task and offer a system which uses multiple clients for designing the

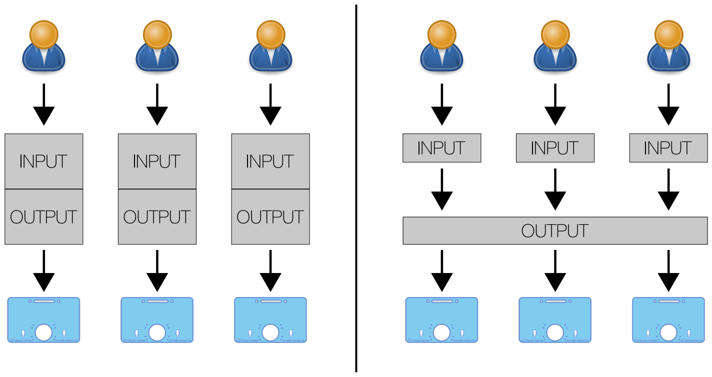

Figure 5.1: Two proposals for an increased throughput. (1) Multiple independent devices for each user (left). (2) Multiple clients and one back-end (right).

name tags. The milling jobs could be sent to a more powerful milling machine as back-end device which schedules them and engraves the name tags of all users (figure 5.1, right).

5.2.8 Name Tags

To afford other shapes of workpieces which can be inserted into the device, the card holder could be redesigned or an adapter could be developed which fits into the current card holder and can be plugged into it.

5.2.9 Card Insertion

The current prototype requires the user to open the safety door in order to insert a blank card. A more comfortable mechanism could be developed which affords inserting the card from the outside without having to open the safety door.

5.2.10 User Studies

Further user studies could be conducted in order to survey the educational impacts of such devices on children. A formal user study should prove the observations from the informally conducted user study of this work. It may also be interesting to conduct a study with another target group of users in order to receive additional feedback about the user interface.

Appendix A

Arduino Shield – Schematic and Board Layouts

The EAGLE files of the Arduino Shield schematic and board layouts are provided on CD-ROM and the newest version can also be downloaded from the GitHub repository below.

Arduino Shield – Schematic and Board Layouts[a]

[a] https://github.com/KniSmth/BadgeMaker-ArduinoUNOShield

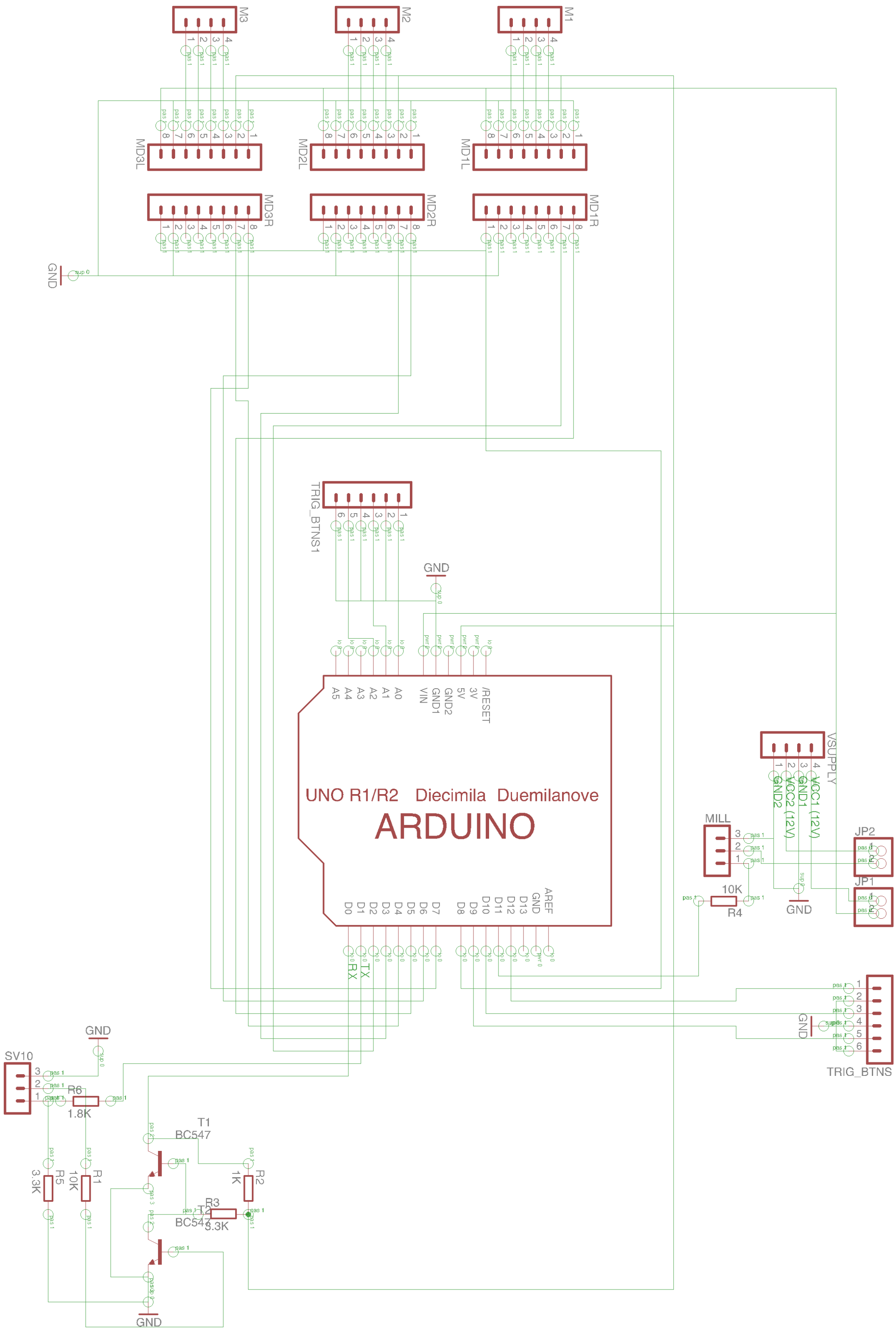

Figure A.1: Arduino Shield Schematic

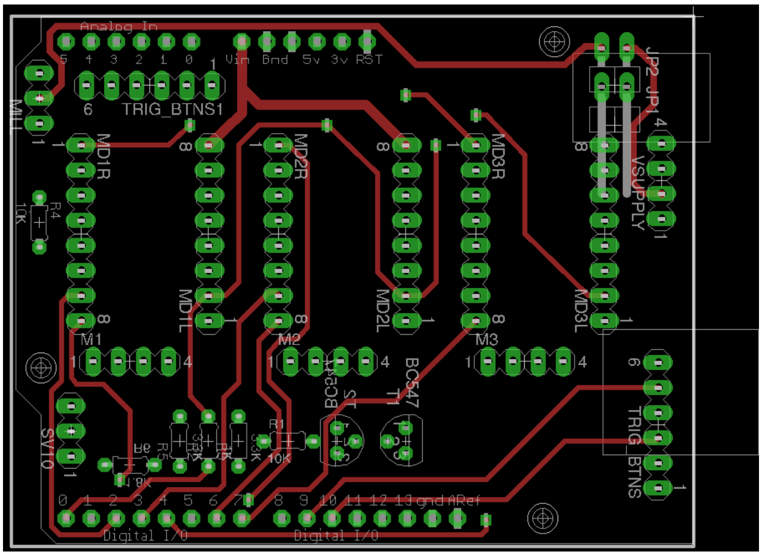

Figure A.2: Arduino Shield Board Layout Top

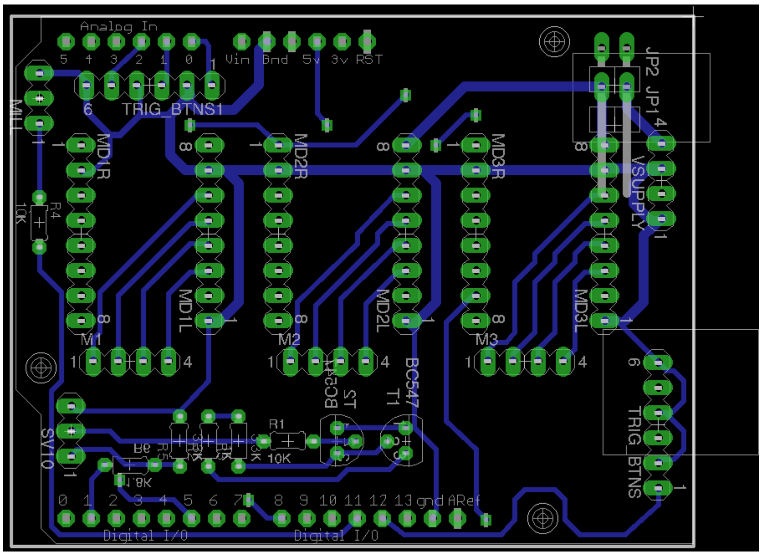

Figure A.3: Arduino Shield Board Layout Bottom

Appendix B

Construction – CAD Files

The CAD files for the construction are provided on CD-ROM and the newest version can also be downloaded from the GitHub repository below. The files are split into two folders: One for the linear motion system and one for the case.

Construction – CAD Files[a]

[a] https://github.com/KniSmth/BadgeMaker-CADFiles

Appendix C

Source Code – GUI Application

The source code of the Java GUI application is provided on CD-ROM and the latest version can also be downloaded from the GitHub repository below.

Software – GUI Application[a]

[a]https://github.com/KniSmth/BadgeMaker-FrontEndGUI

Appendix D

GUI Screenshots

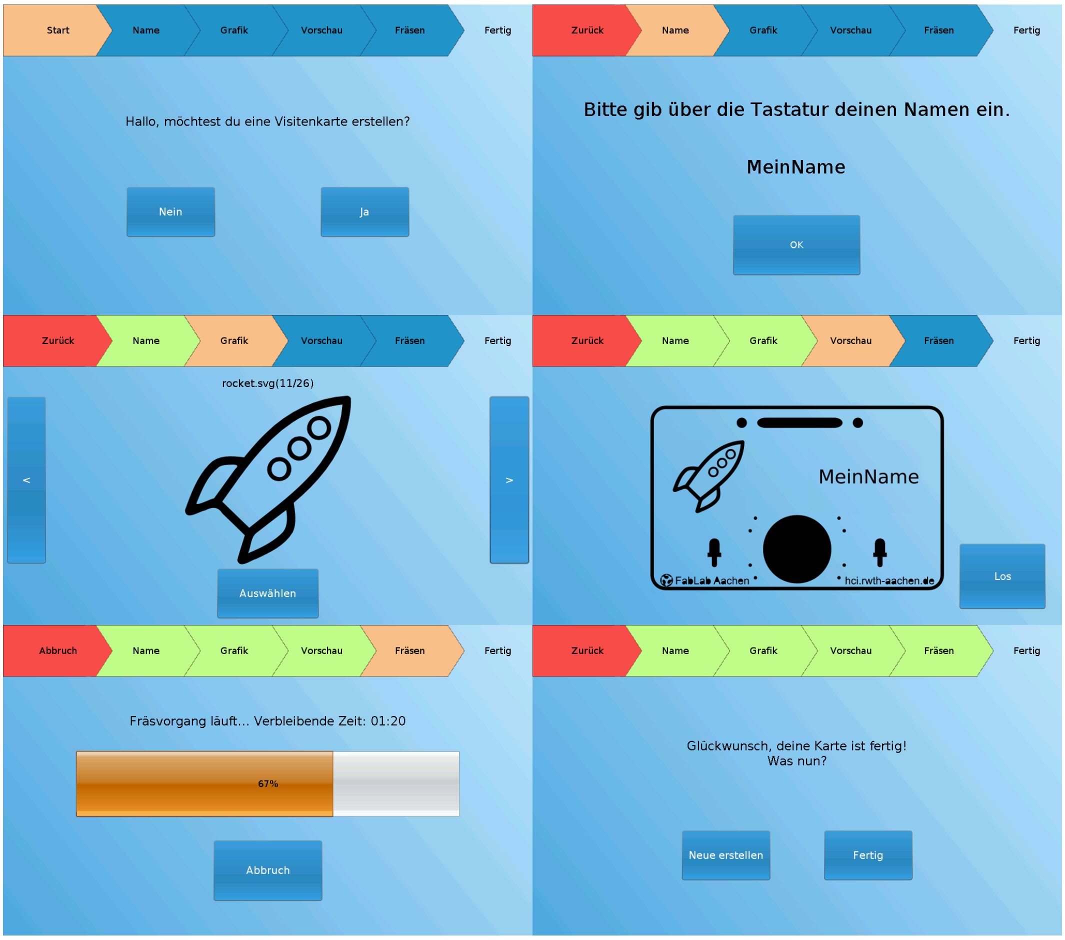

Figure D.1: GUI screenshots of the different manufacturing steps. (from left to right, from top to bottom)

Appendix E

Source Code – WS2812 Driver

The source code of the WS2812 driver (ATtiny85) is provided on CD-ROM and the latest version can also be downloaded from the GitHub repository below.

Source Code – WS2812 Driver[a]

[a] https://github.com/KniSmth/BadgeMaker-WS2812Driver

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