Digital Delft Blue

A new approach

MISCHA DE HAAN

Thank you
In front of you lies my master Thesis for the master Integrated Product Design. My final project at the Technical University of Delft, which consumed most of my time for the past 6 months. Luckily, I had a group of people around me who helped me through this process. Here, I want to say thanks.

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I am grateful that I could graduate on this topic and I hope you enjoy this thesis.

ABSTRACT

Royal Delft is the oldest manufacturer of delftware that is still producing Delft Blue using traditional techniques up to this day. At the core of their company lies the craftsmanship of producing delftware by hand, from creating the moulds to hand-painting each piece of Delft Blue. With a fast moving industry, Royal Delft needs to innovate constantly to keep their market presence. By modernising their designs and collaborating with external companies, they manage to create contemporary Delft Blue.

Apart from hand-painting and transfers, Royal Delft wanted to look for new possibilities to decorate delftware. Through a collaboration with TU Delft, a first prototype was made with a lot of potential, which let to this master thesis.

This thesis presents an improved design of a Delft Blue painting robot with a working demonstrator. This demonstrator is able to autonomously decorate tiles with different techniques, ranging from creating personalised anniversary tiles to gold lustering and painting large tableaus. The consistency of the painting robot is achieved by analysing the surface of each tile and adjusting the brush accordingly. The robot uses the traditional brush and paint as hand-painted delftware, meaning that the robot is able to change brushes and dip the paint automatically.

The benefit of this production method is the quick personalisation and cost efficiency compared to other production methods. As hand-painted products are easy to customise but very expensive, and transfer products require a large batch, robotic painting is a good alternative that is both easy to customise and affordable.

An attempt was made to expand the product range to 2.5D products, such as plates and dishes. After scanning the surface and writing the software to follow the surface, the results lacked consistency due to the accumulation of uncontrolled variables, making 2.5D painting not viable with this configuration.

Finally, a design was presented for implementing the robot into the Royal Delft production process. The concept was validated with a showcase product, a demonstration day in the museum and a discussion with the account managers of Royal Delft. The results were promising, and the robot could be a valuable addition to Royal Delft.

LIST OF ABBREVIATIONS

B2B
Business to business

B2C
Business to consumer

TRL
Technology readiness levels

DMF
Digital Manufacturing methods

CNC
Computer Numerical Controlled

NFT
Non-fungible token

INDEX

INTRODUCTION

PROJECT CONTEXT

In 2021, Royal Delft and Delft University of Technology collaborated on a project to see if new digital manufacturing techniques could be used in the production process used by Royal Delft. This Minor project focused on the possibilities of combining the traditional painting of Delft Blue with a robotic arm. The results of this project laid the basis of combining Royal Delfts craftsmanship with robotic painting. The team of students managed to paint different tiles with the use of a robot arm and a 3D printer and created a unique visual style that was suitable for the robot to paint.

The potential shown by these results were the motivation to start this project, to further develop the technique and use of painting Delft Blue digital manufacturing techniques.

ROYAL DELFT

Royal Delft is the oldest manufacturer of delftware that is still producing Delft Blue using traditional techniques up to this day. The company is located behind the TU Delft campus, aon the Rotterdamseweg, easily recognised by the large letters "De Porseleyne Fles" on the façade.

During this project, Royal Delft will have the role as a client, providing general information, knowledge about the topic and facilities for testing and creating Delft Blue products.

Figure 1: Building of Royal Delft, with their old name "De Porseleyne Fles" on the façade.

PROBLEM STATEMENT

The results of the previous project were promising and showed a lot of potential to bring value to Royal Delft. However, there were still a lot of issues that would have to be solved regarding the technology. The prototype did not have the consistency to autonomously paint tiles without interference of one of the team members.

While solving this problem is one of the main goals, there was also still a lot of improvement needed in the integration with the company. It is important to develop a valuable vision for a painting robot at Royal Delft. What is the purpose of the robot? Who will use it ? What will it paint and for who?

The aim of this graduation project is to answer these questions and to solve the problems with inconsistency. This leads to the assignment defined on the next page.

ASSIGNMENT

Develop a design direction for Digital Delft Blue, a Delft blue painting robot, by researching the technology, context, and stakeholders. To improve the consistency of the robot, the technology should be implemented and validated with a demonstrator.

APPROACH

The project will be divided into two phases. The goal of the first phase is to define a vision for the product based on technology, stakeholders and context, together with a plan to improve the feasibility of the product. These are covered in part I and II. The phase concludes with design drivers and a design direction to kick off the implementation phase.

The second phase, covered in parts III, IV and V, consists of further development of the chosen design direction. By implementing the chosen technology in a demonstrator, the results can be evaluated and recommendations can be done for further development of a painting robot at Royal Delft. Alongside the demonstrator, a design proposal is made which envisions the painting robot at Royal Delft with the new insights gathered from the evaluation of the demonstrator.

ANALYSES

LITERATURE   INTERNAL   EXTERNAL   TECHNOLOGY

**PART I
DISCOVER**

INSIGHTS

SWOT

CO-CREATION

DESIGN DRIVERS

**PART II
DEFINE**

IDEATION

DESIGN DIRECTION

LIST OF
REQUIREMENTS

USE CASE

EMBODIMENT

**PART III
EMBODIMENT**

SUB SYSTEM DESIGN

DEMONSTRATOR

VALIDATION AND EVALUATION

**PART IV
VALIDATION**

DESIRABILITY
CONSUMER
INTERACTION

FEASIBILITY
SHOWCASER

VIABILITY
DESIGN TEAM

CONCLUSION

**PART V
CONCLUSION**

FINAL DESIGN PROPOSAL
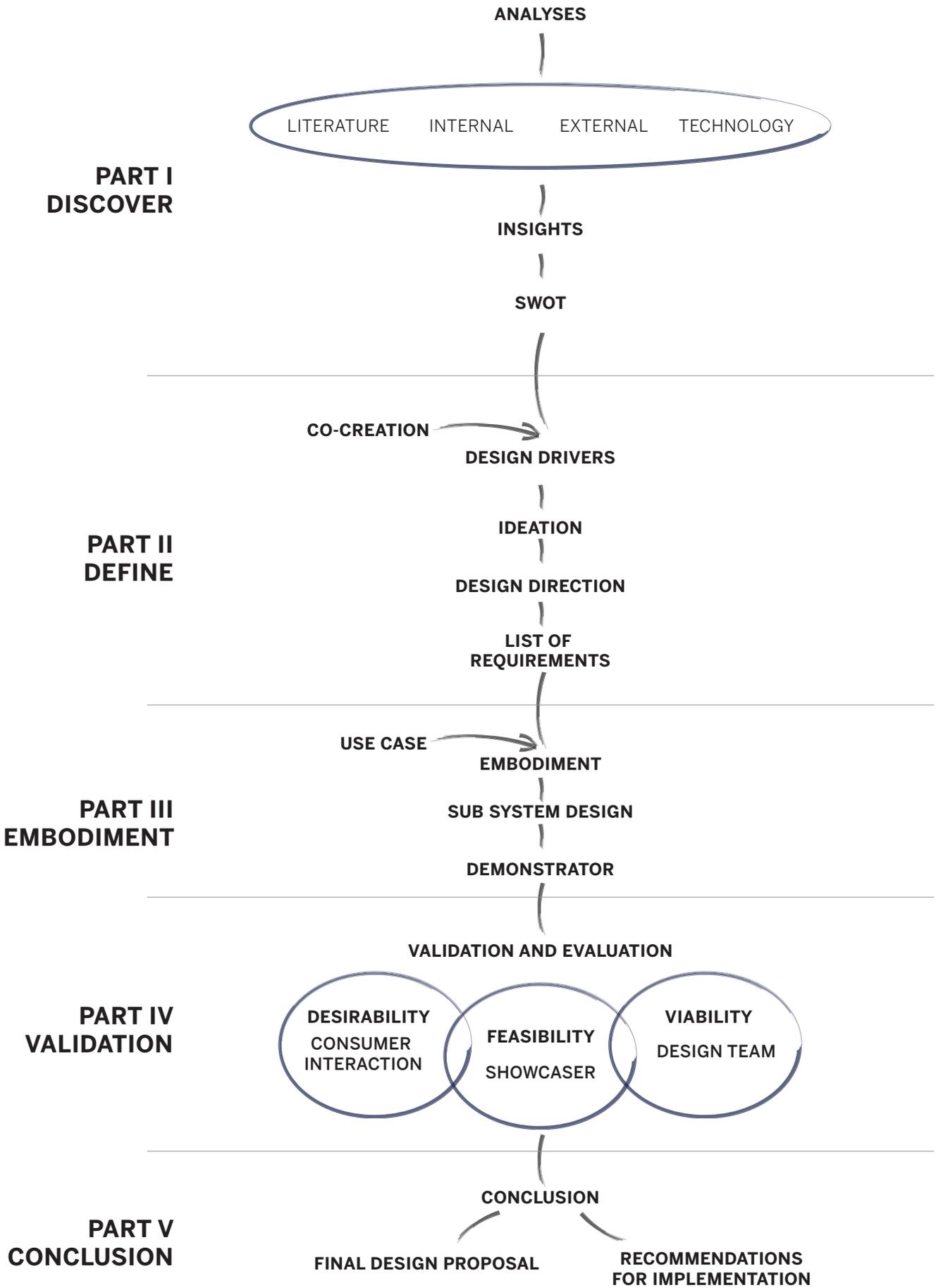
RECOMMENDATIONS
FOR IMPLEMENTATION

Figure 2: Approach used in this graduation
project

PART I DISCOVER

The goal of the first part is to gather as much information as possible from different directions and gather these into insights. With these insights a SWOT analysis is made to create a foundation for the upcoming parts.

CHAPTER 1
LITERATURE ANALYSIS

The literature analysis kicks off the analysis phase with understanding the research done in the development of craft and digital manufacturing methods.

Figure 3: Traditional craft - Handmade functional or decorative products that are physically shaped or decorated by the craftsman. Image retrieved from royaldelft.com

1.1 CRAFT AND DIGITAL MANUFACTURING

Within the scope of this project, the aim is to combine digital manufacturing methods with the old artisan craft of decorating ceramics. In literature, this development is discussed often with the term digital craft. This section researches the meaning and value of craft and explores the two distinct worlds of craft and digital manufacturing. It includes an overview of research done on this topic and how craft and digital manufacturing methods can add value to each other.

TRADITIONAL CRAFT

"The term "craft" denotes a skill, usually employed in branches of the decorative arts (e.g. ceramics), or in an associated artistic practice (e.g. lace-making)" (Ruskin & Morris, n.d.). Some of these traditional crafts are centuries old and still practised today. Delftware is an example of this, still made at Royal Delft. Their craftsmanship in ceramics dates back to the 17th century and apart from some innovations, the handmade production is still the same. The fact that it is handmade, is one of the core elements of traditional craft. With crafted objects, the production process becomes relevant to the viability of the product. "Consumers have a special appreciation for the human factor in production; hand-made products are perceived to be made with love by the craftsperson and even to contain love, and this perception is a significant contributor to the positive handmade effect on product attractiveness" (Norton, Mochon, and Ariely 2012). Although machinal production has the advantage of consistency, lower price and high precision (Liebl and Roy 2003; Markoff 2012), crafted products are associated with "more uniqueness, higher quality and more effortful to produce" (Yair, K., & Schwarz, M., 2011).
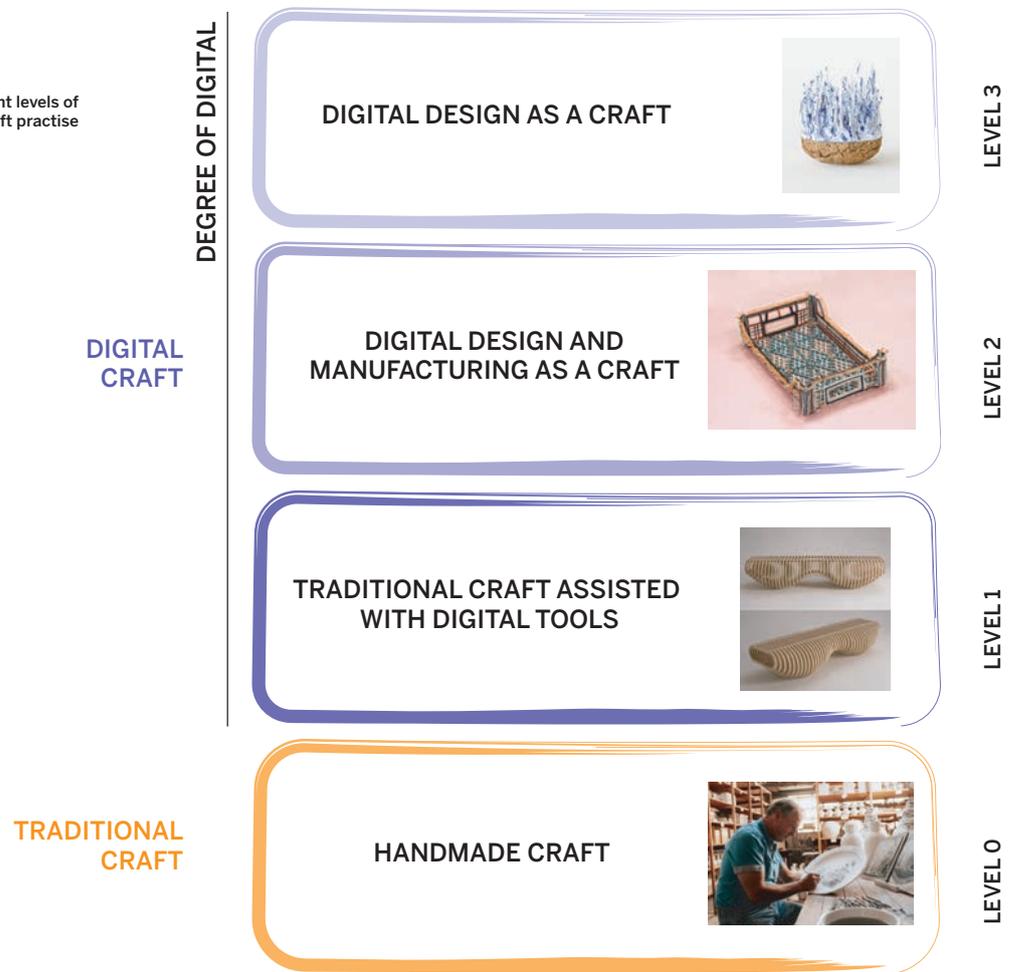
DEVELOPMENT OF CRAFT

Craftsmanship has been evolving over the years due to developments such as the third and fourth industrial revolution. Digital fabrication tools are accessible for craftspeople and not exclusively used in industrial production (Schwab, 2017; Song, 2021). The current definition of craft states that it is "skill and experience, especially in relation to making objects; a job or activity that needs skill and experience, or something produced using skill and experience" (Cambridge University Press, n.d.). One could argue whether something is still craft as digital methods take over. Dormer (1997) states that "it is not craft as 'handcraft' that defines contemporary craftsmanship: it is craft as knowledge that empowers a maker to take charge of technology." Based on this explanation, we could state that craft is defined as creating something that requires knowledge and skill rather than the physical interaction between craftspeople and material. The definition of the term craft therefore evolved from only encompassing handmade traditional fabrication methods

There is a lot of development where these digital tools enter the realm of craftsmanship. The use of digital tools in craftsmanship is often called *computer-aided craft, digital fabrication* or, the most common, *digital craft*. These developments can be distinguished by how far the integration of digital tools goes. Figure 4 shows an overview of the different levels in which digital tools are used in craft practice.

DEGREE OF DIGITAL

DIGITAL CRAFT

DIGITAL DESIGN AS A CRAFT — LEVEL 3

DIGITAL DESIGN AND MANUFACTURING AS A CRAFT — LEVEL 2

TRADITIONAL CRAFT ASSISTED WITH DIGITAL TOOLS — LEVEL 1

TRADITIONAL CRAFT

HANDMADE CRAFT — LEVEL 0

Level 1: Traditional craft assisted with digital tools

This method involves the practise of crafting with traditional tangible materials with the assistance of digital manufacturing tools. The most common technique is computer numerical controlled (CNC) machines used in woodworking, for example. The pros and cons of this assistance of digital tools are debated in literature: the loss of tactile contact vs. new freedoms of new design methodology and versatility of material output (Bottomly, et al., 2004). Apart from this mature method of implementing digital craft, there is also research done on new ways to involve digital tools in craft. These developments play with the tactile input of a craftsperson and transforms that to digital data. An intriguing example is the l'artisan Electronique, by Unfold & Knapen (2010). This project translates the hand gestures of a craftsperson to a digital 3D file that is printed when finished. However, the lost of intimacy with the material resulted in an undesirable experience (Wang, 2019). Another example is the research done by Hidekazu Saegusa et al. (2016) on mimetic machines. They tried to create new types of roles for digital manufacturing methods to collaborate with the craftsperson. This research is discussed later in this section.

Level 2: Digital design and manufacturing as a craft

This level of digitisation replaces the traditional materials and techniques with a fully digital work flow, where the craftsperson designs, prepares and creates the product using digital tools. With this type of craftsmanship, the emphasis lies on the knowledge of the craftsperson on implementing digital manufacturing methods to create a tangible and unique product. Additive manufacturing techniques are the most common, from 3D printing plastics to ceramics or metal. Zoran (2013) explored this method by reassembling a hand-crafted product with new parts that were made using digital tools. This research focused on artefact uniqueness, where the final product had the same artefacts and unique characteristics as traditional crafted products.

Another interesting research was done by Van Der Veen et al. (2019). Their goal was to explore and combine traditional materials and knowledge of a craftsperson with 3D printing wood. They concluded that active involvement and the senses in a fully automated process would start to shape new opportunities and possibilities, solving problems with a new point of view (Van Der Veen et al., 2019).

Level 3: Digital design as a craft

This final stage of digitising craft completely leaves the physical realm and solely focuses on the creation of a digital product. This is where computational craftsmanship and generated images are replacing the physical end-product. "The emergence of computation as a medium, rather than just a set of tools, suggests a growing correspondence between digital work and traditional craft" (McCullough, 1998). He describes the digital realm of craftsmanship, where "electric form-giving is described as a rewarding hands-on experience." With the rise of non-fungible tokens (NFTs), the fully digital craft practise became more relevant than ever. Digital images became more valuable than ever, and this resulted in a large increase and interest in this type of craft. An example is the Bread Prosthetics, by Zeitguised (figure 5). A fully digital piece of craft that represents traditional materials (ceramics) in a digital space. These pieces can only be bought as a digital copy, redefining the way how people look at the ownership of art and craft.

Figure 5: An example of level 3 of digital craft: Digital design as craft. This digital image has no physical element, but is created with the knowledge and skill of a digital craftsperson. Bread Prosthetics. Retrieved from zeitguised.com

DIGITAL CRAFT AT ROYAL DELFT

With the exploration into different developments of craft in literature, the next step is to place this project somewhere in these developments and find out how to approach this project based on the previous research. As this project focusses on the development of a digital tool for a hand-crafted product, the best position to place this would be between level 1 and level 2 of digitisation, as it is not clear how much this digital tool would replace the existing method.

Figure 6 shows an overview of different research topics in the physical space of digital craft. All papers can be divided between two different roles, for digital craft and the craftsman.

First, substituting the craftsman discusses creating technology that can create craft-like products. Here you see a lot of research and developments in painting robots and how to simulate the imperfections of a craftsman. It also covers more social questions about when something is completely made by a robot, does it still count as craft?

The other approach to digital craft in a physical space is creating tools to support the craftsman. This is shown as well with computer-aided craft, but by taking it a step further, where the craftsman has more creative freedom to influence the result. They are able to tweak parameters using their knowledge as a craftsman to create high quality products (Van der Veen, 2019).

Research in this approach searches for the division of roles between the craftsman and the tool, as shown in the figure.

THE VALUE OF COMBINING CRAFT WITH DIGITAL MANUFACTURING METHODS

The introduction of a painting robot at Royal Delft could be positioned within the digital craft development. It would fit in the described physical space. At this point in the project, it is not clear if the robot will be substituting or supporting the craftsmen at Royal Delft.

To understand which direction is the most valuable, it is important to consider where this project is developing from. As Royal Delft normally paint their ceramics by hand, the values of this hand-craft need to be considered and compared with the added values of digital manufacturing methods. This integration means that some values might be lost. The different values of both are described on the right.

Characteristics of traditional craft
- Uniqueness
- Quality
- Contains love
- Handmade
- Physical interaction with material

Characteristics of digital manufacturing
- Automation
- Easy customization
- Highly automated
- High investment
- High accuracy and repeatability

The goal of this integration is to try and create a solution that keeps the most values of both craft and digital manufacturing.

A robot can create uniqueness and high quality products. The painting robot should be able to create the same or even higher accuracy in paintings than the master painters. It should not strive for perfect repeatability, as it should show the uniqueness of every single product, just like in craftsmanship.

Aspects that are hard to add, are the handmade label and the 'love' crafted products contain. However, it would be best to strive for these values, by keeping the craftsman involved in the process.

Use the craftsman knowledge to adjust digital manufacturing parameters (Van der Veen, 2019)

Active involvement

Robot translating other movements

Robot connecting different inputs together

Robot imitating the craftsman

Different roles *(Saegusa, 2016)*

Interaction

How can craftsmen adapt to DM tools? *(Song, 2021) (Yair, 2011)*

Workshops   *Knowledge gap*

What do craftsmen think of DM tools? *(Song, 2021)*

Eager to learn   *Quality sometimes dissappointing*

Acceptance

Supporting the craftsman

DIGITAL CRAFT

Substituting the craftsman

Technology developments

Social developments

Reproduction through 3D scanning

Image processing (Scalera, 2019)

Painting on arbitrary surfaces (Song, n.d.)

Different painting techniques (Scalera, 2020)

When is something still craft?

A craftsman has to be involved for it to be craft.
A computer can be used as a tool.
(Nitsche, 2019)

Does a robot have creativity?

With the use of algorithms it is possible, although it is still a debate and topic of discussion
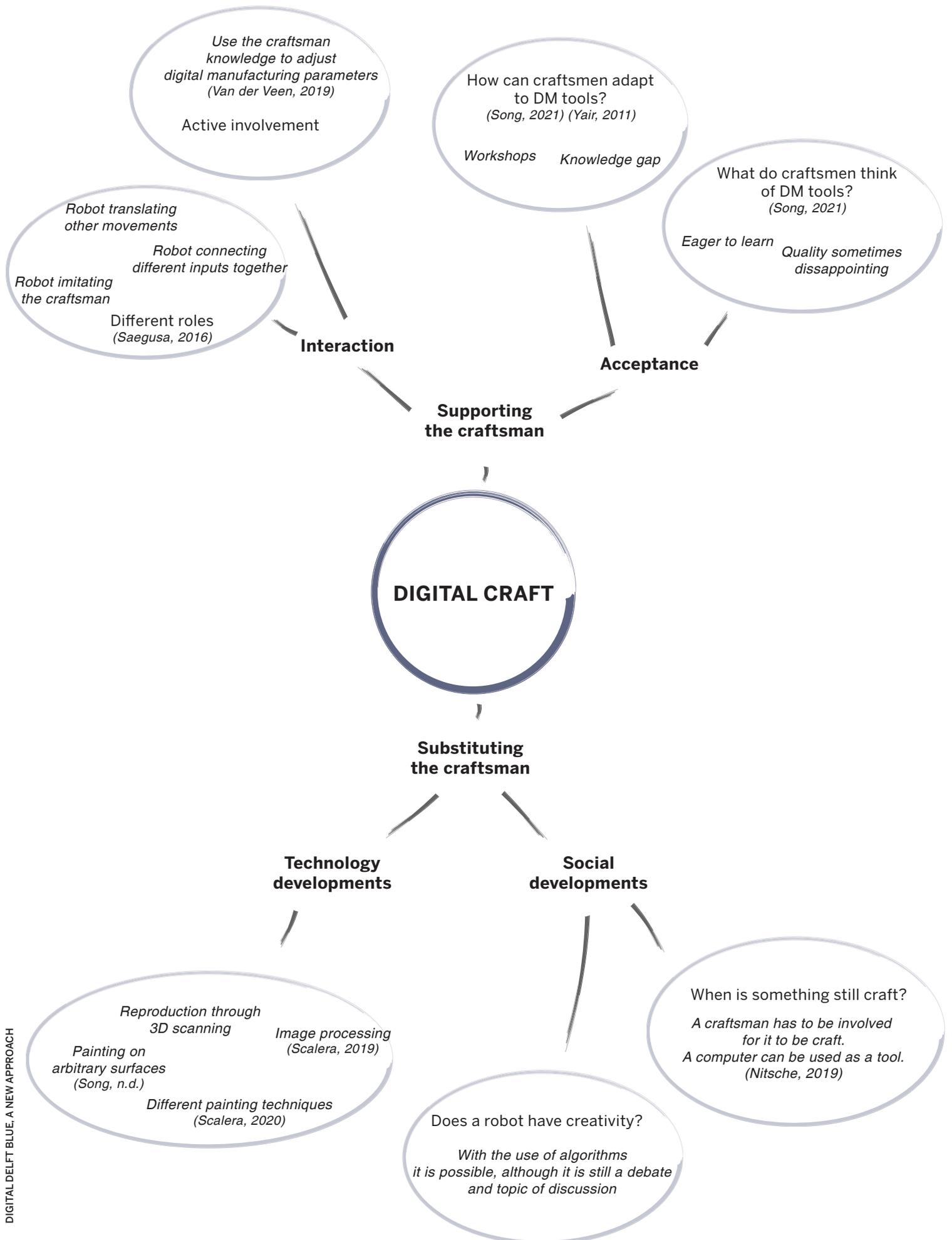
Figure 6: Overview of the different research topics in the second level of digital craft.

1.2 TRENDS IN TECHNOLOGY AND INDUSTRY

A lot of developments are happening in the world of technology, industry, and production. We are in the middle of a new industrial revolution, and consumer needs are changing fast. This section aims to explore the most important developments for Royal Delft and find opportunities for the solution space of this project.
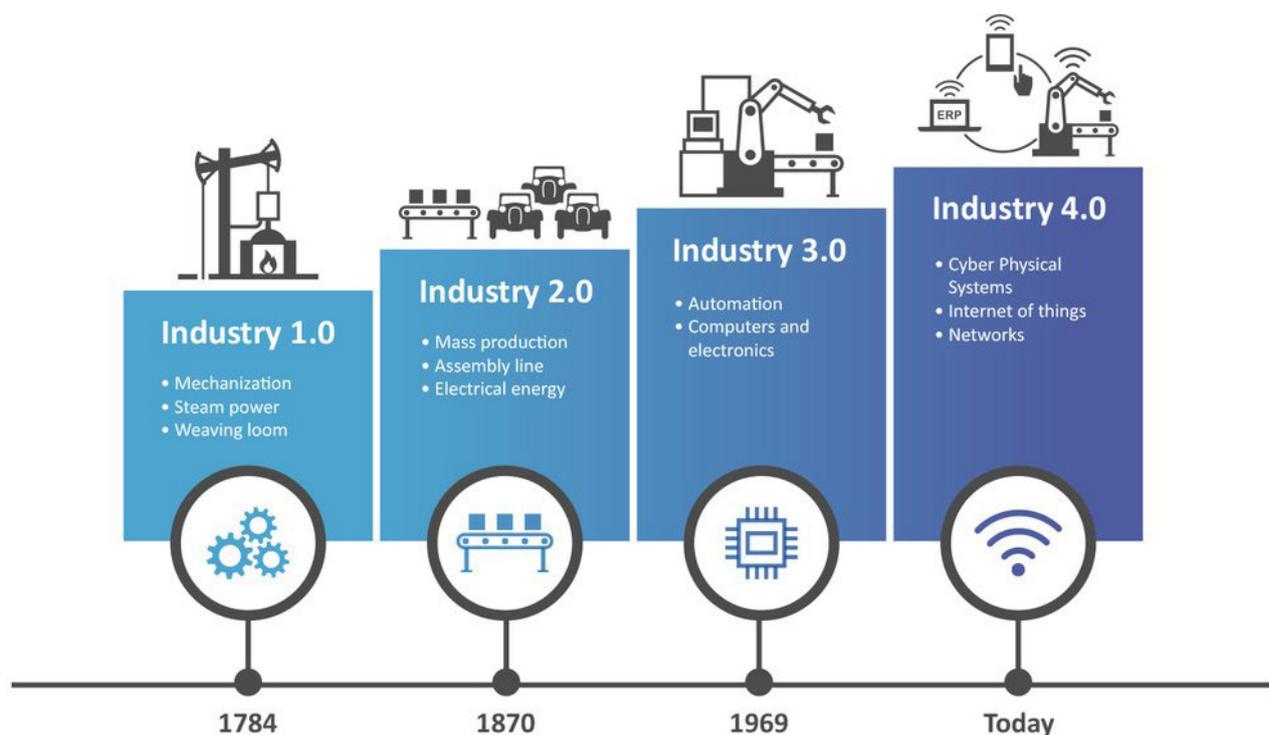

Figure 7: The four different industrial revolutions. Image retrieved from btelligent.com

FROM DIGITAL TO SMART: INDUSTRY 4.0

One of the largest technological developments we are currently in is the fourth industrial revolution. Where the third revolution developed the industry to a digital space, introducing digital manufacturing and robotisation, Industry 4.0 started a smart revolution. Digitalisation of production is developing rapidly, and all the stages in a production process are connected to communicate with each other and create smart factories.

The pillars of Industry 4.0
- Cyber-physical systems
- Digital twins
- Advanced digital manufacturing
- Autonomous robots
- Bespoke products

When we compare this to Royal Delft, which uses mostly traditional manufacturing techniques and only uses digital manufacturing methods in the design phase (3D printing prototypes and mock-ups), making the step towards Industry 4.0 might seem a bit too large. However, there are interesting pillars within the developments of this revolution that could be interesting for a traditional craft manufacturing company such as Royal Delft.

Industry 4.0 is one of the responses to the changing consumer habits, where individualisation and personalisation are some of the main drivers. As described in the previous chapter, Royal Delft provides a lot of customisation options, being one of their strengths. This overlapping feature could be interesting to further investigate.

ROBOTIC PAINTING

The developments in robotisation and automation reached the art community and resulted in the combination of robotic painting (Song, 2018). This new movement sparked the birth of large communities showcasing their developments in robotic painting. One example is the competition called robotart.org. Here, independent competitors can showcase their developments in robotic painting and contribute to the growing robotic art community. Another is the active Twitter community called '#plottertwitter' where community members use plotter machines to create generative art (Twigg-Smith, 2021).

Figure 9: image of #plottertwitter feed.

CHAPTER INSIGHTS

Literature shows a lot of development in painting robots and achieving creativity, but it lacks technological development in painting other than 2D surfaces. There is only one paper involving impedance measurements (Song, 2018).

Combining craft and digital manufacturing means combining both strengths. The solution should create unique, high quality products that are made with the help of a craftsman.

There is a knowledge gap between traditional craft and digital manufacturing, which often leads to disappointment.

The development and community around painting robots is growing, for both plotter-based robot as painting robots. It shows that it is a relevant topic. For drawing with other tools than pens, they often use a feedback system to control the quality of the result.

Figure 10: Inside the Royal Delft Museum shop, showcasing the collaboration with Schiffmacher.

CHAPTER 2
INTERNAL ANALYSIS
The internal analysis gathers insights from Royal Delft, by analysing their history, production technique, and product portfolio.

2.1 BRIEF HISTORY OF ROYAL DELFT

Royal Delft, once called De Porseleyne Fles, has a rich history which started in 1653 and later received the royal title. To better understand the context of a company with a centuries old history, it is important to cover their progression throughout these years.

THE ORIGIN OF DELFT BLUE

In the 17th century, Chinese porcelain was very popular in the Netherlands, especially the white porcelain with blue decor. When a shortage in supply was caused by civil wars in China, craftsmen in Delft started to create their own ver-sion of this porcelain. With the absence of white porcelain here in the Netherlands, they experimented with brown clay and white glaze to create a similar effect. Dozens of factories showed up in Delft to create this new version of Chinese porcelain. They started to create new decors with typical Dutch landscapes and icons such as windmills. This was the beginning of Delft Blue. In 1653, De Porseleyne Fles was founded. There were over 30 different factories creating Delft Blue at that time (Van Erkel, 2013). Now, only Royal Delft remains.

Figure 11: The hand-painted signature of Royal Delft products

PRODUCT DEVELOPMENT AT DE PORSELEYNE FLES

This was due to the fact that delftware, at that time, was out competed by other ceramic producers, such as the well-known British Wedgwood. With lower quality than the competition, the market for Delft Blue plummet and a lot of factories closed their doors in Delft.

A significant moment for De Porseleyne Fles was a radical change in the manufacturing process of Delft Blue. When Joost Thooft became the owner of the company in 1876, they reinvented the creation of Delft Blue. The brown clay was replaced with a new mixture, creating a lighter colour. The decorating of the delftware was done on the unglazed surface, and a final transparent glaze protects this decor, creating a much more durable product. This new method was the revival of De Porseleyne Fles. It sparked the ideas of creating different types of decor, such as polychrome. This revival is remembered until this day as the initials of Joost Thooft are part of the signature mark of Royal Delft (see figure 11). The mark shows a small jar, the initials J T, and the name Delft.

Figure 12: Historic image of De Porseleyne Fles. Retrieved from royaldelft.com

PRESENT

For the restoration of the fame of Delft Blue, De Porseleyne Fles was awarded the predicate "Royal" in 1919 as an appreciation. Jumping to 2008, the Royal Delft Group expanded by taking over Leerdam Crystal BV and Royal van Kempen & Begeer BV. Throughout their history, Royal Delft has produced many types of decoration next to the well-known Delft Blue. Currently, only Delft Blue and polychrome are made at Royal Delft. We do see a change in design language, where more contemporary designs are created together with external designers or surprising collaborations with famous artists and brands. This latest development is Royal Delfts method to always keep innovating and to stay relevant while also being true to their heritage.

2.2 THE ROYAL DELFT PRODUCTION PROCESS

This chapter dives into the Royal Delft production process. The production of Delft blue ceramics can be divided into two stages, creating the shape and decorating that shape.

The focus of this project lies on the second stage. Therefore, the decoration of Delft Blue will be analysed in more detail, covering different techniques. But first, the general process is described below.

MIXING MATERIALS
The raw materials are mixed. It's a composition of more than 10 different raw materials. The most important are feldspar, quartz, kaolin and chalk.

CASTING
The clay mixture is cast into moulds, made by Royal Delft. These moulds are made of plaster and extract the moisture from the clay mixture. They are emptied after a layer of clay has dried, leaving a hollow product.

FIRING
After removing the product from the mould and cleaning imperfections, the product is sprayed with a thin layer of liquid clay, called 'engobe'. Afterwards, the product is fired in a kiln at a temperature of 1160 degrees Celsius for 24 hours.

PAINTING
The biscuit is painted by one of the master painters at Royal Delft. Other techniques for decorating the biscuit are explained later in this chapter.

GLAZING AND FIRING
A layer of clear glaze is applied on the painted product. Then, it is fired again in a kiln for another 24 hours at 1200 degrees Celsius.

QUALITY CONTROL
The final product is evaluated for imperfections and prepared to be sold in the shop.

DECORATING DELFTWARE

The painters all have their preferred method to paint different types of decor, but the basics are similar.

Design of decor

A new decor is designed with the development of a new product or when a custom order requires a new design. This is primarily done by one of the master painters. Depending on the product complexity, this is done on a glazed prototype or on paper. After the final iteration, the illustration is transferred to a mock-up to evaluate the final result.

Different methods of decorating

There are three main techniques to decorate Delft Blue: hand painting, transfers and gold lustering. Each step requires a slightly different approach in production (see figure 14).

Figure 13: Example of a hand-painted product (Schiffmacher collection). Retrieved from RoyalDelft.com

Hand-painting

• Hand-painting is the core decoration method of Royal Delft, only done by the master painters.
• The paint is applied directly on the biscuit.
• Product is fired twice: before and after painting.

Transfers

• The transfers are placed on a glazed product.
• Product is fired an extra time after the transfer is placed.
• Placing the transfer on the product requires a lot of precision.

Gold lustering

• Gold lustre is hand-painted or transferred on a glazed product.
• The product is fired an extra time after the gold lustre has been applied.
• Gold lustre is often separated from large decors and assembled at a later stage to prevent risks of failing.
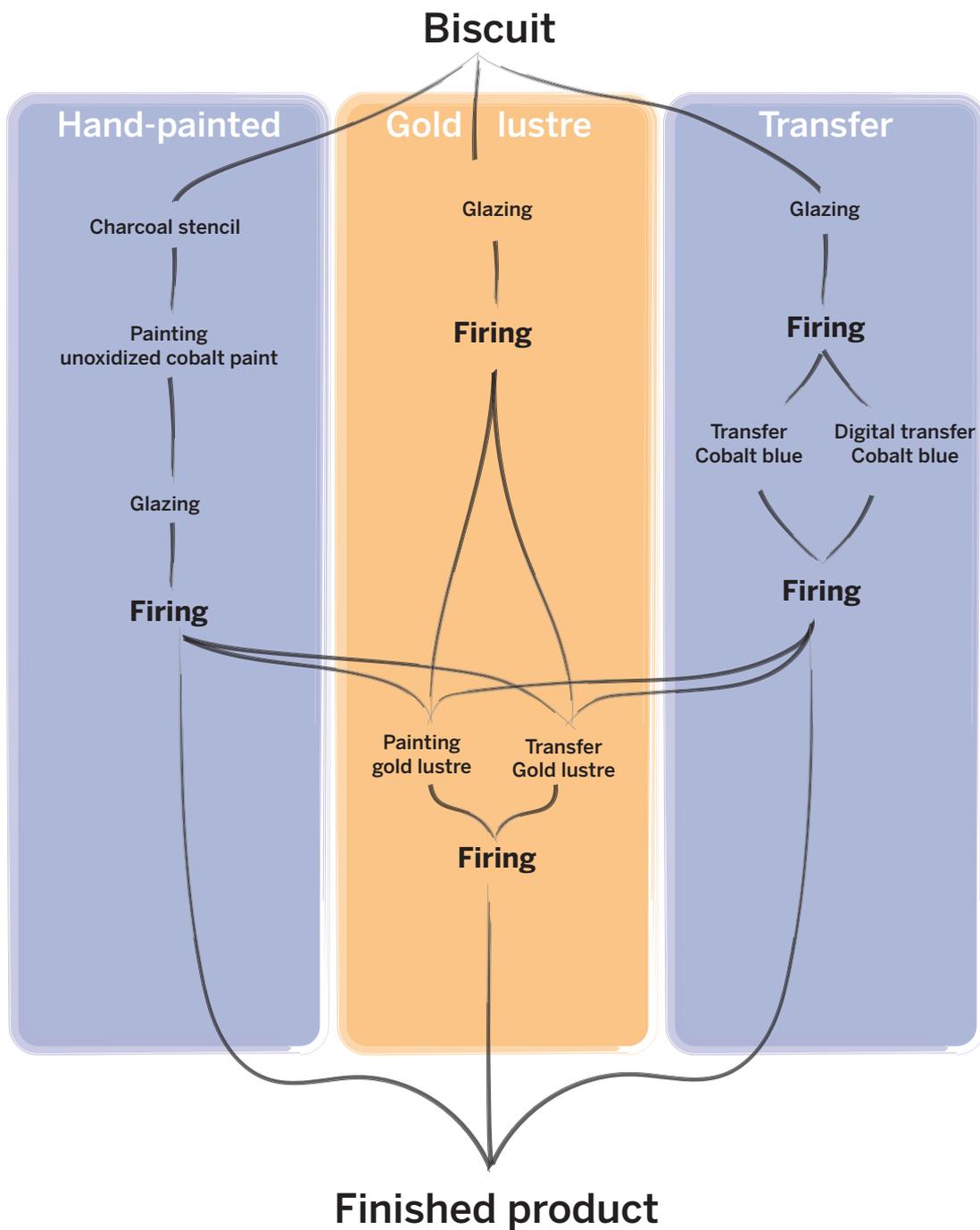
Biscuit

Hand-painted

Charcoal stencil

Painting
unoxidized cobalt paint

Glazing

Firing

Gold lustre

Glazing

Firing

Painting
gold lustre

Transfer
Gold lustre

Firing

Transfer

Glazing

Firing

Transfer
Cobalt blue

Digital transfer
Cobalt blue

Firing

Finished product

Figure 14: Overview of the steps required for different decorating techniques

Combining the techniques

Sometimes, products require a combination of different techniques. Gold lustering is often combined with hand-painted decor or a transfer.

Especially with custom work, hand-painted decor can be combined with a transfer, when for example the logo of a company has too many details to be hand-painted. This means that the product has an extra long lead time as it needs to be hand-painted, glazed, fired, transferred and then fired again.

Different techniques, different applications

Apart from the price differences between the different decoration techniques, there is also another reason to choose a certain method.

Hand-painted products are mainly used for decorative products. If a product needs to be food safe, a transfer decoration is preferred. Although the glaze protects the user from the cobalt paint, it is not recommended to use a hand-painted plate for daily use at a diner table.

Another benefit of a transfer product is that these can be made dishwasher safe.

Stencil
Water bowl
Cobalt paint
Brushes
Mix plate

Figure 15: A painter painting a figurine. These types of decorations can require over 30 different brushes.

HAND-PAINTING PROCESS

This section describes a thorough analysis of the hand-painted process at Royal Delft. It covers the materials needed and the steps that are taken to create a Royal Delft decor.

Materials

The materials used are marked in figure 15. It shows how many brushes are used for a medium sized paint job.

Biscuit

The semi-finished product, called a biscuit, is prepared with an engobe layer, a thin layer of clay to create a matte surface that is ideal for painting as the paint is easily absorbed in the engobe layer.

Charcoal stencil (ponsief)

The master painters at Royal Delft often use a carbon stencil to paint the Delft Blue decors on the biscuits. These stencils help the painters to precisely reproduce the decor on multiple products, giving them guidelines to follow while painting large decorations, so that everything is aligned correctly. These stencils are made beforehand by perforating a thin piece of paper. This stencil is placed on the biscuit and dusted with charcoal, leaving the outlines of the decor on the biscuit.

Mixing the paint and dipping the brush

The painter creates different shades of blue by diluting the cobalt paint with a small amount of water on a mixing plate. The painter intuitively adds the right amount of water to get the correct colour and fills the brush by turning it multiple times. The brush is primed on a piece of paper to get rid of excess paint.

Painting

The painter usually starts painting the outlines with the line brush. These outlines require high accuracy and a steady hand. To paint consistent lines, the painter usually paints in a downwards motion, to maximize the control on the tip of the brush. When the line is starting to loose its dark colour, the painters dips the brush and reshapes the tip into the desired position.

At the end of the painting process, the traditional signature of Royal Delft is applied at the bottom of the biscuit, together with the initials of the master painter and the part number.

Glazing and firing

The finished paintings are placed on a cart and brought to the production floor at the end of the day. There, the painted biscuits are strayed with a layer of glaze and fired in the oven at 1200 degrees Celsius for 24 hours. In this firing process, the cobalt paint oxidises and the black colour turns to the recognisable cobalt blue.

Figure 16: Example of a transfer being applied on a product.

THE TRANSFER PROCESS

This part describes the different types of transfer techniques Royal Delft uses for their products.

Unlike hand-painted delftware, transfers are applied on the glazed surface of a semi-finished product. Currently, Royal Delft uses three different production methods to create transferred products.

Outsourcing

Firstly, the most affordable products, such as plates and mugs, are internationally produced. These products are ordered in batches of 800 up to 2000 a time. Royal Delft does this with the cheapest products to keep the prices low. The designs for these products are made at Royal Delft and after a few iterations, the products are ordered.

Screen printed transfer

Screen printed transfers are used for collection products or personalisation with larger batches. The decors are designed by the master painters at Royal Delft. Once the design is finished, the design team arranges these designs so that they are able to align them correctly on the final product. This can take up quite some time.

These transfers are professionally printed in the Netherlands and the transfers are used at the Royal Delft factory. Here employees place the transfers on the glazed products. Aligning the transfers perfectly is challenging and is the most important step in this process.

The transfer consists of the decor with an extra layer (the yellow colour). When firing the product for the third time, this layer melts and seals off the transfer as a protective layer of glaze.

As these transfers are printed by third parties, there is a minimum batch size of around 80 decors, depending on the size.

Digital transfer

A digital transfer is printed with ceramic ink. These smaller printers make it possible to print them in-house and produce a very small batch size, with the possibility of only producing one transfer. This makes the production of one-piece products more viable. However, the quality of these prints is currently lower than the more professional screen printed transfers. There is less colour variation. Due to the stiffness of the material, the digital transfers can only be used on flat objects, such as a personalised Miffy tile for example. Currently, Royal Delft is developing this technique to offer single personalised products.

THE GOLD LUSTRE PROCESS

Gold lustering is the process of applying a gold paint on a ceramic product. Some products of Royal Delft have golden accents or are completely gold. These are all made with gold lustre.

Unlike the cobalt paint, gold lustre has to be applied on the glaze. That's why this process is always the last layer on a piece of delftware. It does not matter if the piece was hand-painted, a transfer, or even a blank glazed product. On all these types you can apply a gold lustre layer.

This layer has to be fired again in a kiln for 24 hours.

Similar to the Delft Blue decorations, gold lustre can be applied by painting or with a gold lustre transfer. Depending on the complexity of the decor, the choice is made which method would be best. Small decors with a lot of details are often transferred.

Figure 17: Proud Mary with a gold lustre head, hand-painted.

Figure 18: Royal crockery. Transfer decor and logo with a hand-painted gold lustre edge.

Painting gold lustre

The painting process of gold lustre is physically more demanding than that of cobalt paint. Gold lustre paint is a syrup like paint with toxic fumes, meaning that it can only be applied in well-ventilated conditions, and while wearing a face mask, as long exposure to the smell of fumes is unpleasant. Because of the viscous form of the paint, the lustre is applied at a much lower speed, meaning that covering a large area with a gold lustre decor takes a lot of time.

Gold lustering is currently done by only two master painters at Royal Delft. They mentioned in an interview that it is a tricky job that can often fail after firing. Cracks or uneven painted surfaces arise only after the products come out of the kiln, meaning that the success rate is significantly lower than that of normal decorating. That's why gold lustre objects are sometimes made separately and glued on the final object to prevent failure of the complete product.

2.3 PORTFOLIO ANALYSIS

Throughout their history, Royal Delft has created a wide variety of products. These products differentiate from shape and decoration. The traditional Delft Blue aesthetic remains the core of Royal Delft and is part of its DNA. Although the company produces a lot of different products with contemporary designs, one aspect remains always true to this DNA. Figure 19 shows a visual way how products produced by Royal Delft are always tradition-al in shape or in decor. A modern shape with modern decor lacks the DNA of Royal Delft, therefore it is not produced.

Diving into the portfolio of Royal Delft, categorising all products is a challenge. The project differentiates their collection from project work. Apart from manufacturing and selling products from their collection, Royal Delft also does a lot of projects with or for other companies, which will be covered later.
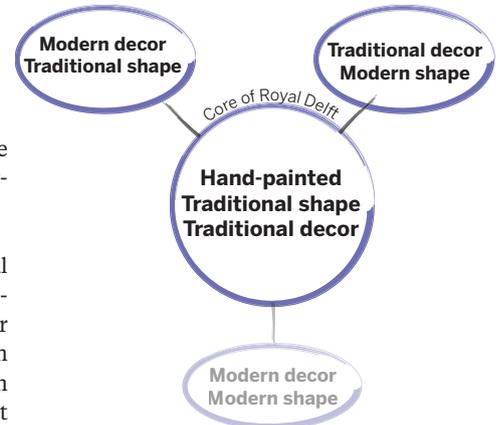
Figure 19: DNA of Royal Delft can be found in every product

ROYAL DELFT COLLECTION

The original Blue

Blueware

Peacock symphony

Proud Mary

Wunderkammer

Blue D1653

Miffy birth tiles

Pebbles

Anniversary plate

TRADITIONAL:

The traditional line is the most famous line of Royal Delft. The products range from small tiles to large tableaus or vases, all painted with a traditional decor. These products are especially targeted at the international market, where traditional designs are popular. In the traditional collection, we see two different branches, based on the manufacturing technique.

The original Blue

This range is hand-painted and are the often the centrepieces of Royal Delft. These products have a high price tag due to the manufacturing technique, sometimes costing over 10.000 euros.

Blueware

A less expensive alternative is the Blueware range. These products are made with transfers, significantly reducing the price for these pieces, while still showing the traditional style of Delft Blue.

CONTEMPORARY:

The contemporary line consists of different collections designed in-house or as a collaboration with an external designer, such as Schiffmacher or BlueD1653. All these collections step away from the traditional visual style of Delft Blue and create more modern, contemporary designs.

These products appeal more to the Dutch market. To make the products available to a wider range of consumers, they often offer both hand-painted products and transfers.

BESPOKE:

The personalised products Royal Delft produces has a wide range of customisation: from standardised products where a name is added, like Miffy tiles, the memento blue pebbles, to fully custom-designed 3D ceramic products, such as the miniature houses.

Buying a standardised personalised product is simplified by entering custom text on the website when ordering your desired product. The more complex personalisation requires contacting the design team of Royal Delft to discuss the possibilities.

The majority of these personalised products are currently hand-painted, meaning that they are quite expensive. New developments led to opportunities for printing transfers for custom products. These transfers are made using a different technique. This requires a different material that is less flexible, making customised transfer products only possible for flat or semi-flat products (tiles, plates).
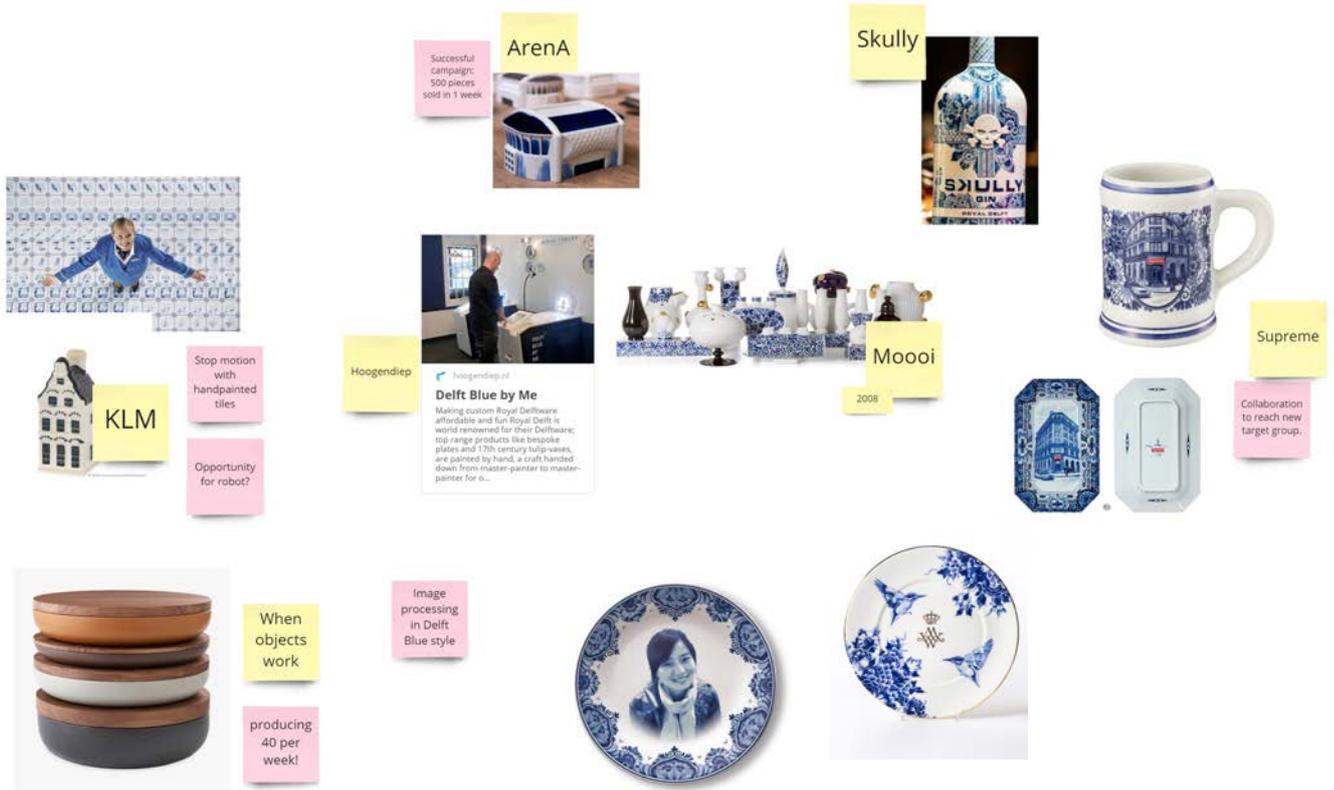
Figure 20: Overview of different collaborations and projects Royal Delft did in the last decade

PROJECT WORK

Royal Delft does a lot of project work, short collaborations or one-time products that are sold for a limited amount of time. These projects are often business to business requests, where a company wants a specially designed and produced product. A recent example is the Johan Cruijff ArenA. This product was requested by them for their 25th anniversary and sold for a limited time. For this particular project, the items were also sold via the Royal Delft website. An overview of different projects Royal Delft has done can be seen in figure 20.

FACILITATOR (ODM)

The production line of Royal Delft is also used for capacity work for other companies. An example of this is are the different bowls produced for 'When objects work'. Royal Delft has been producing over 40 bowls per week for this company.

PRICE RANGE

The overview below shows a general price range depending on the production method and product complexity. The most expensive products Royal Delft makes, are large hand-painted 3D pieces, while externally produced transfer products are often the least expensive.

An interesting observation was that similar products with a different manufacturing technique, can be up to 10 times more expensive depending if it is hand-painted or a transfer. This means that there is a very large price gap between these two types of production methods.

20-50	150-250	500	1.000	2.000-5.000	> 10.000
Transfer 2D	Hand-painted 2D small Transfer 3D	Hand-painted 3D small modern	Hand-painted 3D small traditional	Hand-painted 2D traditional	Hand-painted 3D traditional large

Figure 21: Overview of prices

LEVEL OF PERSONALISATION

As mentioned, Royal Delft does a lot of bespoke products for consumers and businesses. These range from custom text to completely designed products. To organise this process and show the opportunities to the customer, Royal Delft uses an overview with different levels of personalisation. Figure 22 shows such overview.

Level 1

The lowest level of bespoke products is a personalised text or an added logo. Common examples are birth tiles with a personal name, or plates for companies that want their logo on the back. Logos are often placed with a transfer as these could have too much detail to paint by hand. Birth tiles are often ordered as one piece. These are hand-painted or made with a digital transfer. A normal transfer would be too expensive as these go from 25 pieces.

Level 2

Modified decor involves a standard decor where something is added by request from the client. This requires a redesign, which is done by the master painter or designer, depending on chosen the manufacturing method.

Level 3

A completely new decor is designed on a Royal Delft product. The pebbles are an example of this, where someone would want a completely personalised decorated pebble. Hand-painted products start from 1 piece, in contrast to transfer products, which start at 100 pieces.

Level 4

A completely custom product is developed and produced. In practise, this is primarily used by companies, or as a short collaboration. Here, the development of the shape takes a lot of time.

Hand-painted   **Transfer**

Level 1
Add logo/text

2-4 weeks   3-4 weeks

Level 2
Modified decor

6 weeks   6 weeks

Level 3
New decor

10-12 weeks   10-12 weeks

Level 4
Completely custom

4-6 months   4-6 months

FIgure 22: Levels of personalisation

Figure 23: One of the latest products of the Schiffmacher collaboration. Image retrieved from royaldelft.com

CHAPTER INSIGHTS

History

Royal Delft is a very old company with a lot of heritage. Throughout their history they have been innovating their production process. Although they seem very traditional, innovation is part of Royal Delft. The key is to adapt to new trends, while staying true to their core, which is the craftsmanship of creating delftware.

Production

Transfer product are fired an extra time, meaning that they take relatively more effort to produce apart from the decoration process.

Mixing the right colours for a decor is done on intuition. It is important to keep track of how the paint flows on the biscuit to get the perfect colour.

Gold lustering is a labour intensive method to decorate delftware.

Portfolio

With a large product portfolio, there are a few insights that can be derived from the analysis.

Royal Delft is broadening their visual style to appeal to a larger target group.

A lot of transfer products are produced in other countries to lower the price.

There is a very large price gap between hand-painted products and transfer alternatives.

Figure 24: Royal Delfts external pop-up store. Retrieved from royaldelft.com

EXTERNAL ANALYSIS

The external analysis covers the external factors that influence this project regarding Delft Blue.

3.1 COMPETITOR ANALYSIS

Royal Delft claims to be the only company left to produce real Delft Blue ceramics in Delft. While this is true, there are still other companies competing with Royal Delft in the Delft Blue market.

With a competitor analysis (figure 25), an overview is made to showcase the competitors on different levels: product form, product category, generic and budget.

PRODUCT FORM

These are the direct competitors of Royal Delft. These companies manufacture Delft Blue using similar techniques. Heinen Delfts Blauw is a strong competitor, creating very similar products, while also offering a range of functional tableware at a lower price than Royal Delft. Their products are sold at a lot of places, from their physical stores in the city centre of Delft to online shops such as Fonq. Although this company lacks the heritage, as it was founded in 1985, its presence is substantial.

PRODUCT CATEGORY

These companies compete with Royal Delft on similar product categories. Other famous traditional ceramics, such as Boerenbont or Wedgwood are strong competitors. Tichelaar is more active in the field of architecture, often combining Delft Blue with building ceramics.

GENERIC

Generic competitors fulfil the same customer needs, meaning that these are companies that sell tableware or decorative home products. One of the biggest competitors would be Ikea, offering both tableware for a low price and decorative products. Other large competitors are Blokker and Fonq. What these competitors have in common is that budget and convenience are often the main drivers when choosing to buy products from these companies. They all sell a very large range of different products at different price ranges. This means they have a very large and diverse target group.

BUDGET

This category competes on the same budget as products from Royal Delft. As the prices of their products range from a few euros to more than 10,000 euros, this category could be very broad. What might be important to learn from this category is that for the low budget products, other souvenirs could be competitive, such as tulips or clogs. For the higher price range, competitive products could be furniture or pieces of art.

Budget

Generic

Product category

Product form

fonQ

WEDGWOOD
ENGLAND 1759

blokker.

Villeroy & Boch
1748

SCHOONHOVEN SK KERAMIEK

HEINEN
DELFTS
BLAUW.

creating
new traditions

makkum

Bunzlau Castle®

IKEA

Figure 25: Competitor overview based on four different levels: Product form, product category, generic and budget.

3.2 PERCEPTION ON DELFT BLUE

Delft Blue is part of Dutch heritage and is well-known throughout the whole country. As Royal Delft wants to reach a new generation of potential buyers, it is interesting to understand how Delft Blue is perceived. By interviewing potential consumers, both Dutch and international, this small research tries to answer the question of how Delft Blue is perceived and when a product is Delft Blue.

SETUP

The interview consists of two parts. In the first part, the participant is asked a few questions about their knowledge of and opinion on delftware.

- Do you know Delft Blue?
- What are the first things you think about when I say Delft Blue?
- Do you own something that is Delft Blue?
- What do you think of Delft Blue?

In the second part, the interviewer shows the participant different pictures of Delft Blue products or products that are inspired by Delft Blue. The participant is asked to rank the products on a scale from 1 to 10 if they think it is delft blue or not. The next question was if they liked the product.

Figure 26: Searching for participants in Delft

RESULTS

Eight participants were interviewed in the city centre of Delft. Three out of these eight participants were of foreign nationality, and four were approximately over 40 years old. It was interesting to see that only 1 of the eight participants owned a Delft Blue product, but all of them knew about Delft Blue.

Delft Blue as perceived

With the first part of the interview, the goal is to understand how Delft Blue is perceived. By asking them what comes to mind when thinking about Delft Blue, the participants are answering their associations with delftware, which can be interesting to understand how Delft Blue is perceived.

Figure 27 shows a word cloud of the most common associations the participants had with Delft Blue. Surprisingly, these associations range from the strengths of Royal Delft, such as 'heritage' and 'craft', to the stigmas of Delft blue: 'touristic', 'expensive' and 'old-fashioned'.

Figure 27: Results of associations with "Delft Blue". Size correlates to number of responses

Like

Fake Delft Blue

Authentic Delft Blue

Dislike

Figure 28: Results of perception of Delft Blue products. Average of all the answers.

When is something Delft Blue?

Delft Blue comes in all kinds of products and shapes. From delftware to shoes. Often, Delft Blue is referred to as a visual style of cobalt blue illustrations on a white background. To better understand when something is perceived as Delft Blue, the participants were shown different products and asked if they thought it was Delft Blue or not.

Figure 28 shows the results of the participants mapping the different products. The range of products differs from product category (ceramics, clothing, furniture) or visual style (traditional, modern, cartoon, line art).

There are some interesting things to notice with the results of this study.

Traditional painted Delft Blue on delftware was always considered as real Delft Blue. However, changing the composition or visual style of the decor also changes their opinion. It is less recognisable for Delft Blue.

The type of product also has this same influence on the opinion if it is Delft Blue or not. Products such as the bed sheets, lamp or shoes with traditional Delft Blue visual styles, are perceived as less Delft Blue.

When looking at the line drawings made with the robot, the similar thing happens. As this visual style is not the same as the traditional style, they are perceived as less Delft Blue.

Another interesting insight is the differences in preference. The more modern visual styles and compositions, such as the peacock, Schiffmacher, and the robot painted view of Delft, are preferred over other visual styles such as the traditional and bold styles seen in the other products.

Figure 29: Product of Heinen Delfts Blue. They differentiate by moving completely away from traditional styles and mixing different materials. Retrieved from heinendelftsblauw.nl

CHAPTER INSIGHTS

Competitors

Royal Delft has some important competitors, such as Heinen Delft. This company is very present in Delft, with numerous physical shops in the city centre. Because they are in a lower price segment, they can sell their products in more regular shops, compared to Royal Delft. This results in potential customers with a smaller budget buying Heinen Delft Blue.

Perception of Delft Blue

Delft Blue is perceived both as traditional and historic as well as touristy, old-fashioned and expensive. Although new Delft Blue is often more contemporary, people still associate the traditional style as Delft Blue.

This means trying to achieve the traditional style, is not desired right away. The goal should be to try to move the associations with Delft Blue towards the more contemporary and modern designs.

Figure 30: Luminance measuring at the faculty of Industrial Design.

CHAPTER 4
TECHNOLOGY ANALYSIS

The technology analysis explores the challenges of the current prototype and analysis different painting techniques with the robot to prepare for the embodiment phase.

4.1 ANALYSING THE PROTOTYPE

After analysing the prototype together with the students who worked on the project, a simple overview of the components is made (figure 31). The prototype consists of a 3D printer with a custom brush holder and a python script that can transform vectors into gcode commands. They would place a tile on the print bed, prepare a svg image in a vector graphics editor program called Inkscape, and process this file with their python script. This file is transferred to the 3D printer using a SD card. Before starting the file, the brush is dipped into the paint and placed in the brush holder. After these steps, the prototype is ready to paint the tile.
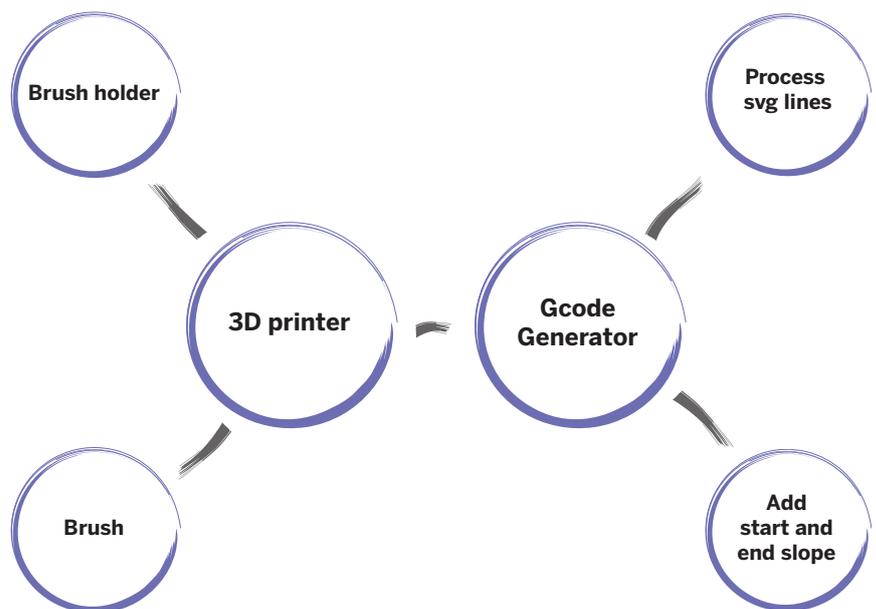

Figure 31: Overview of the two parts of the prototype

TECHNICAL INSIGHTS FROM THE PROTOTYPE

This section explains the different conclusions that were drawn from this prototype and which topics are interesting to investigate.

Paint lines

The robot excels in painting lines, while it struggles with infill. It lacks the precision and feedback to paint within the lines, resulting in an offset of the line art and the respective infill (see figure 32). By taking advantage of the precision of the line art, the group advised to create a new art style that uses hatching techniques or other line art to create the decorations for the robot.

Figure 32: Tiles decorated by with the prototype by the student group. The difference between line art and the traditional infill.
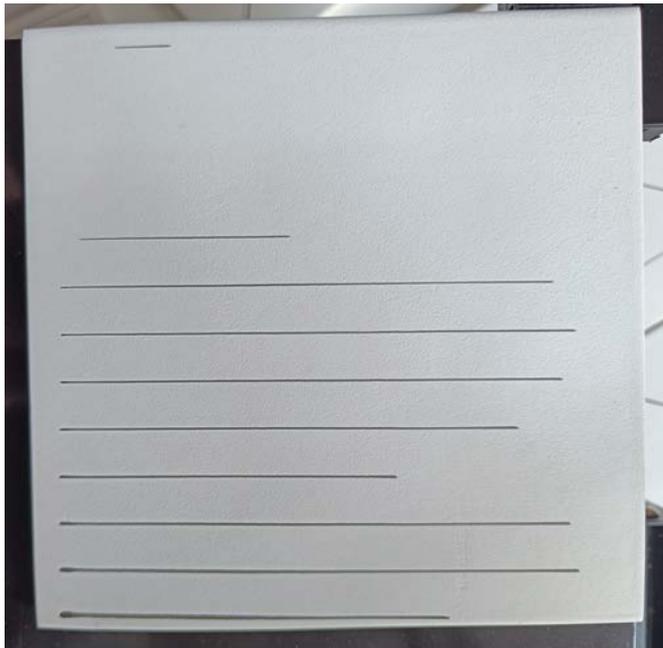

Figure 33: Result of painting a tile without considering the height differences. The tile should be covered with lines.

Resolve the Z offset issue

The irregular surface of the tile results in a inconsistent painting where some lines are painted too close on the tile while other lines are not even visible. The master painters do not have this issue as they follow the surface of the product. The robot on the other hand moves the brush in the same plane, resulting in missing the surface of the tile. This was overcome by manually changing the Z-offset of the brush and repainting the lines that were missed. They recommended to use a technique to take the varying surface height of the tile into account when painting.

4.2 PAINT BEHAVIOUR ANALYSIS

This section covers two analyses about the behaviour of painting on delftware. The first analysis tries to quantify the relationship between the paint-water ratio and the final colour. The second analysis covers a different decoration technique: gold lustering. This was suggested by Royal Delft as an interesting topic to cover.

PAINT RATIO

The paint used for painting Delft blue decors is called cobalt paint, which is manufactured in-house. This paint needs to be watered down to create different shades of blue. The master painters at Royal Delft can intuitively change the paint-water ratio to achieve the perfect colour, as shown in the production analysis in chapter 2.2.

Unfortunately, a robot lacks this intuition, so it needs to depend on quantifiable data to recreate the different shades that are present in Delft blue decors. The goal of this small study is to quantify the influence of the painting ratio on the final colour and learn more about the influence of oxidizing the colour on this.

Test setup

Firstly, six paint mixtures with different ratios of water and cobalt paint were measured. The different amounts of paint were 0.1, 0.3, 0.6, 0.9, 1.2 and 1.8 grams over 10 grams of water. These ratios were discussed with a master painter to represent the different colours that are often used in a Delft Blue decor.

To eliminate other variables that could influence the colour of the paint, the tests would be done on the robot. This would result in the same speed and movement for all the different samples.

Figure 34: Tools setup for mixing samples

A large brush is used for the test to create a sufficiently large surface area to measure the colour with a luminance sensor.

Per sample, the robot paints a stroke of 100 mm, after dipping the brush, another two strokes are painted on top of the previous ones to understand how increasing the layers of paint would affect the colour intensity.

To measure this intensity of the colour and be able to quantify it, a sensor is used that is able to measure the luminance of a colour.

"Luminance is also considered the human perception of brightness, or how bright we perceive the light that is reflected off of the surface" (Wilkinson, 2020). However, there is a difference between luminance and the brightness we see. Luminance is the measured light reflected from a surface. Brightness on the other hand is the subjective attribute of light, influenced by our eyes and the surroundings. Our eyes do not perceive each colour and brightness level the same way.

This research, measuring the luminance is to achieve a quantifiable result to recreate the desired colours with the lack of intuition. Therefore, the relationship of water-paint ratio and the luminance is sufficient for this project.

LUMINANCE OF DIFFERENT PAINT RATIOS
Showing unoxidised versus oxidised paint

- Unoxidised
- Oxidised

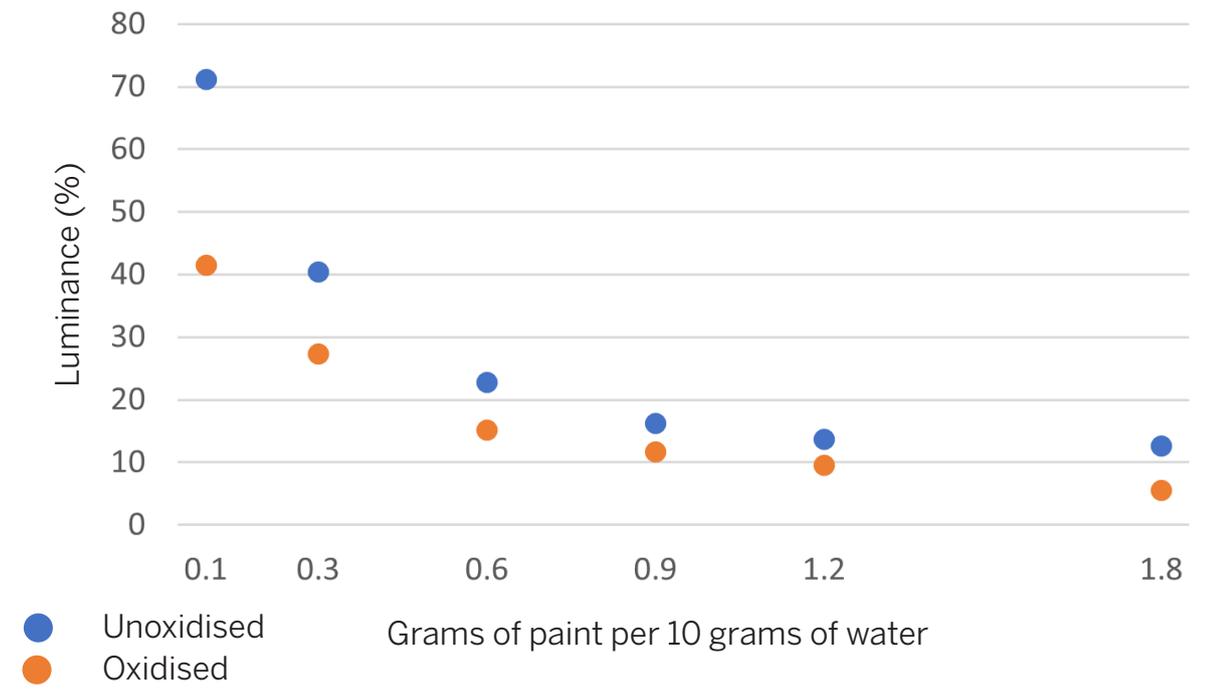Grams of paint per 10 grams of water

Figure 35: Results of the luminance tests

Results

The results show an exponential relationship between the amount of paint and the final colour, showing a smaller change in luminance, the more paint is used.

This data can be used to recreate the paint colour used in a previous decor and resupply the robot with new paint when needed. The decreasing difference in colour when approaching darker shades of blue can help with choosing the mixtures for the final demonstrator. It might be desirable to mix more smaller ratios to create more distinguishable colours.

As shown in the graph above, the relationship between ratio and luminance changes when the colour is oxidised. The blue colour behaves differently compared to the black unoxidised paint.

This confirms the observations that were made when one of the first tests where painted. The colour looked even, but after showing it to one of the master painters, he said that the image was too light at the end. "Just wait until it comes out of the kiln", he said.

Figure 36 shows the differences before and after. When painting on a tile, keeping track of the colour is very important as the differences are a lot more extreme after firing.
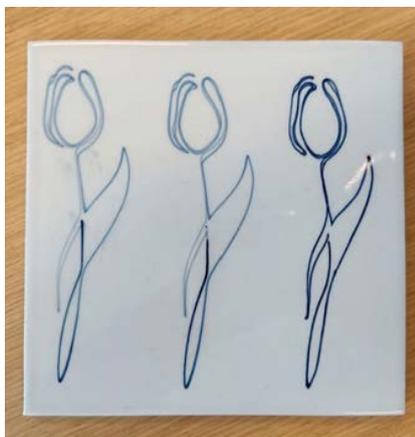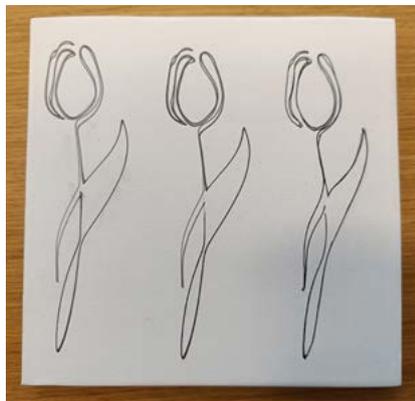

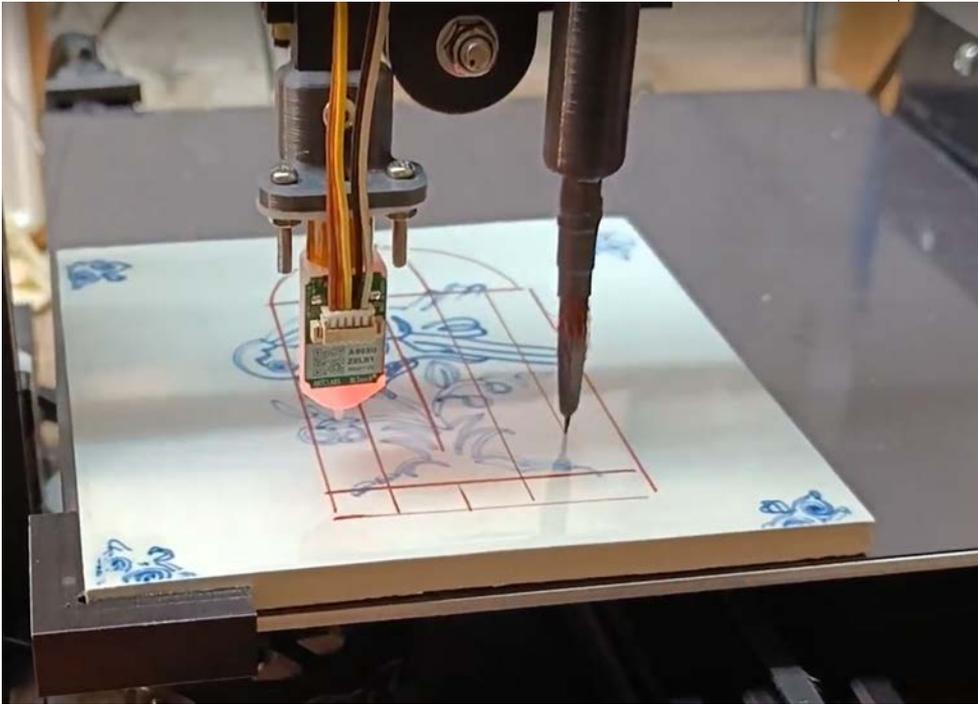**Figure 36: Test painting by the robot. The same tile before and after firing.**

Figure 37: Gold lustering test. The paint is red before firing.

4.3 GOLD LUSTERING

Gold lustering is a physically demanding activity, currently done by only two master painters at Royal Delft. It is done in a separate room, as a mask is required when using this paint.

The benefit of this paint is that it does not need to be diluted with water. It can be applied using the same type of brush as is used for regular decor. It is also possible to add gold lustre as a transfer component, which is applied after the cobalt blue transfer is fired.

Right now, Royal Delft does not do a lot of gold lustering. In their collection, only a few Proud Mary's have a golden head. Next to that, one of the objects from the Moooi collection has a gold component as well.

After talking to one of the master painters about gold lustering, he described that gold lustering is a tricky technique, especially when creating decors with a lot of detail and thin lines. The viscous paint does not flow quickly and does need a very steady hand to paint straight as the painting speed is much slower than that of regular cobalt paint.

THE TEST

This test aimed to see if the robot was able to paint with gold lustre and could create a consistent result. As the robot is able to create steady motions at different speeds, this technique could be an interesting opportunity for the painting robot.

The robot painted a simple design of a bird cage on a fired tile. For this experiment, the speed of the robot was slowed down to one third of the speed when painting with regular cobalt paint, as this was suggested by the master painters.

RESULT

Figure 38 shows the result of the robot painting with gold lustre. A minimalistic style birdcage was painted to 'capture' the bird on the decor. The results were promising as the lines looked very consistent. The only issue was the alignment of the circle due to the dragging of the brush, which is a minor issue that can be solved.

The final reactions of the master painters were positive about the result, making gold lustering an interesting topic for the Delft Blue painting robot.

CHAPTER INSIGHTS

Z-offset

When painting on a tile, the robot has to compensate for the height variation. This should be developed in the embodiment phase.

Ratio

The colour ratio is quantified, meaning that it is possible to approximately create the colour you want with the correct ratio. Keep in mind that the colour in black is very different than the oxidised colour.

Gold lustering

Gold lustering is a promising option when it comes to the painting robot. The precision at slow speeds of the robot are a benefit that can outperform painters.

A SWOT (Strength, Weaknesses, Opportunities and Threats) analysis is used to create an overview of the insights gathered from the analysis phase. The overview covers insights from analysing Royal Delft, the technology and literature.

The SWOT analysis supported in distinguishing 4 different views on the problem statement. They are described below:

CONTROLLING THE UNPREDICTABLE

The robot has to overcome a lot of variables that are hard to control, such as the behaviour of the brush when touching the biscuit and dipping in paint. Other variables such as the paint and the surface quality of the biscuit are also influencing the final quality.

FILLING THE GAP

The robot has a lot of potential in providing an alternative to hand-painted and transferred products. Right now, hand-painted delftware is expensive, and a transfer product is often outsourced. A price gap of factor 10 means that there is a large gap to fill where robot painting could provide a cheaper alternative to hand-painting, while still being using the traditional techniques instead of the use of a transfer.

HIGHLIGHT THE STRENGTHS, NEGATE THE WEAKNESSES

Royal Delft has a lot of strengths: Heritage, quality, brought portfolio, flexibility to customisation. On the contrary, Delft Blue is frequently perceived as old-fashioned and touristic. The challenge is to highlight these strengths while also removing the negative perception on Delft Blue.

Technology Literature Business

Strengths

Robot = cheaper than hand-painted

Heritage Linework

Able to work 24/7

High quality products

Robotic precision

Customisation

Customisation

Large media reach

Combine strenghts of craftsmanship and digital manufacturing

Weaknesses

Difficult to control infill painting

Currently only 2D surfaces

Paint mix expires after 2 weeks

Small details are lost

Loses the perceived value of hand-painted

Long lead time of post processing

Perceived as touristic

Royal Delft is perceived as expensive

Positioned between hand-painted and transfer products

Attract new innovative companies

Promote technology with external digital artist

More in-house rapid customisation and prodution

Quick personalisation

Custom handwritten text

Gap in literature for 3D painting robot

Large scale painting Tableaus

Application for craftsman 4.0

Opportunities

Robotic painting might not be accepted

Technology does not meet expectations of craftsmen

Robot might require a lot of time and knowledge to maintain

Hard to keep up with consumer demand (high customisation, low price)

Visual style too distant from Royal Delft DNA

Hard to keep up with changing industry

Threats

Figure 39: SWOT analysis

PART II DEFINE

After gathering as much information and insights as possible, the next step is to converge it into ideas and a final product vision. In this part, a co-creation session with Royal Delft was organised to compare the insights with the view of Royal Delft, to make a final decision for the product direction.

Figure 40: results of a warming up during the co-creation session.

CHAPTER 6
CO-CREATION

A co-creation session was organised with employees of Royal Delft to gather their insights on design directions.

During this project, the employees of Royal Delft were an important source for information in the analysis phase, both for problem finding and insights into the work flow at Royal Delft. One aspect that was missing was a collective view of Royal Delft on the introduction of a painting robot within their company. That is why a co-creation session with different Royal Delft employees was organised.

The goal of this session was to create an overview of Royal Delft's vision for the painting robot. This was done by inviting employees from different departments for a collective brainstorm session. The participants would follow a predefined co-creation session based on the book Road Map for Creative Problem Solving Techniques (Heijne & van der Meer, 2019). The session involved a warm-up, associative thinking techniques and a brainwriting session. This session contained the following how might we's:

• How can a painting robot create value for Royal Delft?
• How can a painting robot help the master painters of Royal Delft?
• How can a painting robot create its own collection?
• How can a painting robot promote Royal Delft?
• How can a painting robot support custom products?

After using different diverging techniques to create as many ideas as possible, they were asked to create clusters and pinpoint the ideas that they think are most promising.

Clusters of possible directions for a painting robot at Royal Delft

• Designing decoration
• Promotional
• Custom work
• Ergonomic
• Robot skills
• Attraction
• Robot as an artist
• New style
• Input

The clusters focused on different kinds of roles for the robot (promotional, solving ergonomic problems or specialised in custom work) or the different variations of input/output. What kind of style could the robot have? How is the design of the decoration determined?

After a brief discussion about the chosen ideas, we tackled the purpose of the robot within Royal Delft. The purpose of the machine was mostly shifting between a promotional standpoint and an efficiency standpoint. The promotional standpoint focused on providing a new experience for visitors of the museum, by creating a stand-alone automated experience. On the other hand, the efficiency standpoint focused on improving the ergonomics of the master painters (described in the 'ergonomic' cluster). Here, the focus lay on helping the painters backstage with their work (line work mostly).

These two very different views on creating value for Royal Delft were interesting to see. The robot has potential for many purposes. Which one is the most valuable will depend on other factors as well, described in the next part.

Hoe kan een schilder... zijn eigen Delft promoten?

Hoe kan een schilder/robot helpen bij maatwerk?

Hoe kan een schilderrobot de schilders helpen?

Hoe kan een Schilderrobot zijn eigen collectie maken?

CHAPTER 7
DESIGN DRIVERS

The design drivers are statements derived from the gathered insights from the SWOT analysis and the co-creation session with Royal Delft.

TECHNOLOGY

Inspire further development of digitally painting Delft Blue

This project is only the beginning of introducing digital manufacturing methods to Royal Delft. The product should therefore be improve the technical capabilities of painting delftware and also inspire for further technical development.

Integrate in the production process of Royal Delft

By integrating the robot painter into the production process of Royal Delft, the company can embrace the innovation more seamlessly than when this robot is seen as a complete separate production method.

BUSINESS

Fill the price gap between transfers and hand-painted products

There is a large price gap between transferred and hand-painted products. This gap can be filled with robotic painting.

Enable more in-house production

The cheaper products, Royal Delft sells, are produced externally. By introducing a cheaper method for painted products, this external production could partially move back in-house. Locally produced products are more valuable in terms of sustainability and the Royal Delft as a production company.

USER

Change the negative perceptions of Delft Blue

This new, innovative method of painting Delft Blue can be a push in the right direction for more positive perceptions on Delft Blue.

Show innovation to the public

Royal Delft wants to openly show their innovation. Their current production process is displayed in their museum, which is always updated with their latest products and innovations. If a painting robot would be integrated into their production method, showing the process to visitors would help excite potential customers for robotically painted products.

CHAPTER 8
IDEA DIRECTIONS

Four different ideas, gathered from brainstorms and insights, are presented as possible directions to take in the next phase of this project.

THE ENTERTAINER

The entertainer is a autonomous painting robot in the Royal Delft museum. Visitors can design their personalised painted tile or plate by combining different predetermined designs and optionally adding personalised text. When ordered, the robot starts painting directly, while the visitor can watch how the robot creates their personalised product. When finished, the product is moved to a storage rack, ready for glazing and firing. The consumer is able to choose between picking it up after a few days or shipping it to their home.

This product's goal is to showcase innovation at Royal Delft, while also providing a unique experience and the possibility to quickly personalise a Royal Delft product.
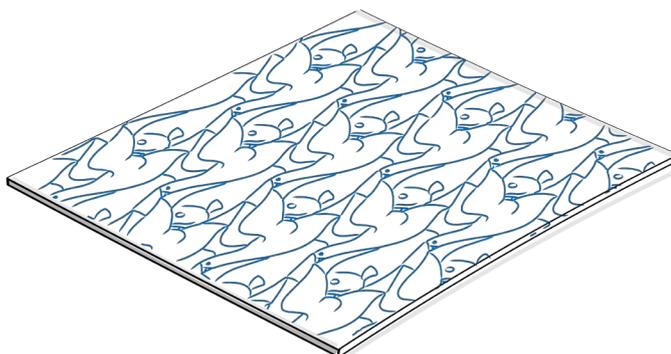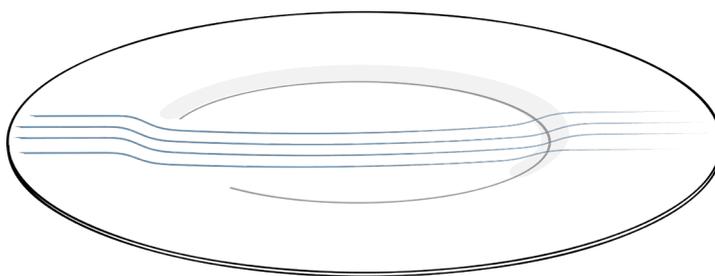
THE EMPLOYEE

The flexible employee assumes that the robot is perceived as an employee of Royal Delft, being widely applicable for custom work to create new collections. The robot interacts with the design team to create new products for Royal Delft.

The robot is placed on the manufacturing work floor. This decreases the movement of the biscuits and painted products while also operating in view for visitors of the museum.

THE ENHANCER

Royal Delft has a large collection of traditional painted tiles, with old-fashioned decors. The enhancer robot uses gold lustering to enhance these traditional decors with a touch of modern design. This gold lustre robot is able to create a new collection for Royal Delft that combines the heritage with innovative techniques and modern designs.
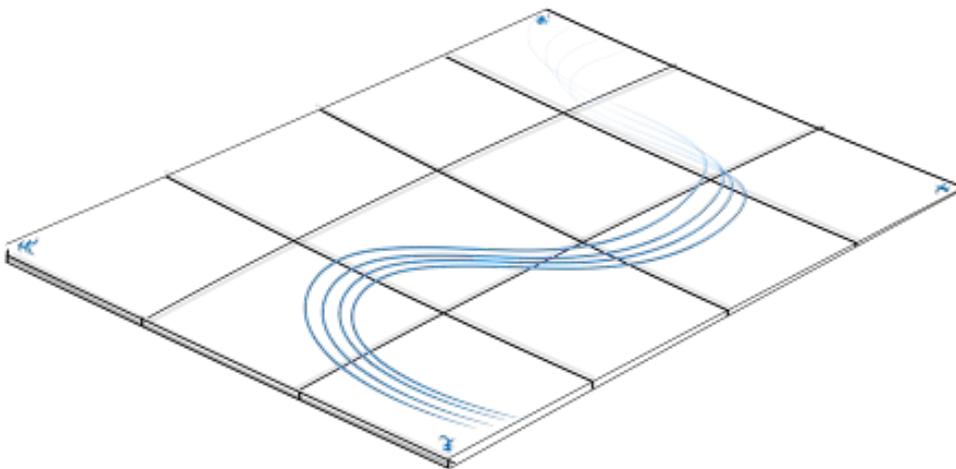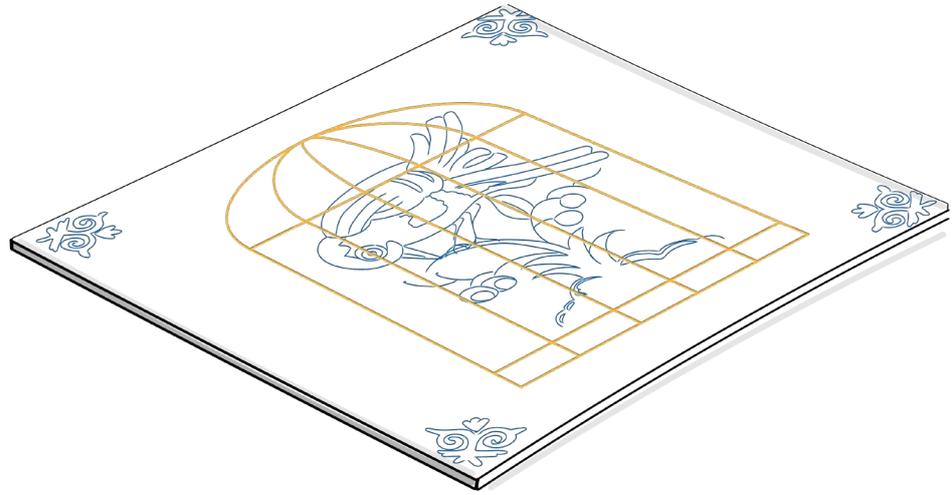
THE SUPPORTER

The supporter robot assists painters in their job by preparing decors with line work. This robot specialises in large tableaus of tiles, as this is one of the more difficult things to prepare. The painters are the main users of the robot as they collaborate on creating a tableau. Aside from drawing line work for further painting, the robot is able to create completed decors as well.

CONCEPT DEFINITION

From the four different design directions, a foundation is made for the next phase by prioritising one the these directions. The one chosen is the starting point and the others serve as inspiration and potential functionality.

All four idea directions are interesting to develop further within this project. They all provide a different view on how to implement the robot within the production process at Royal Delft.

To choose one direction and disregarding the rest, would be undesired at a relatively early stage of development.

For this graduation project, one concept direction chosen as an basis on how the robot should be implemented at Royal Delft. The other directions serve as an inspiration for features and problems to solve with the new prototype. This way, the next phase has a more scoped down goal, with extra use cases to solve with the prototype.

Main direction

Figure 41: Combining the idea directions into a concept direction

THE EMPLOYEE

The employee is chosen as a foundation for the next phase. Integrating a painting robot as another employee that can decorate, opens up a lot of opportunities for product development, customisation and optimisation. This directions is aligned with the design drivers and makes it possible to integrate aspects of the other directions as well.

From these directions, functionalities such as gold lustering, up-scaled paintings and showing the painting process could all be added as wishes to the development of the concept. These would fit the role as "an employee" as well. Figure 41 visualises how these directions merge.

.

The chosen direction is very broad, leaving much room for further development and more specific implementations. For this stage in the project, leaving these possibilities open is important to encourage further development. Right now, improving the technology and integration into the Royal Delft production is the most important step. This will be the focus for the next chapters.

CHAPTER 10
MAIN
SPECIFICATIONS

The main specifications for a painting robot at Royal Delft are shown below. These specifications are based on the chosen direction and the insights from the analysis phase. A more in-depth list of requirements can be found in Appendix A.

The first set of specifications apply to a painting robot that paints 2D products such as tiles. The second set is added when the robot also has to paint 2.5D objects, such as plates.

2D PAINTING ROBOT
From the employee direction
- Able to paint a tile with multiple colours and brushes
- Able to automatically dip the brush when needed
- Able to paint a vectorised file accurately
- Able to create products with high repeatability
- Facilitate easy customisation
- Able to adjust the height according to the surface
- Must be intuitively to use and operate

Functions to add value
- Able to gold lustre
- Able to paint decoration over multiple tiles

2.5D PAINTING ROBOT

- Able to paint a small plate
- Able to measure the surface of a plate
- Able adjust its height accordingly
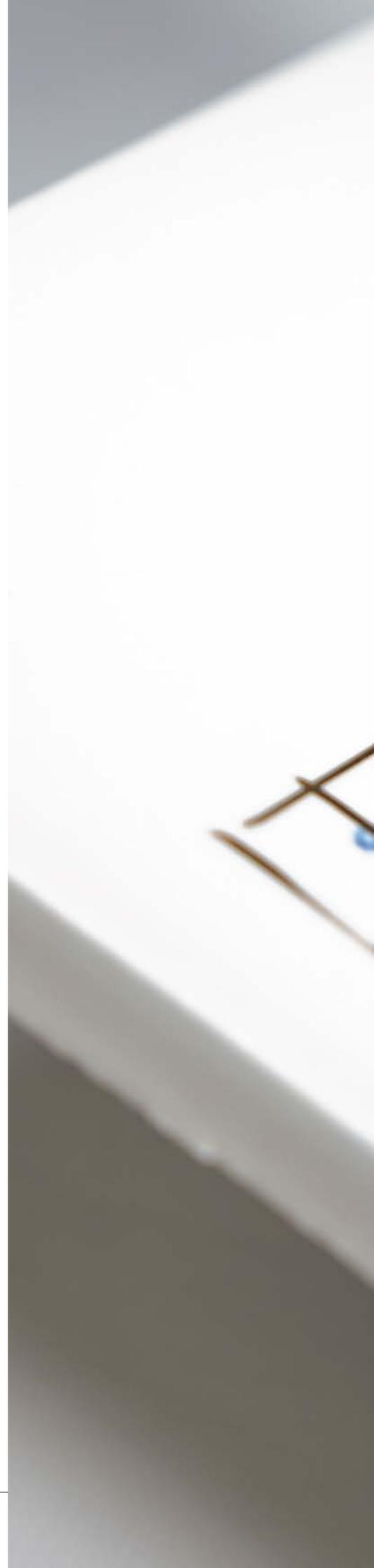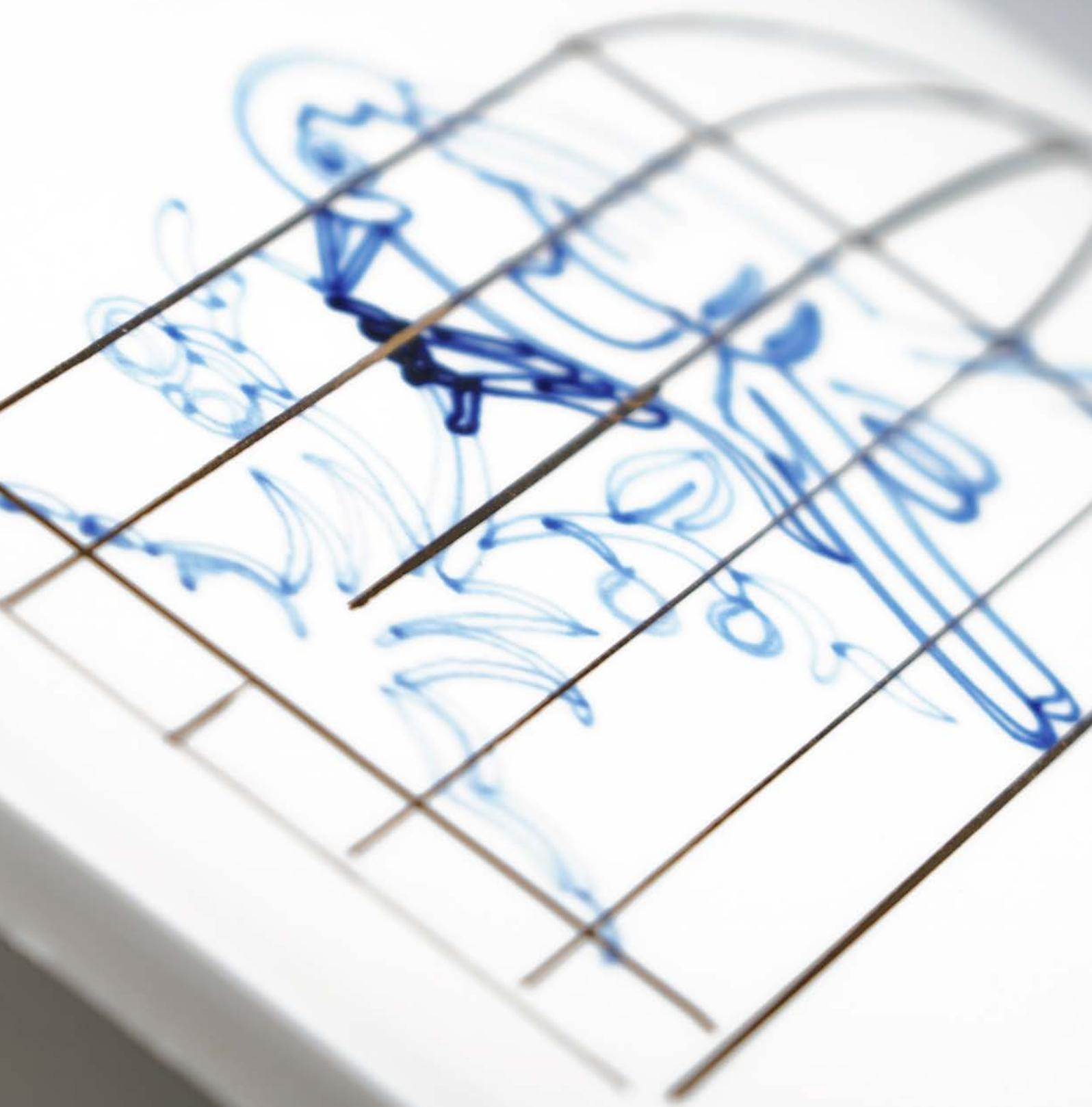
PART III: DESIGN & EMBODIMENT

This part of the project describes the development and embodiment of the Royal Delft painting robot. A suitable design direction is chosen, and the goal is to develop a product and demonstrator within this direction.
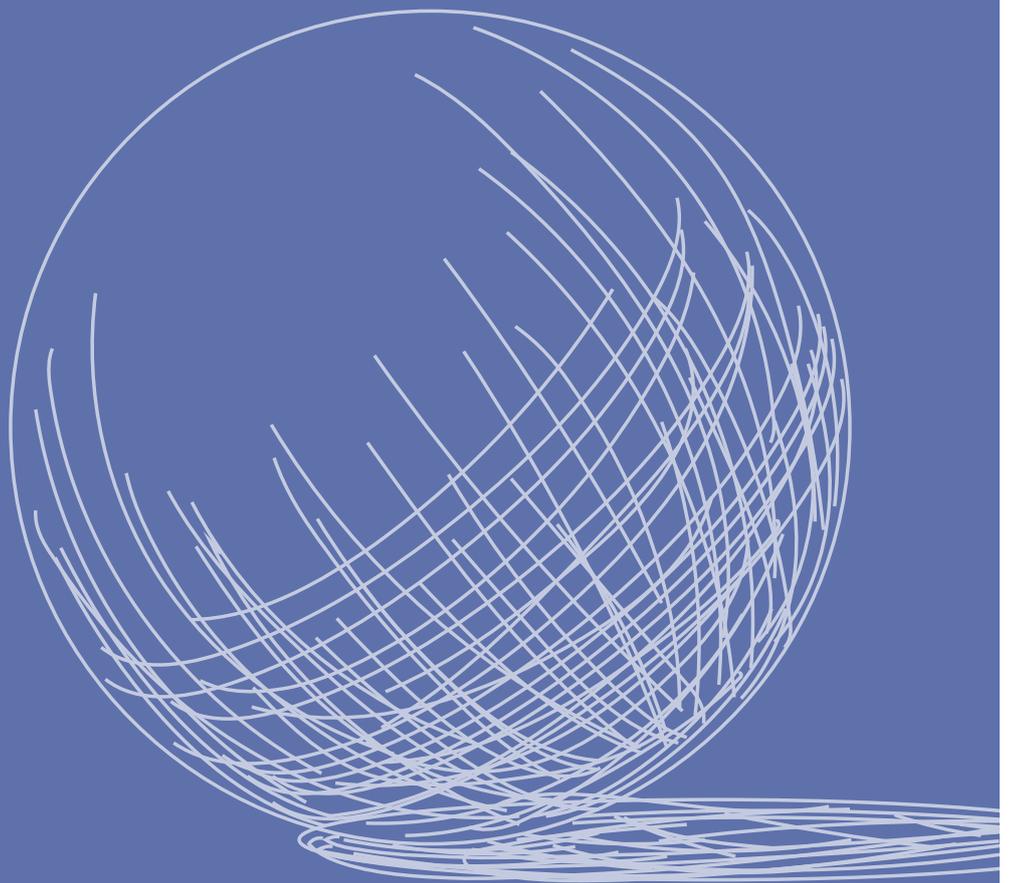
The chosen direction, the flexible employee, describes a painting robot at Royal Delft as another painter: Someone that can paint a variety of things, collaborating with the design team to develop new products or paint custom orders.

This design direction is still quite broad, making it interesting but also hard to design within the scope of this project. To make this next phase manageable for the given duration, a use case is proposed. By consulting the marketing and design team of Royal Delft, this case is representative of a custom order for Royal Delft products.

Company X approaches Royal Delft for a custom order as the company is celebrating their 20th anniversary. Roel, one of the project managers, shows the company different options of products and customization with different price ranges. The company wants around 20 pieces, all uniquely personalised with a name for their biggest partners. Roel recommends robot painting, as this method is cheaper than hand-painted pieces and provides the flexibility of creating one-of-a-kind products. The company agrees and can choose the level of customization which are:

Level 1: Predetermined design with personalised text/logo
Level 2: Modify the design by reframing an illustration
Level 3: Provide an image/logo that is redesigned in the style of the robot
Level 4: Custom made design by one of the designers at Royal Delft

The company orders:
15cm plate with level 1 customisation (15 pieces)
Tile with level 3 customisation (3 pieces)
They choose the desired illustration and the different texts for all 15 plates.
For the tiles, they provide a picture of their office building, which is redesigned by the Royal Delft design team. After the approval of the design, the chosen biscuits are collected and placed in the robot.
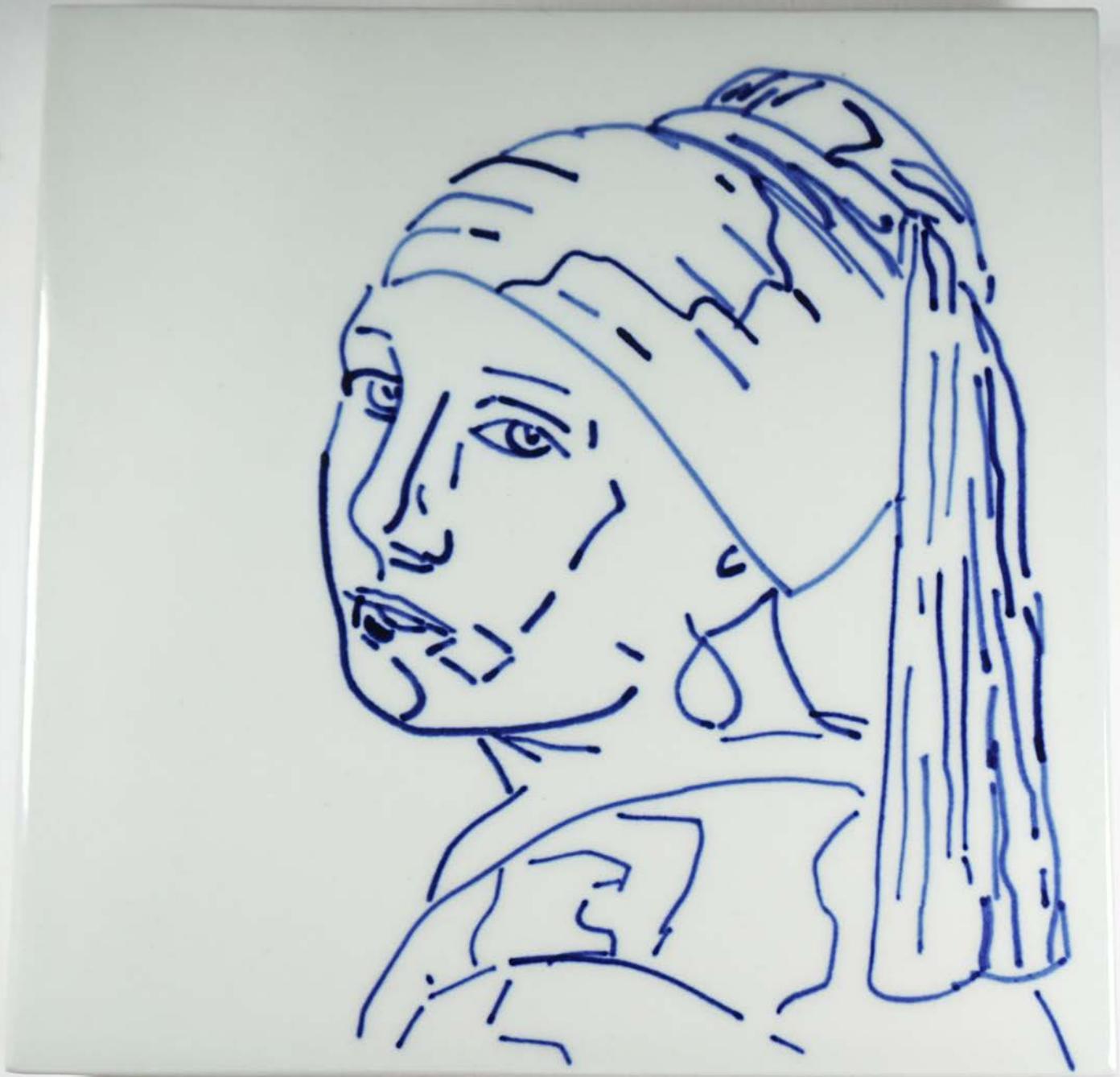
**Figure 42: Test painted with the protoype.
Example of a product that could be made.**

Figure 43: Isometric view of the demonstrator

CHAPTER 12
SUBSYSTEM DESIGN

This chapter dives into the technical challenges of the painting robot that can fulfil the use case described before. By designing a demonstrator, it is possible to validate the concept .
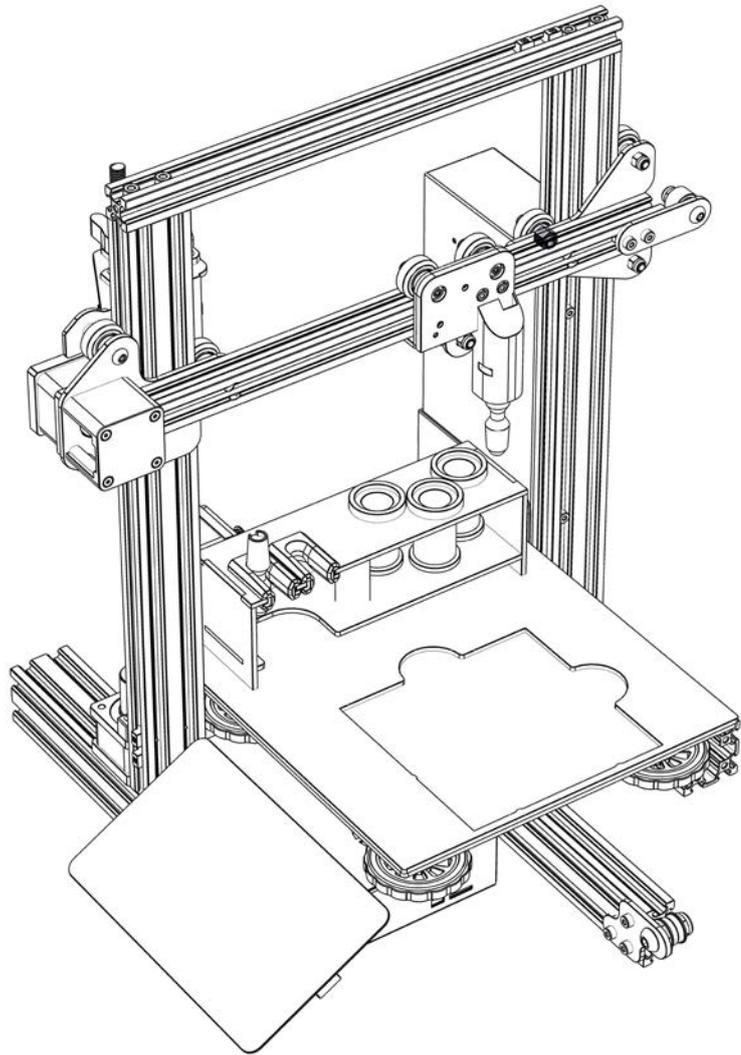
With this design direction, new functions are added to the existing prototype, described in chapter 4. The existing challenges are tackled and the new requirements from the chosen design direction are added. The most important and challenging function is the ability to paint a curved object, such as a plate.

To structure this embodiment phase where the demonstrator is developed, a system tree is made to define the different sub systems and modules needed in the demonstrator. Figure 44 shows the system tree.

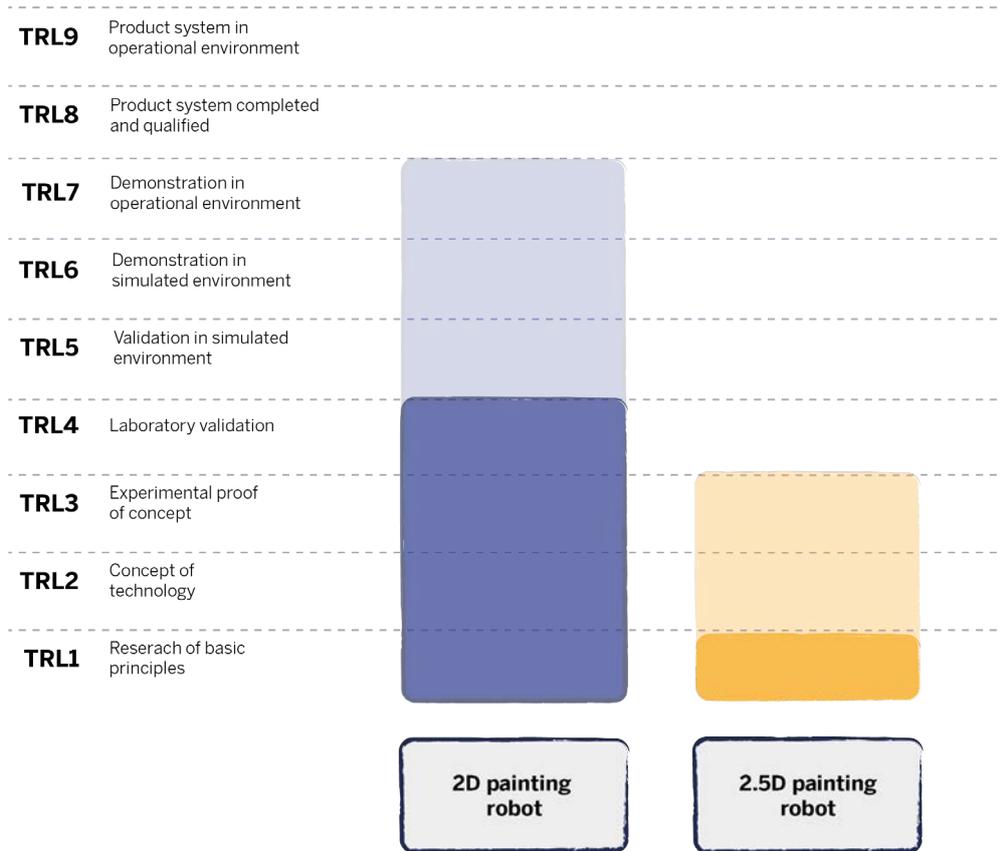| Level 0 Context	Level 1 Systems	level 2 Sub-systems	Level 3 Modules	Level 4 Components/ sub-assemblies
Painting Delft Blue	Painting robot	Motion system	Linear actuators	X motion
				Y motion
				Z motion
			Feedback system	Z probe
				X endstop
				Y endstop
		Work area	Paint head	Brush Gripper
			Brush station	Brushes
				Toolholder
			Dip station	Paint mixtures
				Stir mechanism
				Wipe mechanism
			Alignment	Tile alignment
		Control	Input system	Touchscreen
				Microcomputer
			Firmware	CNC firmware
				Web server
				User interface
			Motion control	Microcontroller
				Stepper drivers
	File preparation	Preprocessing	Gcode generator	SVG analyser
				Gcode generation
				Paint styles
				GUI
		Design creation	SVG generator	Vector graphics editor

Figure 44: system tree

TRL9	Product system in operational environment
TRL8	Product system completed and qualified
TRL7	Demonstration in operational environment
TRL6	Demonstration in simulated environment
TRL5	Validation in simulated environment
TRL4	Laboratory validation
TRL3	Experimental proof of concept
TRL2	Concept of technology
TRL1	Reserach of basic principles

2D painting robot

2.5D painting robot

Figure 45: TRL of different subsystems with the desired level after validation. The yellow systems are added when 2.5D painting is required.

12.1 TECHNOLOGY READINESS LEVELS

With the design of the demonstrator, it is important to set goals how far each system will be developed. With the use of Technology Readiness Levels (TRL), an overview is made of the desired level for each subsystem.

Due to technical challenges, the demonstrator is divided into two types. First, a demonstrator is build with the functions of painting 2D products. The second has the added functions of painting 2.5D surfaces. The goal of this project is to make a working demonstrator that can be tested in its operational environment by Royal Delft and make a proof of concept for 2.5D painting. This decision was made to keep the project manageable within the given time frame.

Figure 45 shows the current and desired TRL of both the 2D and 2.5D prototype.

As shown in the figure above, there is a difference in the targeted TRL of the systems for painting a tile (2D) versus painting a plate (2.5D). With the technical challenges in mind that are required to achieve 2.5D painting, and the given time frame of this project, it was decided to build a 2D painting robot that is able to be demonstrated in an operational environment. For the 2.5D painting, the goal is to create a proof-of-concept by testing the technology and providing recommendations for further development.

With these two goals in mind, the current and desired TRL of all the subsystems are defined and shown in figure 47.

In the upcoming sections of this chapter. The 2D demonstrator will be developed per subsystem. The next chapter will dive into the proof-of-concept of the 2.5D demonstrator.
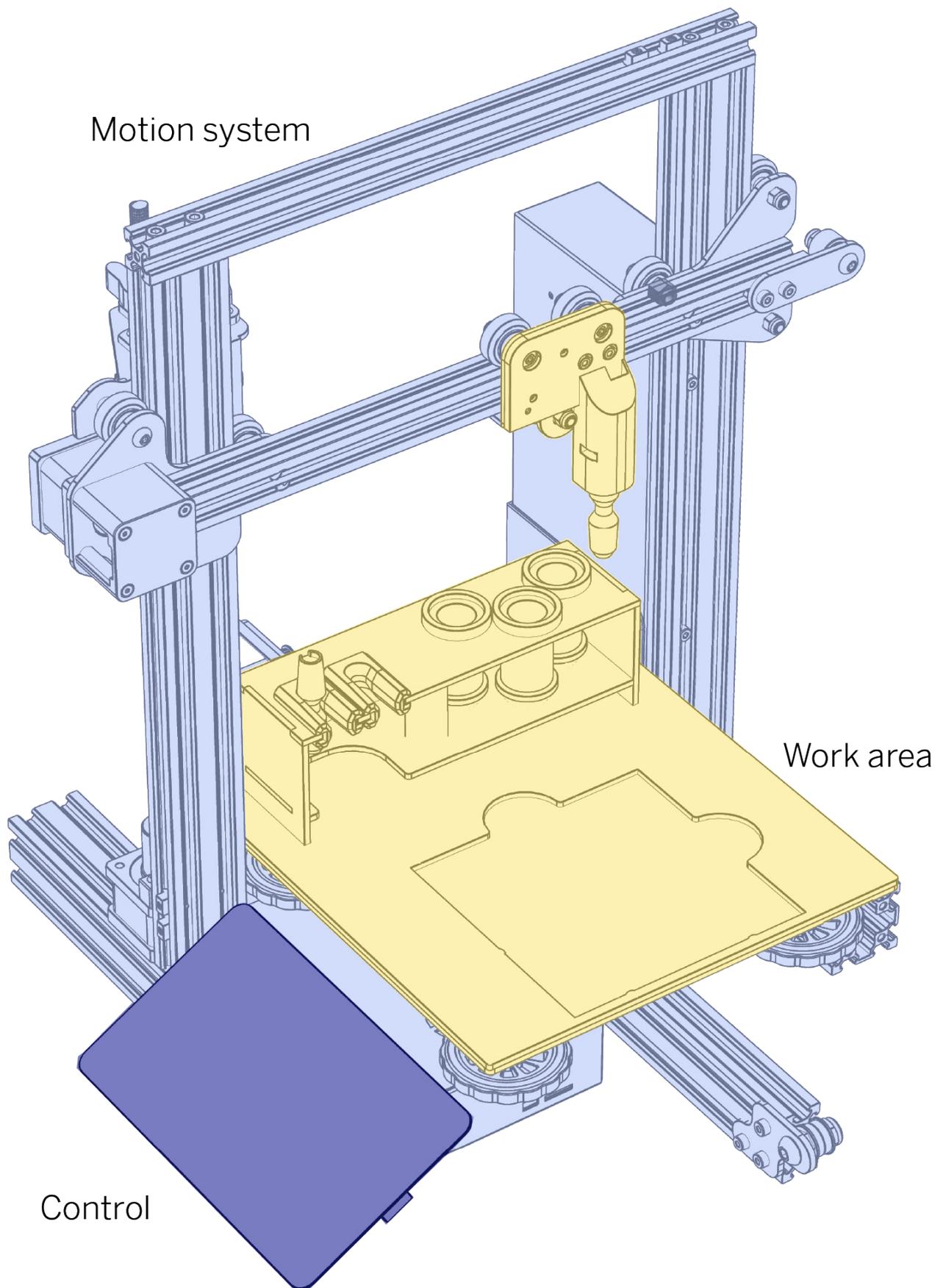
Motion system

Work area

Control

Figure 46: Overview of the different subsystems of the demonstrator.

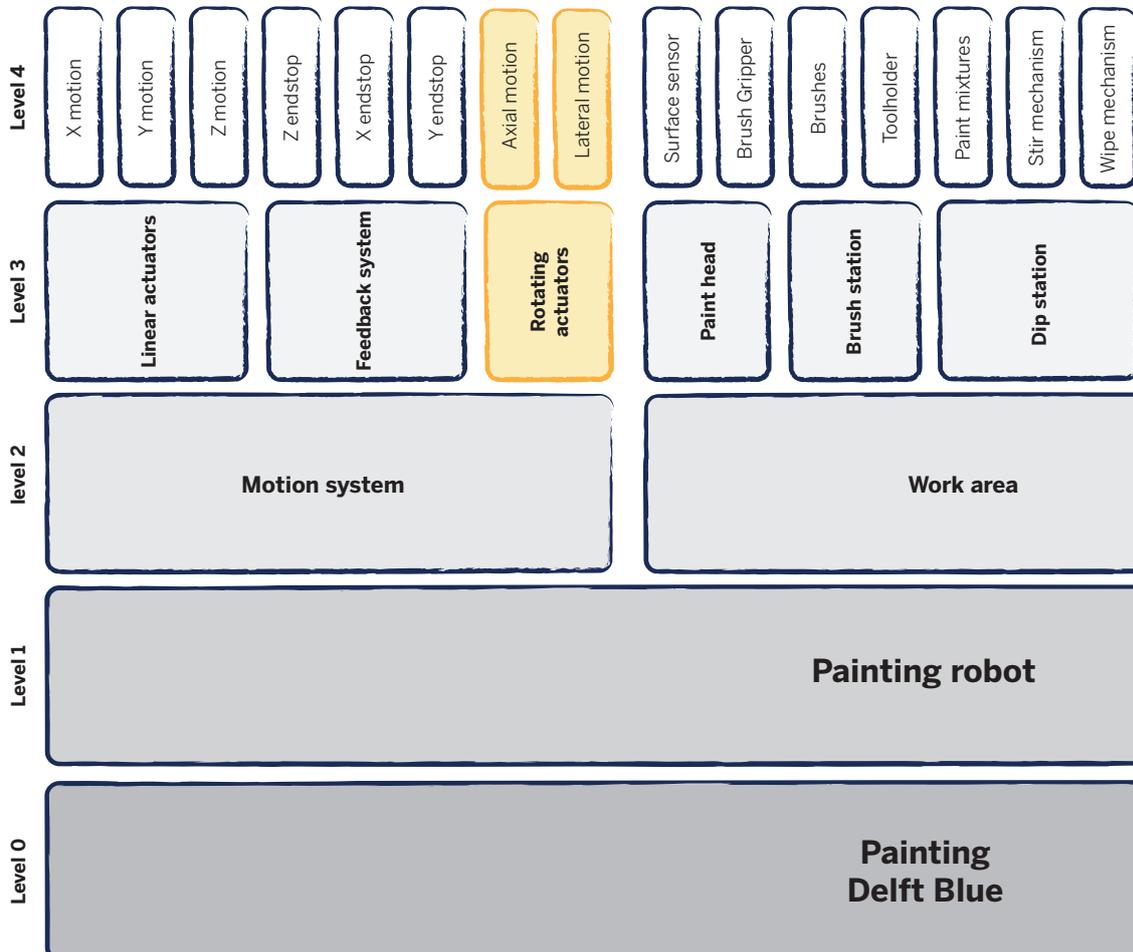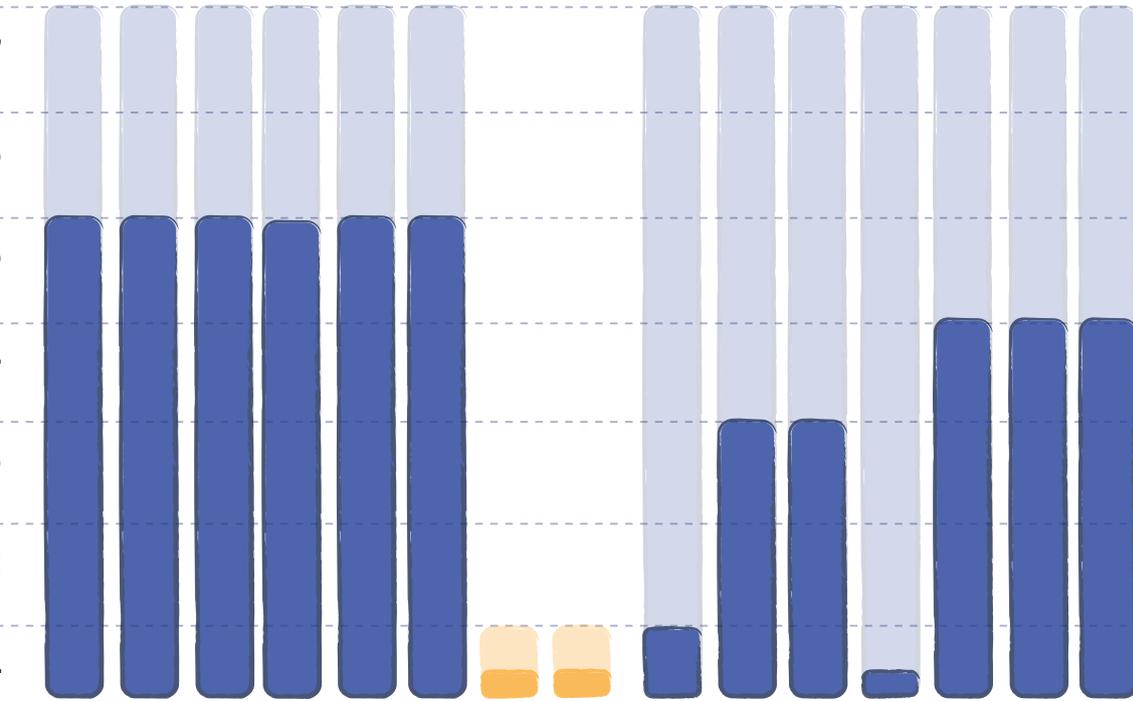# SYSTEM TREE WITH TECHNOLOGY READINESS LEVELS (FIGURE 47)
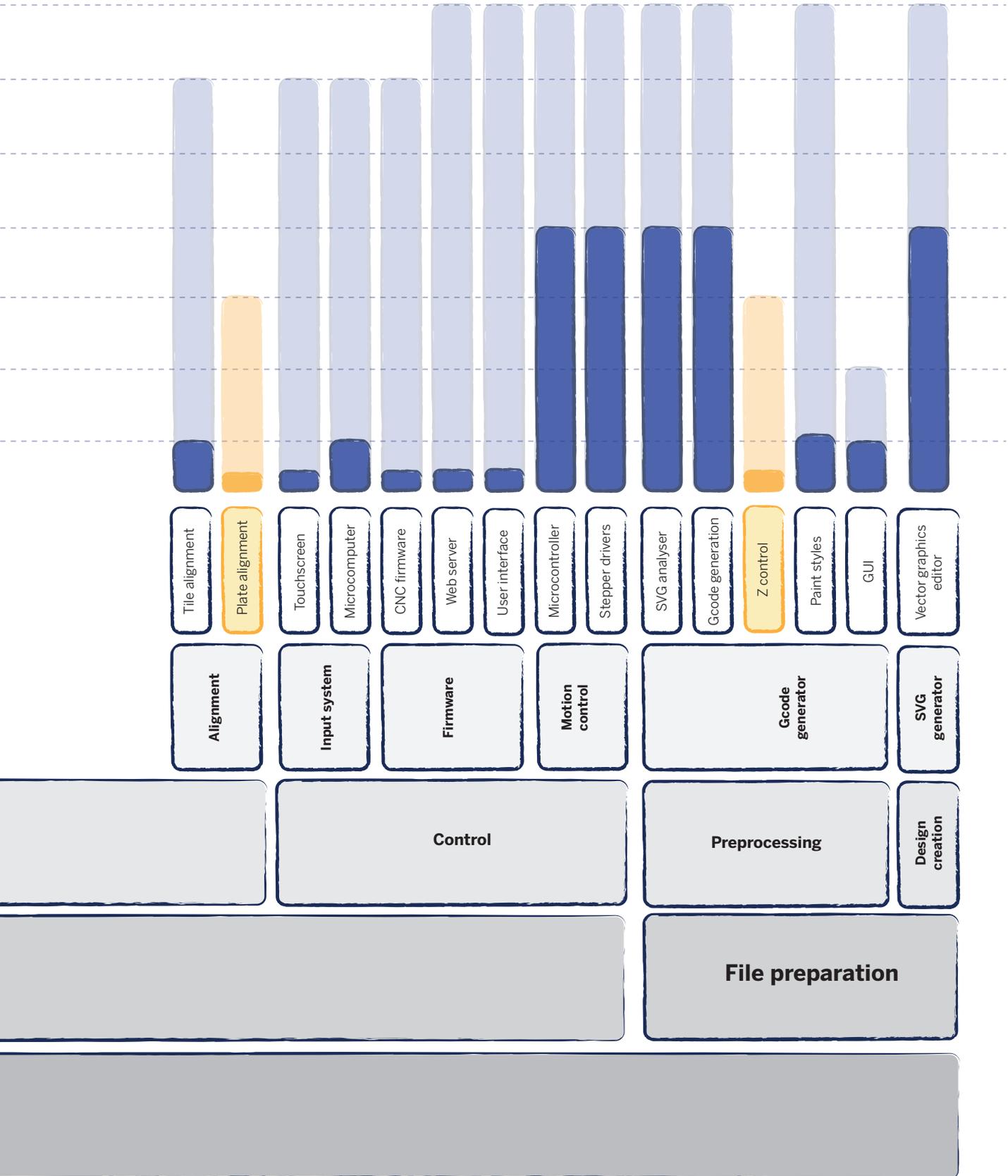

TRL9
TRL8
TRL7
TRL6
TRL5
TRL4
TRL3
TRL2
TRL1

Level 4

| X motion | Y motion | Z motion | Z endstop | X endstop | Y endstop | Axial motion | Lateral motion | Surface sensor | Brush Gripper | Brushes | Toolholder | Paint mixtures | Stir mechanism | Wipe mechanism |

Level 3

| Linear actuators | | | Feedback system | | | Rotating actuators | | Paint head | Brush station | | | Dip station | | |

level 2

| Motion system | Work area |

Level 1

| Painting robot |

Level 0

| Painting Delft Blue |

Legend:
- Current TRL
- Desired TRL
- Current TRL (2.5D)
- Desired TRL (2.5D)

Chart categories (from left to right):

Alignment:
- Tile alignment
- Plate alignment

Input system:
- Touchscreen
- Microcomputer

Firmware:
- CNC firmware
- Web server
- User interface

Motion control:
- Microcontroller
- Stepper drivers

Gcode generator:
- SVG analyser
- Gcode generation
- Z control
- Paint styles
- GUI

SVG generator:
- Vector graphics editor

Grouping levels:
- Control → (Alignment, Input system, Firmware, Motion control)
- Preprocessing → (Gcode generator)
- Design creation → (SVG generator)
- File preparation → (Preprocessing, Design creation)

12.2 MOTION SYSTEM

LINEAR MOVEMENT

In the previous project, two different types of motion systems were tested which were able to move the brush in 3 or more degrees of freedom. The first type was a Cartesian system with XYZ movement. The second type was a robotic arm with 6 degrees of freedom. Even though the robotic arm had more freedom and could perform more complex movements, the Cartesian movement system was preferred. Due to the inaccuracies of the robotic arm, caused at the joints of the robot, it was more difficult to perform precise movements. They also concluded that three degrees of freedom was sufficient for painting 2D surfaces.

Festo is an expert in motion system, which is why they were consulted for advice on different solutions that would be beneficial to use for a painting robot. The criteria for the movement of the robot helped with choosing a system. The most important criteria were the operating dimensions in which the robot has to move the brush. Festo suggested a H-bridge gantry system (as seen in Figure 48), which has a relative small form factor.

Unfortunately, within the time frame of this project, we were not able to implement such system in the demonstrator, but they provided with insights for the final design which will be covered in the conclusions of this project.

For the demonstrator, the choice was made to use the existing Ender3 frame that was used for prototyping. With small moderations to the electronics, this would be suitable for a demonstrator.

FEEDBACK SYSTEM

For homing the Cartesian motion system, regular end-stops are convenient options for the X and Y axes. The Z-axis is equipped with a probe (such as the BLTouch). This probe is attached to the paint head, which will be developed in the next part.
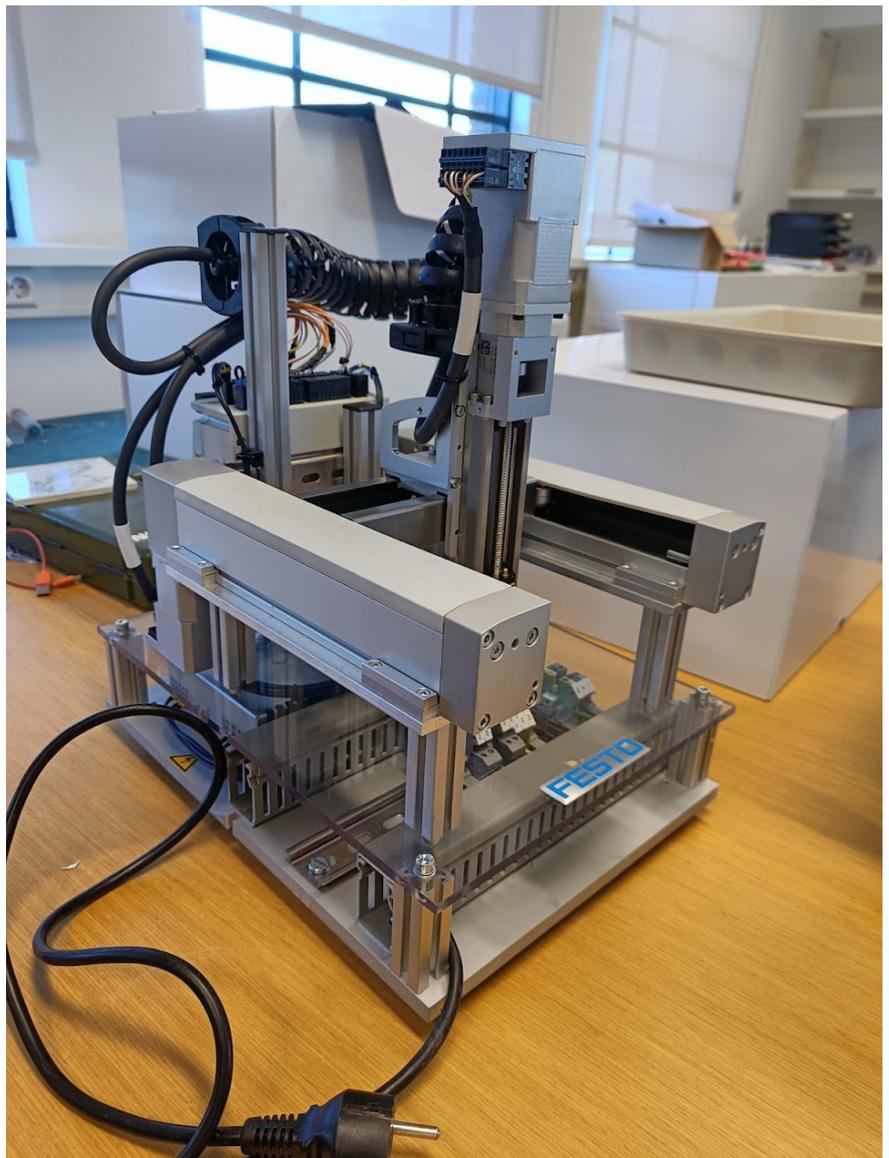
Figure 48: example of a Festo H-gantry system

12.3 WORK AREA

PAINT HEAD - PROBE

The irregular surface of the biscuit was one of the issues to overcome after the previous project. The painting surface of a tile can fluctuate with + - 1 mm, meaning that these dents drastically influence the consistency of the painting robot. The robot is set at a specific Z height to create enough pressure for the tip of the brush to paint the surface. It does not take the differences in height into account, resulting in hovering above the surface or plunging too deep into it.

This issue can be solved by measuring the height difference of the tile before starting the painting process so that the robot can compensate by lowering or raising the brush when the height of the tile changes.

4 methods are described below, each with a different level of complexity.

Drag knife

Providing pressure with a spring, the pencil is attached to a wheel that follows the height contour of the painting surface.

Probing

By measuring the height of a specified grid, a mesh is created that is used to actively change the height during the print, to compensate for small differences.

Impedance

Using an active feedback loop with an impedance sensor, the system can actively change the height of the system to compensate for large differences and irregular surfaces.

3D scan

By creating a digital twin of the product by scanning the surface beforehand, the system could move the pencil around the object, compensating for height differences.

Figure 49: BLtouch probe sensor

Choosing a method

After considering the different options, probing had to most potential for measuring the height of the tile. A drag knife system would need to touch the surface while painting, which could interfere with the already painted lines. Impedance requires the ability to measure the pressure of the brush on the tile. Because the brush is made of marten hair, this can not provide the pressure needed.

Finally 3D scanning the surface would be interesting, but sensors for implementing this would be a lot more expensive than a probe.

BLTouch

The probe sensor chosen for this demonstrator is a BLTouch probe.

This sensor probes each point on a grid individually and saves the mesh for painting. To analyse what was the optimal number of mesh points, different mesh resolutions were tested (see figure 50). A mesh of 7x7 resulted in the best performance while keeping the probing time acceptable (3 minutes for 1 tile).

Figure 50: Mesh resolution test

DIPSTATION

To paint a Delft Blue tile, the brush needs to be dipped regularly to paint consistent lines. Continuing on the previous research done on auto-dipping the brush into the paint, this section will focus on further testing different solutions and finding the best method to dip and paint.

Method of master painters

To make full use of the brush, the painters dip this thoroughly, filling the 'reservoir' of the brush. By laying the brush flat in the paint and turning it, they evenly fill the brush, after which they prime it on a small piece of paper to get a consistent line (as described in the process analysis).

The current prototype is not able to position the brush as a painter does. The brush is positioned vertically, making it unable to dip the reservoir of the brush on a flat plate with paint. This can be compensated by creating a narrow paint reservoir, where the brush is fully submerged while minimizing the amount of paint needed.

The paint mixture needs to be stirred often to prevent the paint from separating and the cobalt from falling to the bottom of the reservoir. The previous project solved this issue with a stirring station using magnets to continuously stir the paint, inspired by an electric lab stirrer.

Continuous paint refill

Another solution to keep the brush filled with paint is to use a syringe that continuously adds a small amount of paint to the brush. This means that the brush does not need to be dipped and could paint lines continuously. This method was tested, and the results showed potential in creating extra long lines without needing to dip the brush. However, this test also gave some other insights:

The paint separates in the syringe, meaning that a stirring mechanism should be developed if this method was chosen.

Automatically dipping the brush is one of the more exciting elements of the robot for viewers. Taking this away would probably result in a less entertaining product.

Figure 51b: Example of a magnetic lab stirrer

Figure 51c: Testing a syringe to feed paint continuously.

Figure 52: The new tool/dipstation

Design of the dipstation

The dip station contains the different colours of paint which the robot uses while painting. This system was already developed within the previous prototype. The inspiration came from lab stirring machines, which uses a rotating magnet to continuously stir the liquid remotely. The containers hover above a small rotating magnet which are actuated by a small DC motor and a couple of gears.

The different colours that are suggested depend on the type of decors the user wants to make. For a good range of colours, the ratios 1.2/10, 0.9/10 and 0.6/10 (grams paint/water) are recommended. The user has the option to change a container for other colours (for polychrome designs) or even gold lustre.

BRUSH STATION

The brush station holds the different brushes the robot can equip during painting. The robot is required to automatically change tools during painting, meaning that a reliable tool changing system had to be designed.

Figure 52 shows the design of this system. The tool changer is designed to easily change brushes with the use of magnets and self-aligning shapes. When picking a brush, the tool head aligns above the brush and slowly moves down. The magnet snaps in place and the brush can be removed from the holder. To remove the brush, the tool head makes the opposite movement and the brush is locked in place due to the double conical shape.

ALIGNMENT

Aligning the tile in the demonstrator is used with a laser-cut insert. The user can place the tile in this insert and press it against the three protrusions, fully defining the tile, while compensating for the crooked shapes.

12.4 CONTROL

INPUT SYSTEM
The screen of the Ender3 is replaced with a Raspberry Pi 3B+ and a 7-inch touch screen. By using a small single board computer such as the Raspberry Pi, the robot has wireless accessibility through Wi-Fi and a more pleasant interface that is easier to use. The Raspberry Pi is used to host a server to monitor the robot from a distance. Next to that, it replaces the motherboard of the 3D printer for processing the G-code, which will be explained in the software section. The benefit of this change is that the Raspberry Pi has a lot more processing power, which result is steadier movements at higher speeds and less noise.

FIRMWARE
The firmware used on the demonstrator is called Klipper, an open source 3D printer software that can be customised for other applications. This software is flashed on the Raspberry Pi, which makes it possible to use the processing power of the Pi for controlling the robot. With this increased power, the robot can move faster and more accurate with less noise.

This firmware uses a configuration file where someone can change the set system variables to their needs. The full config file can be found in Appendix B. In this file the stepper motors for each motion system is configured, together with commands such as measuring the surface of the tile as creating custom macros.

Macros
These functions called macros are a unique feature of Klipper. Within the config file someone can create custom G-code commands that can execute a series of G-code lines based on different variables.

Figure 53: Touchscreen of the demonstrator with Klipperscreen.

For this application, macros were used to create functions for dipping the brush and changing brushes. These functions depend on which colour is selected or which brush is currently in the tool holder. With the use of macros, the generated G-code that start a job, only has to call the macro, and the firmware selects the correct colour or brush.

USER INTERFACE
Fluidd
To make the demonstrator user-friendly, a web server and user interface are installed. Fluidd is the open source user interface used for this demonstrator. This software comes with a customisable web interface that is accessible on a local network. Through this interface, it is possible to control the demonstrator, upload new jobs and start these jobs. It is also possible to edit the configuration file and monitor the status of the demonstrator.

Moonraker
Moonraker is an API that Fluidd uses to connect to the Klipper firmware on the demonstrator. This is also installed on the Raspberry Pi.

Klipperscreen
To control the demonstrator directly, Klipperscreen is used to create a user-friendly touch screen interface. From this interface, the user can access macros or directly control the demonstrator and start jobs.
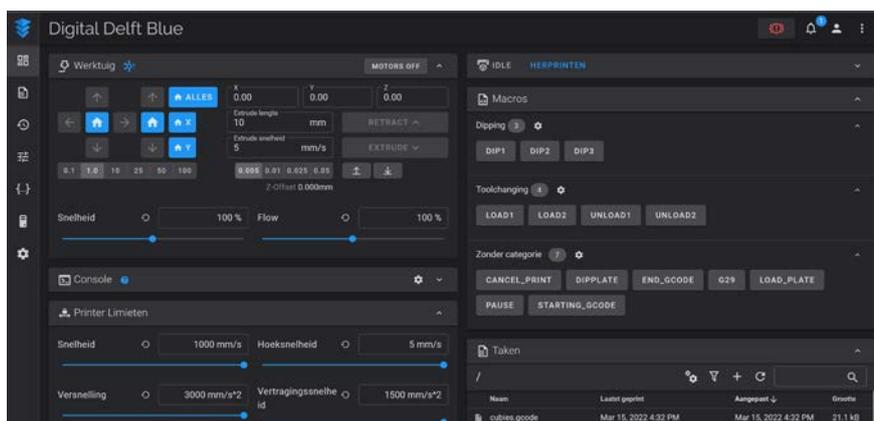

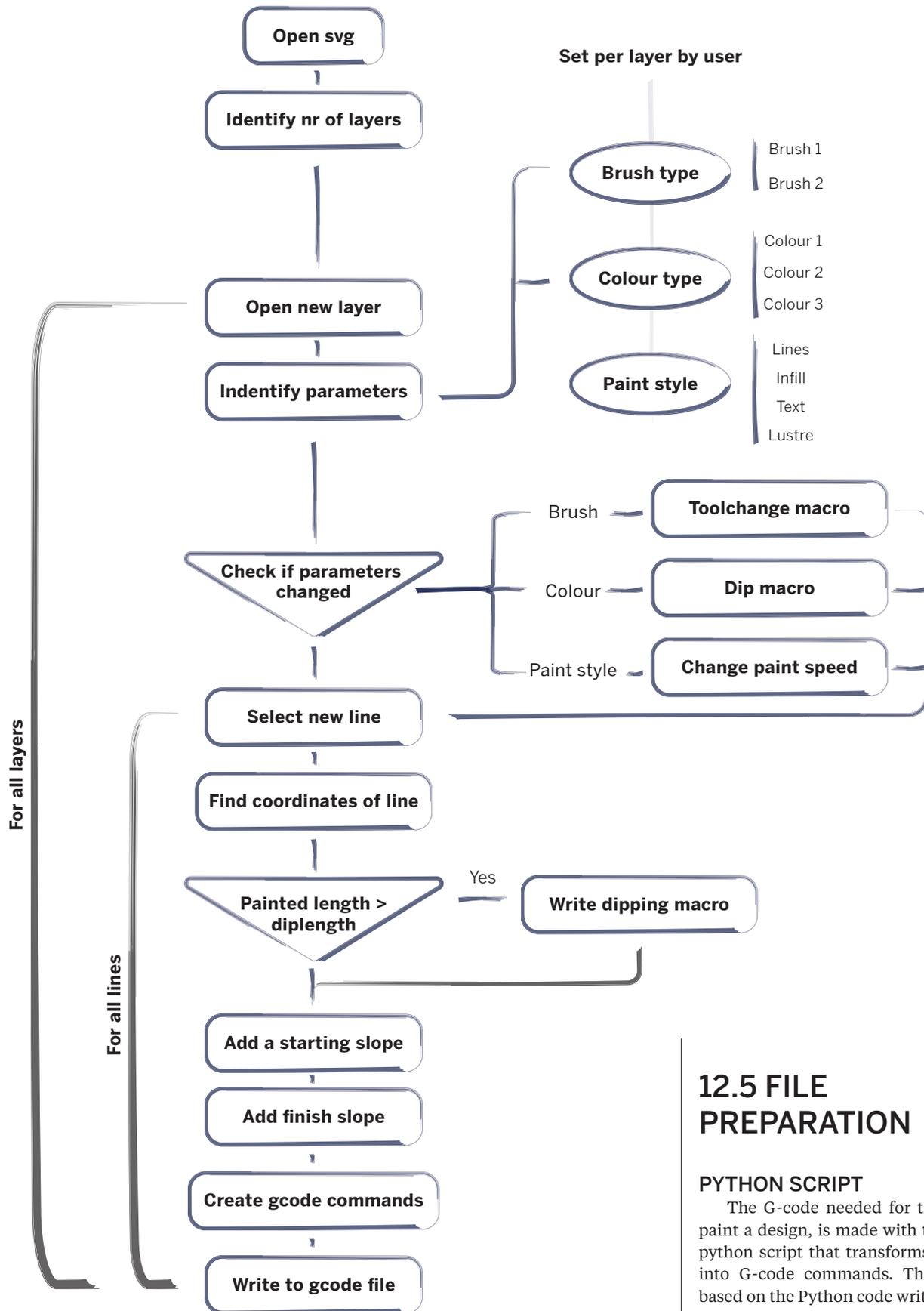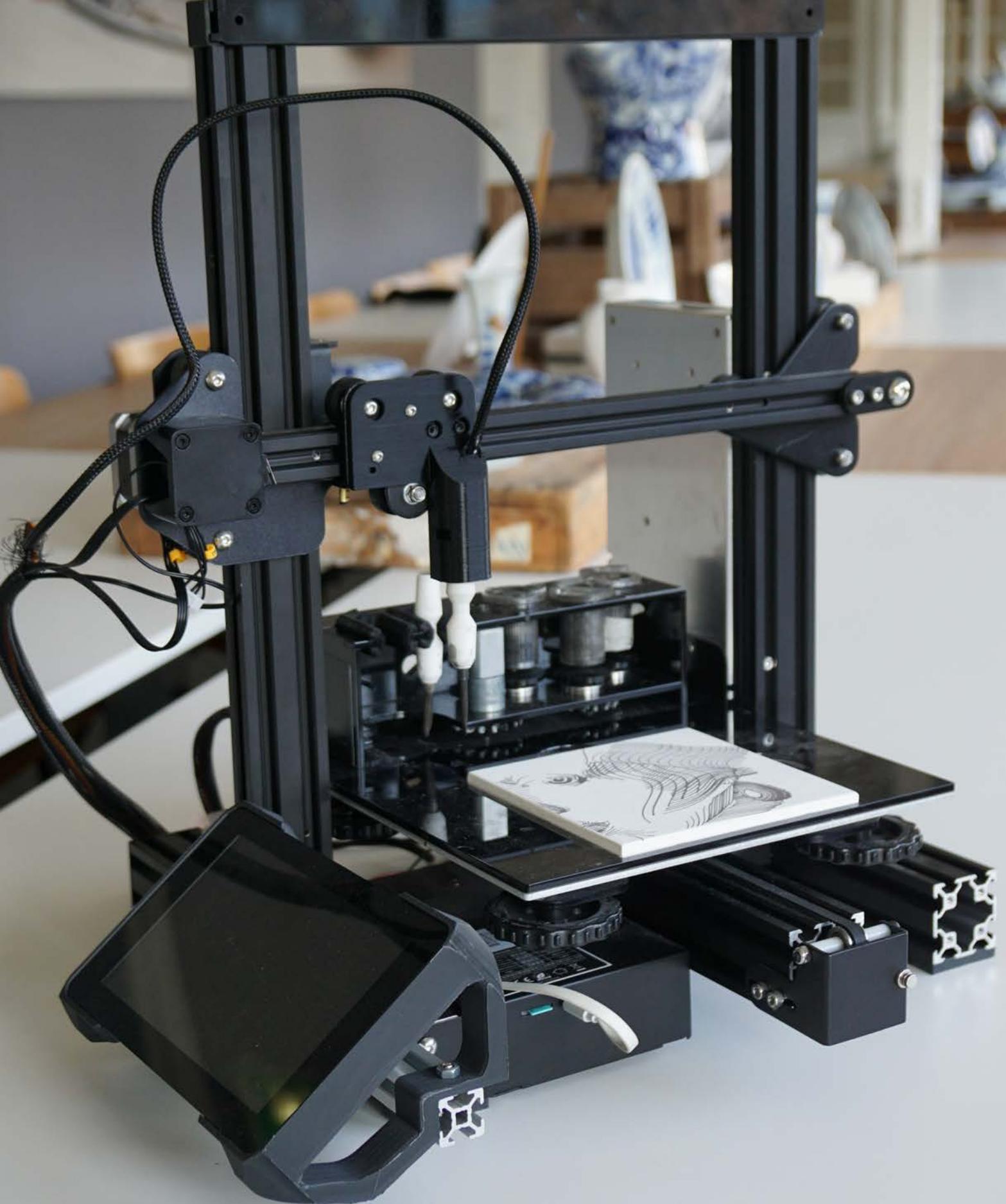
Figure 54: Screenshot of Fluidd web interface.

Open svg

Identify nr of layers

Set per layer by user

Brush type — Brush 1 / Brush 2

Open new layer

Colour type — Colour 1 / Colour 2 / Colour 3

Indentify parameters

Paint style — Lines / Infill / Text / Lustre

Check if parameters changed
- Brush — Toolchange macro
- Colour — Dip macro
- Paint style — Change paint speed

For all layers

For all lines

Select new line

Find coordinates of line

Painted length > diplength — Yes → Write dipping macro

Add a starting slope

Add finish slope

Create gcode commands

Write to gcode file

Figure 55: Flowchart of the Python G-code generator

12.5 FILE PREPARATION

PYTHON SCRIPT

The G-code needed for the robot to paint a design, is made with the use of a python script that transforms a SVG file into G-code commands. This script is based on the Python code written by Lennart Krieg, one of the team members that build the previous prototype. It is altered to work more efficiently, and new functions were added that are new for this demonstrator. The flowchart in figure 55 shows a schematic overview of the steps taken in the script to create a G-code file from a SVG. The complete Python script can be found in Appendix C.

FEATURES

Easy alignment

Auto dipping

Intuitive user interface

Surface mesh compensator

3 different colours at a time

Auto tool changer
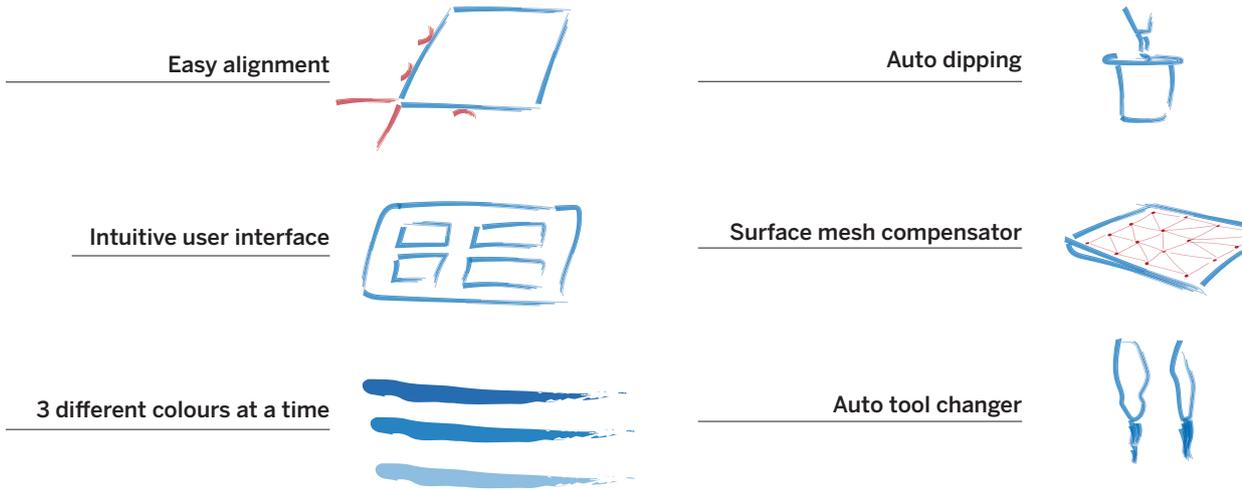
CHAPTER 13
THE 2D DEMONSTRATOR

With the last subsystem covered, the 2D demonstrator is finished. The robot is capable of painting Delft Blue tiles from start to finish without any interference or adjustments from a user. This overview covers the functions and the user scenario.

SCENARIO

Start

Misch|

Create digital painting

Mischa

Group lines for preprocessing

.SVG

Save as SVG file

Layer 1:
Colour 1
Brush 2

Assign colour and brush to line groups in Python code

>Python

Run code to create G-code file

.gcode

Upload G-code to robot via web-interface

Load robot with new biscuit

PAINT ▷

Start job

Finish

Figure 56: Laser scanner used for this project.

CHAPTER 14
2.5D PAINTING

As the demonstrator for painting 2D products is fully designed, the next step is to develop the technology to create a proof of concept for 2.5D painting. The different subsystems for this, shown in the TRL overview on page 62, are tested and developed in this section.

DEFINING 2.5D

2.5D painting has been mentioned several times in this report, which meant the action of painting on plates or other shallow products. To start developing the subsystems for this, it is important to understand what is meant with 2.5D painting and when something is not considered 2.5D within the scope of this project.

2D painting is applied when the decoration is on the same plane for the whole product. Being it a tile or the flat top of a lid. A flat surface may have slight variation, as delftware is not always perfectly flat. This variation can be up to 1 mm.

2.5D means that the surface is slightly curved up to 45 degrees. The decoration on the product can be seen from one side, and the curves within this decoration are not abrupt. Products such as plates and dishes fall in this category.

3D painting applies to curves over 45 degrees and products that have a decoration that wraps around it, such as bowls, vases, and figurines .

2D   **2.5D**   **3D**

Figure 57: Different product examples for 2D to 3D painting. Image retrieved from royaldelft.com

PRODUCT DIMENSION VARIATION

As discussed in chapter 4, the surface quality of tiles varies significantly per tile to influence the paint quality if the slight change in height is not taken into account. This is due to the material and manufacturing method. Tiles are extruded and cut into rectangular pieces. This method causes deformations, resulting in uneven rectangles and small indents in the surface. Due to the manufacturing method of the biscuit, no product has exactly the same size. Due to shrinkage of the clay mixture and wear of the mould, the biscuits have low tolerances. It is important to know the average variations in different dimensions per product.

Tiles

In contrast to other products that are cast in a mould, tiles are produced by extruding the clay mixture and cutting it into rectangles of 13×13 cm. These tiles are not perfectly straight and differ each by a certain amount. The differences in height are addressed in previous chapters, but the overall shape and differences between each tile are also critical. To get an understanding of these variations, a large number of tiles were measured in different batches. The outer dimensions varied from 126 mm to 131 mm in both directions. The contours were not perfectly straight with dents from almost 1 mm. The top of the tile was measured with the BLTouch on a 7×7 grid. It measured variations of 0.5 mm excluding the edges which slope down drastically.

Plates

Plates are made by pressing the clay into moulds at Royal Delft. Shrinkage is the largest problem of dimensional inaccuracies. However, this manufacturing method results in a higher accuracy compared to the tiles. After measuring different plates, and comparing three different 3D scans, the dimensional differences were within 0.5mm range.

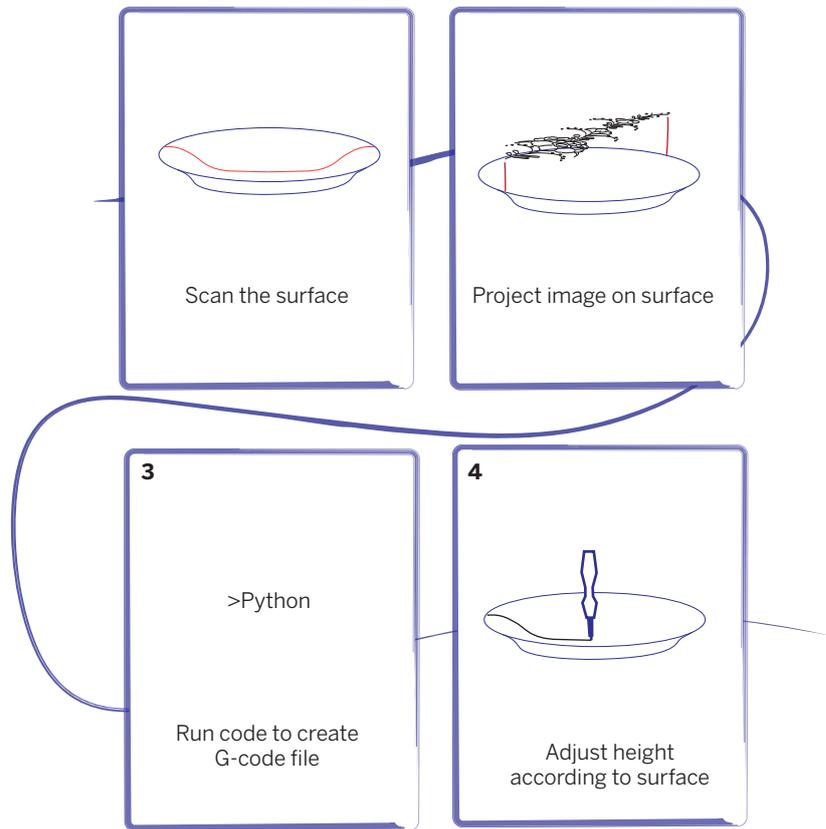|	
Scan the surface	Project image on surface
3 >Python Run code to create G-code file	4 Adjust height according to surface

Figure 58: Steps taken to paint a plate by adjusting the Z height to the surface.

SUBSYSTEMS

To move towards 2.5D painting with the current demonstrator, the required subsystems need to be developed. As shown in the TRL overview on page 62, these systems are:

- Rotating actuators
- Height sensor
- Alignment
- Z control

These systems are required to do the following: A plate must be placed in the robot (alignment). The robot must know the shape of the paint surface (Height sensor). It has to adjust its Z height so that the brush follows the surface of the plate (Z control). Finally, the brush might need to rotate to paint accurately on the curved surface.

These subsystems are developed in the next section. However, to start the development, a technique is chosen to scope down the process.

Selecting technique

With the product dimension variety known, it is possible to select the most promising technique to measure the surface of a plate.

Different sensors and techniques were discussed. The two measurement systems that will be used for further testing are a 3D laser scanner, and a laser distance sensor. These types of sensors have a high accuracy and a very small measure area. Both sensors have options to mount on the robot paint head, making them promising options as a height sensor for the painting robot.

Following this section, a proof of concept is made using the 3D laser scanner technique. With these tests, the goal is to get a better understanding of the challenges and potential of painting 2.5D objects. With the insights from the proof of concept, recommendations are made for further development and implementation.
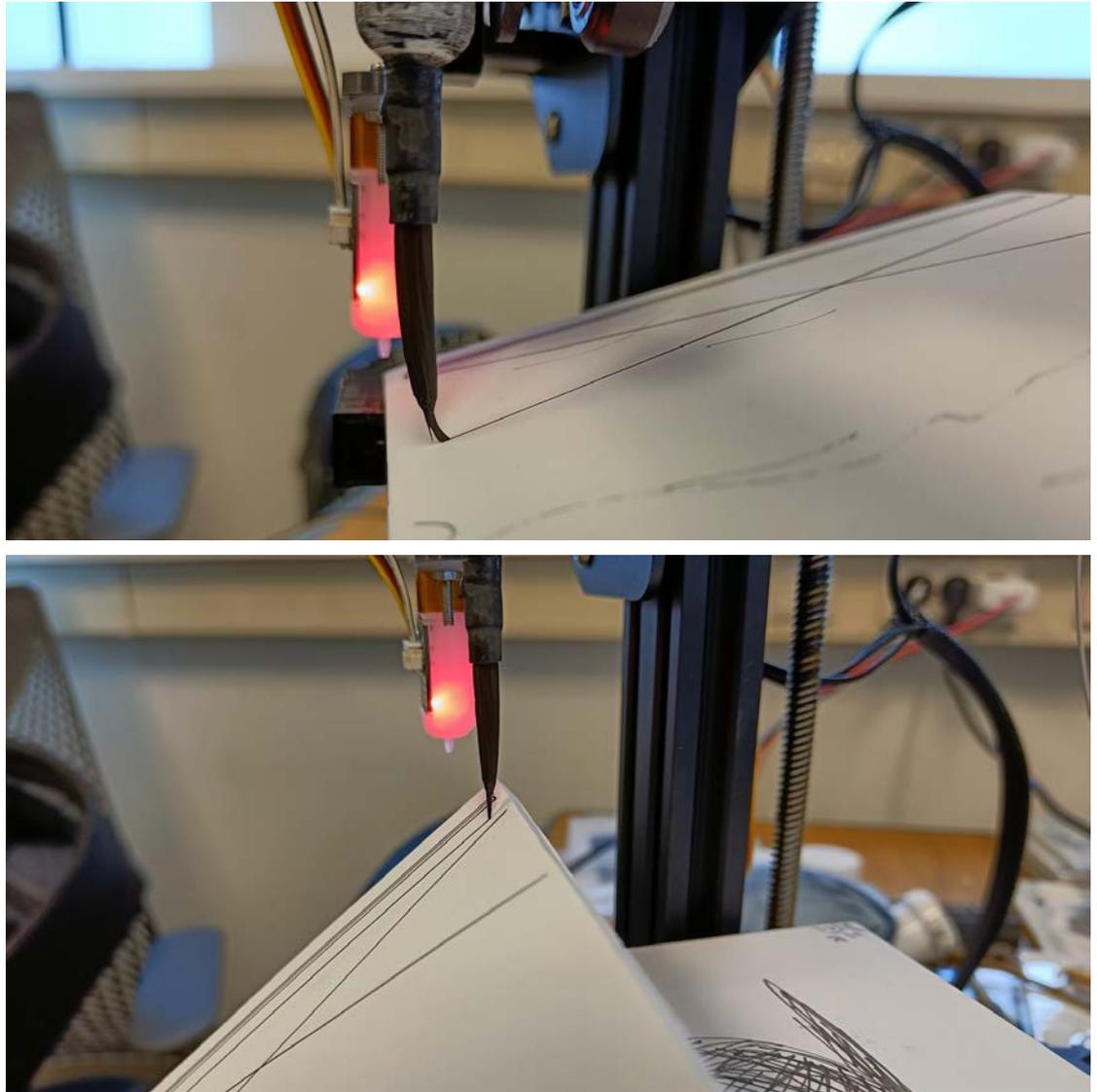
14.1 SUBSYSTEM: MOTION

So far, the brush orientation on the painted surface has been approximately perpendicular. When introducing products with relief, the angle of the surface relative to the brush changes. Multi axis robotic arms are known to adjust the angle of the brush so that the tool is always in the correct orientation towards the surface. Whether this is needed for the painting robot depends on the performance of painting on a tilted surface and the steepness of the product.

The target products (plates and dishes) regularly have a maximum steepness of 45 degrees. Figure 59 shows the tests done on a tilted tile at a 45-degree angle.

The results show that painting upwards does not affect the quality of the line significantly. However, painting downwards results in buckling of the tip, creating an offset of the painted stroke, which is not desirable. This means that painting at an angle up to 45 degrees is sufficient if the stroke is made in an upwards motion.

Although three axes are sufficient in this use case, it is not ideal for accuracy and precision. Having the brush at the same angle at all times improves the accuracy and simulates the motion of real painters better. However, to keep this project doable within the given timeframe, the hardware will be tested with three axes, as more means a large amount of extra hardware and software to control these axes.

As shown in the tests, the brush needs to paint from low to high to maintain accuracy and prevent the tip from buckling. This can be achieved within the preprocessing software, where the start of a line is always the lowest Z value.

Issues arise when a line goes up and down in Z height, for example, when a line is drawn on a plate from end to end. To solve this, the preprocessing software should split these lines at their lowest points, so that the robot paints them in two parts, always starting low and finishing high.

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Figure 60: 3D scanning the plate

14.2 SUBSYSTEM: HEIGHT SENSOR

This section focuses on imaging the surface of the painted product. Different methods and techniques are discussed and tested to develop a constructive recommendation for the final design.

A number of plates are scanned with a NextEngine 3D laser scanner. This scanner can create an accurate surface scan of the top curvature in 5 minutes. This is relatively slow compared to commercial grade line laser scanners, but this specific scanner is 20 years old, meaning that current scanners would be faster.

The benefit of using this scanner over a more modern scanner, like the Artec Spider, which is a blue light scanner, is that the smooth white surface is hard to capture with a hand scanner, while perfect for a laser scanner. The scanner moves the product around, knowing exactly where each point is measured, perfectly aligning the final scan parallel to the ground.

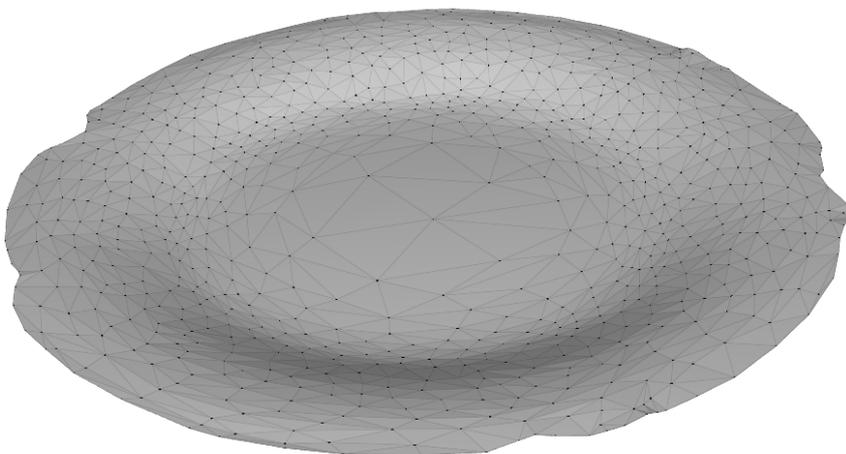One of the scans is shown in figure 61.

Figure 61: 3D scan of the plate

Figure 62: First test plate painted with the same calibration decor.

14.3 SUBSYSTEM: HEIGHT CONTROL

With the surface of the plate known, the next step is to make the generated G-code from a SVG follow this surface.

This can be done within the same Python script that transforms the SVG into G-code. However, when looking at other digital manufacturing techniques, there is already software that can do this efficiently.

CNC milling uses computer-aided manufacturing (CAM) software to create paths to transform the material. This software has a function to project an image on a curved surface, or in this example, a mesh.

With Fusion 360, the project function was used to create a 3D path of G-code commands that follows the 3D scanned surface (see figure 63).

This generated G-code is post-processed in a new Python script that makes sure that all the paths are painted upwards, as described in the Motion subsystem. It also adds the functionalities of the other script, such as dipping and tool changing macros.
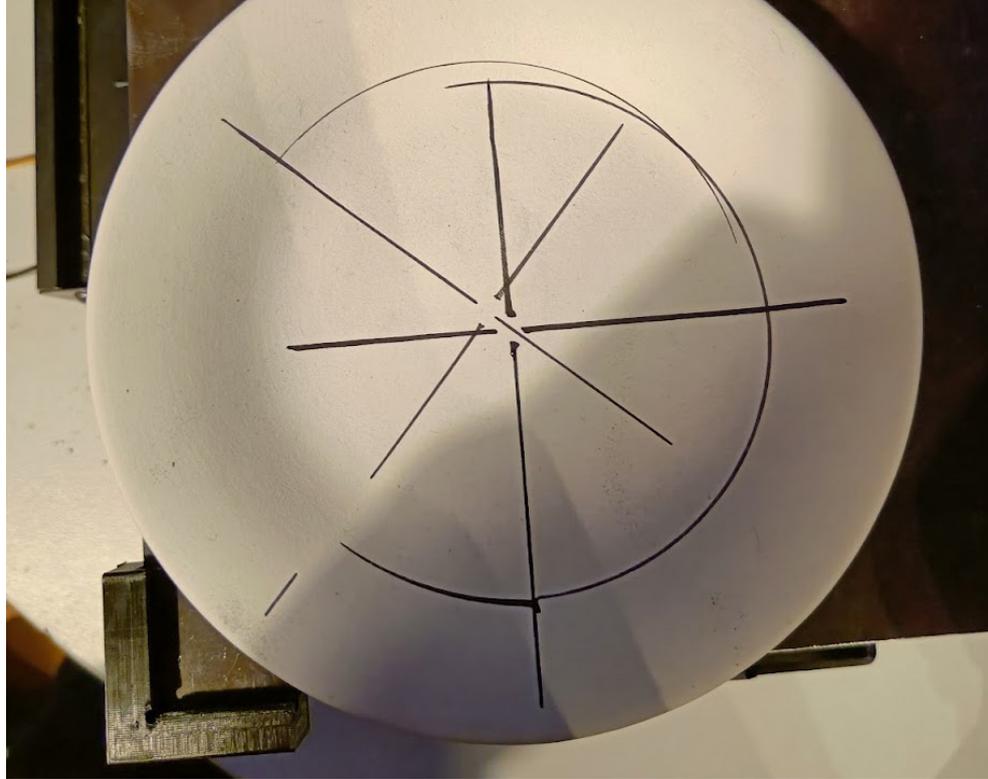
TESTS

With the subsystems set, the first plates were ready to be painted. To see how the brush would follow the surface of the plate, a simple shape was used that covers different areas of the plate (figure 62).

After the first plate was painted multiple time, it was substituted with another plate. The same 3D scan was used for this plate.

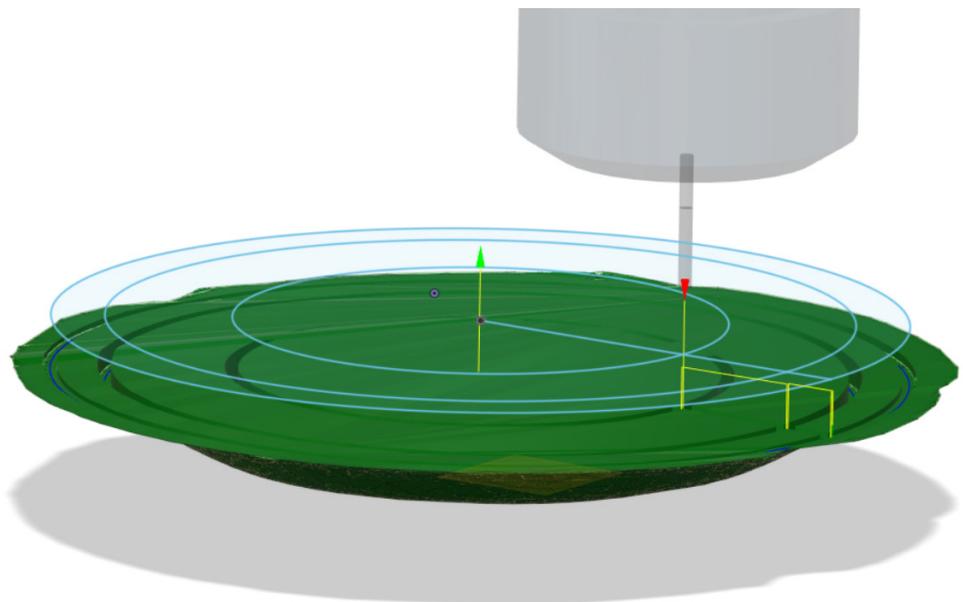The following tests consisted of simple shapes and a more challenging flower decor.

Figure 63: Projection function of Fusion 360 CAM software.

14.4 MAIN TAKEAWAYS

INDIVIDUAL SCAN OR DIGITAL TWIN

For the implementation of this technique in a final product, it is important to know whether a scan is needed for each individual product, or if it is possible to use the same scan for the same type of product. This would mean that Royal Delft could create a digital twin for each type of plate and use these for the painting robot, with scanning a new digital twin after a while to compensate for any changes to the mould.

Unfortunately, with the results of different plates painted with the same 3D scan, it showed a lot of variations in quality. The products differ too much due to the manufacturing method and the shrinkage of the product while drying. With the current technique, using one digital file to decorate multiple plates consistently is not achievable.

LACK OF CONSISTENCY

So far, the proof-of-concept lacks promising results in terms of consistency and quality. Due to the fact that each test would need a new surface scan, creating a proof-of-concept was time-consuming and there was no room for errors. When a plate had a small mistake, a whole new 3D scan had to be made of a new plate, to keep accuracy.

These small mistakes, where the brush would miss the surface of the plate at different points, can be explained by a accumulation of small irregularities of the following:

• Alignment
• Brush
• Scan

Alignment

Aligning the plate correctly (position and angle), with the 3D scan was challenging as there were large tolerances and the angle was positioned by hand.

Brush

As seen many times during this project, the brush brings a lot of uncertainties in the system. If it is not positioned perfectly at the right distance to the surface, the brush will either bend, causing artefacts in the shape of the line, or not touch the surface at all. The stiffness of the brush can influence if the brush stays perfectly straight, or if it bends over time, offsetting the painted lines.

Scan

The scan needs to be post-processed to remove noise and reduce the file size. This was a manual job, meaning that the post-processing could also cause the scan to alter from the original shape a bit.

PART IV: VALIDATION & EVALUATION

With the demonstrator finished and working, it is time to validate and evaluate the design choices. To structure this part of the project, this process is divided into the three pillars of integrated product design: Feasibility, Viability and Desirability. The concept will be validated and evaluated on each of these aspects.

FEASIBILITY

The feasibility of the demonstrator is validated by evaluating the quality of the painted products with a master painter and creating a final product that showcases the technological affordances of the demonstrator.

15.1 PAINTING PERFORMANCE

The finished demonstrator was used to paint a variety of tiles and plates to test the painting performance.

2D PAINTING

These tiles are evaluated together with one of the master painters at Royal Delft. To evaluate the overall quality of the painting, the demonstrator is evaluated on speed, accuracy and repeatability.

Speed

The speed of the demonstrator is measured by how long it takes to paint a certain decor. This speed can be compared to the speed of a master painter to evaluate the efficiency of painting with the robot. The time of the different tiles shown in figure 65 were measured. The flower took 6 minutes and the girl with the pearl earring took 10 minutes. This is faster than the average speed of a master painter. Taking into account that the travel speed of the robot could be increased with better hardware, the efficiency of the robot is sufficient to be valuable.

Figure 65: Comparing the quality of different tiles painting with the demonstrator.

Accuracy

The accuracy of the demonstrator describes how the end result compares to the input image. A highly accurate robot paints a tile similar to the image given. A high accuracy is desired, to predict the outcome. However, with the nature and technique of painting delftware with a traditional brush, the crafted look of imperfections is required. These artifacts are one of the core affordances of craftsmanship and is desired to some extend.

Comparing different painted tiles to their digital counterparts, there are a few lines that are misaligned. These are caused by the offset of the brush when dragging on the surface of the tile. This is especially visible with sharp curves. Apart from that, the overall image is accurate enough when the image is prepared correctly. This means that sharp corners are split up in separate lines to preserve the sharpness of the corner.

Repeatability (precision)

Repeatability measures the similarities over different tiles. A high repeatability is preferred to keep a high consistency and quality of the products the robot produces. To test this, two different decorations were painted multiple times (see figure 65). The repeatability of the demonstrator was sufficient for these two decorations. Especially the quality of the lines were similar. The colour has a bit more variation over different products. Some paintings are a bit darker than others, but it is still in an acceptable range, as discussed with the painter.

2.5D PAINTING

From the insights of the chapter on 2.5D painting, it was concluded that the current prototype could not paint 2.5D products consistently. The brush would miss the surface, or plunge the brush too much into the surface due to the inaccuracies described before.

The demonstrator was challenged to paint the same flower, which it painted before on multiple tiles. Sometimes the result turned out to be promising, where only a few lines were missed, but the overall shape of the flower was convincing, as seen in figure 66 (not minding the thick strokes as these were my error). However, repeatability was an issue as each plate would need a new 3D scan and perfect alignment. Other painted plates were much lower quality, meaning that this illustration with small details was too difficult for the current demonstrator.

The only way to make the current prototype painting 2.5D feasible, is to use simple designs which do not suffer from inconsistencies. If a illustration could be designed that still looks good while some lines are missing, then this demonstrator could be used for painting plates and other 2.5D products.
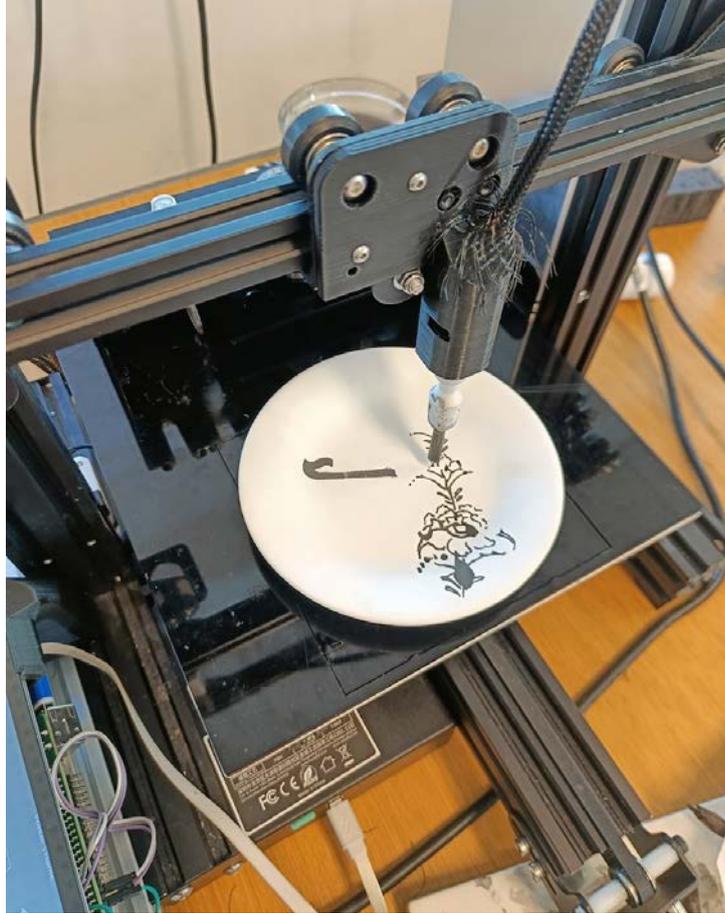

Figure 66: Painting a plate with the demonstrator

The implementation section goes further into solving the inconsistencies and providing tips to further develop this technology, if desired.

Figure 67: Painted proof of concept. The digital file consisted of circles, meaning that some strokes were missed.

15.2 SHOWCASER

To validate the feasibility of the demonstrator, a final showcase product is produced as a pièce de résistance. This product shows the capabilities of the robot, where it shines and what still needs improvement.

TABLEAU

The tableau of R2D2, the famous robot of the Star Wars universe, showcases most of the features of the demonstrator. It included painting with different brushes, colours and multiple tiles; all done autonomously with the robot.

This product was made by vectorising a line art image of the robot and splitting it onto 6 tiles. The line art was painted first as a test, and then the infill was prepared in Illustrator and painted on top of the line art.

A HINT TO A NEW STYLE

With the demonstrator comes a new visual style. The more contemporary designs Royal Delft has been releasing the last couple of years, are an answer to reach a new target group. This is taken one step further with the image of R2D2, the famous robot from the Star Wars Universe. It is used in this showcaser to display one of the most famous characters of pop culture and to show consumers that Delft Blue is not about the traditional imagery but about the craftsmanship. Another reason for this illustration was the personal preference of the author, as I wanted to draw my favourite robot with my painting robot.

Figure 68a: Vector image of the showcase product.

CHALLENGE OF INFILL

The robot excels in painting lines, which was the main inspiration for previously painted decorations. Visual techniques such as hatching and line art are suitable to create a wide range of illustrations. However, it still limits the capabilities of the robot. Painting infill is a lot more challenging, as the thicker brush is harder to control due to the fact that it

has to align each stroke perfectly to the previous one and in between the already drawn lines. With some sort of feedback system, this is hard to do. Nonetheless, the showcaser visualises the possibility for this technique, as it is doable. The current prototype is able to do infill with the infill brush, but the success rate is a lot lower.

FEASIBILITY

The feasibility of this concept can be validated with the given showcaser, together with previously drawn tiles. The goal was to overcome the unpredictable behaviour of the paint, as discussed in the first part of this project. Although there are still imperfections in the decoration, the overall result is feasible and the technology for painting tiles seems promising for further development.
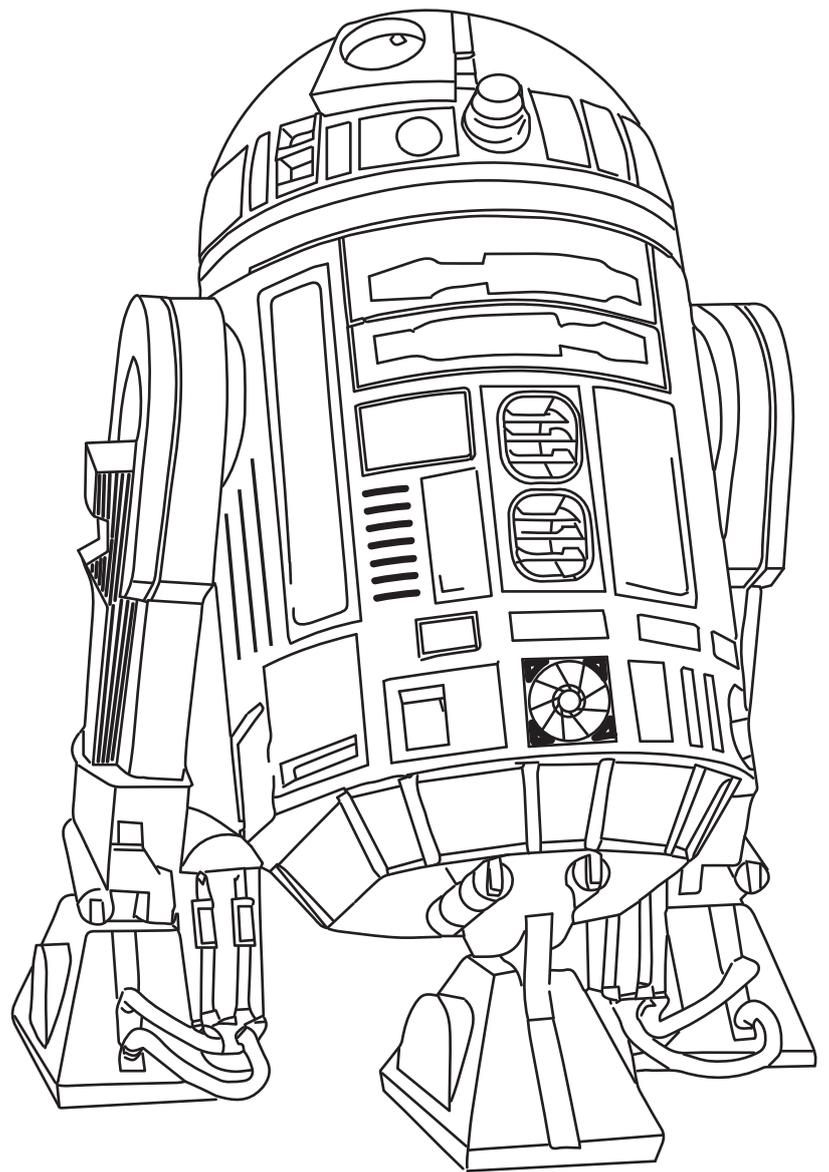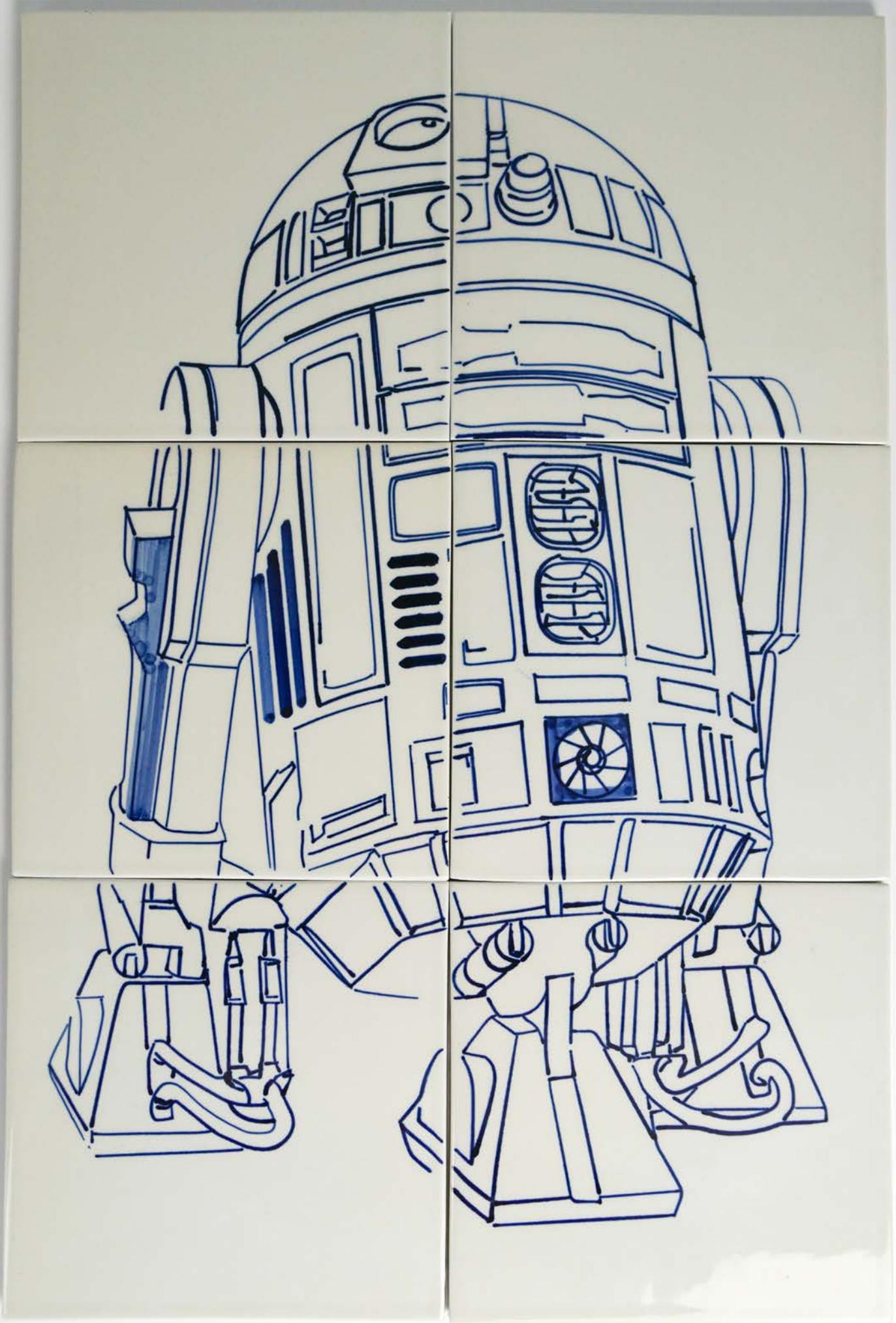

Figure 68b: Infill version

CHAPTER 16
DESIRABILITY

The desirability validates if a concept is desired by the potential customer. This chapter validates and evaluated the desirability with a demonstration.

The desirability of the concept is validated with a demonstration in the royal delft museum. Visitors of the museum can experience the painting robot at a stand in the factory. The goal of this test is to capture the reactions of potential customers and if they are willing to pay (and how much) for a robotic painted tile. Which of the robot's affordances are most interesting for the customer. Is it the customisation? The unique designs? The price?

With this validation step, we aim to answer these questions and validate that the painting robot is indeed a desirable product for Royal Delft and its customers.

SETUP

The robot is set up in the Royal Delft Museum, positioned in its operational environment. The stand displayed the robot, a small poster introducing the product and different tiles painted by the robot. The demonstration is done on a Sunday, as this is one of the busiest days of the week.

During this day, the robot will paint several tiles to showcase the technology to visitors. During this demonstration, the concept is explained, and the visitors are asked a few questions about their experience. The goal was to record their first impressions, their opinion of robotically painted delftware and how much they thought it was worth.

Figure 69: Demonstration day: Continuous flow of visitors at the stand

The latter is challenging to record, as asking someone how much they would pay for something, without actually paying for it, does not result in an honest answer most of the time. To make this step easier, the visitors were shown three different tiles: a hand-painted tile, a robot painted tile and a transfer tile. After providing the prices for the hand-painted and transfer tile, they were asked to place the robot tile where they thought the price should be.

RESULTS

After demonstrating for a full day, the stand was visited by approximately 260 people ranging from 10 to 70 years old. The visitors of the museum approach the stand with a lot of curiosity, often asking questions and sometimes staying at the stand for over 15 minutes discussing the demonstration. From all the gathered reactions, the following insights came to light regarding the desirability of the demonstrator and this decoration technique.

Acceptance of robotically painted tiles

One of the most notable insights during this day, was the acceptance regarding robotically painted tiles. The majority of the visitors understood the development of this technology and thought that the robot painting a tile was a good alternative for transfer techniques. They preferred the traditional materials and methods (painted over transferred). Next to that, they saw this technology as an addition instead of a thread for the hand-painted process and the craftsmanship. The occasionally "What do the painters think of this?" was often accompanied by "This robot could help them with the boring paintings."

Excitement for innovation

Adding to the previous insight, the visitors were excited to see these developments at Royal Delft. Showing innovation next to the traditional craftsmanship was perceived as a logical step for the company to stay relevant in times where production methods are revolutionised. As long as the hand-painted delftware remains

"Can you paint a picture if I send one? I would buy that immediately."

the core of Royal Delft, consumers were excited to see these developments if that would combine craftsmanship with contemporary products that would attract a wider range of consumers.

Personalisation

In terms of the technical affordances of the concept, quick personalisation was the most valuable one according to the potential consumers. The fact that they would be able to submit a picture, drawing, or text, was most desirable. They understood that this technology would make these custom orders easier, and hoped that it would reduce the time and price of customisation.

Entertainment

During the course of the day, visitors often stared at the demonstrator for a significant time. They described it as relaxing and that they could watch this for hours. The motion of the robot painting delftware has an entertaining and relaxing effect on people. After following up with more questions, they mentioned that it would be even better to watch their own product be painted. This validates the entertaining factor of robot-painted delftware and that the showcasing of the technology is an important factor of this concept.

Willingness to pay

Finally, the willingness to pay was measured by the test described before. The answers ranged from 30 to 55 euros for the design of the flower. The higher end of this price range sometimes requested some level of customisation. For example, paying 55 euros for a tile with this design, but being able to add custom text.
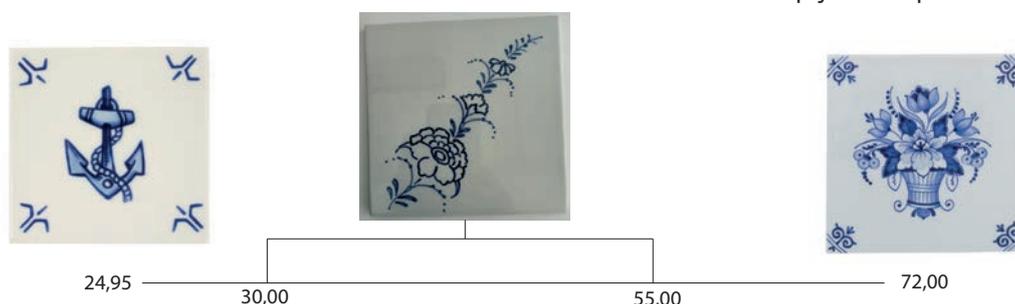
Figure 70: Average price range that people would pay for robot painted tiles.

24,95   30,00   55,00   72,00

Demonstration day
Showcasing the demonstrator
in the museum at Royal Delft.

VIABILITY

For the viability, the goal is to determine if the demonstrator provides enough value for Royal Delft to be a viable product. Are the affordances and benefits it gives worth it compared to the time and investments needed?

Figure 71: Viable example of a bespoke product that the painting robot could create. Personalised birth / anniversary tiles with a predefined design.

To validate the viability of the concept, the outcome and result of the demonstrator was discussed with both account managers of Royal Delft, Roel and Petra. They are responsible for external collaborations, business to business personalised products and contributed to the development of the use case. This interview elaborates on how this development and prototype adds value to Royal Delft on different aspects. Each of these are described below.

INTEGRATED ROBOT

Although the current demonstrator is restricted to 2D products, it still provides a lot of variety in terms of applications. The value is generated by the ability to create new products (showcase product), enhance existing products (gold lustre) and optimise current decoration techniques (prepare line art of tableaus). The robot is a well-integrated perspective for Royal Delft in every aspect of the decoration process.

LEAD TIME

Bespoke products often come with a long lead time. As shown in chapter 2.3, depending on the level of personalisation it could take from 2 weeks up to 6 months to produce custom products. The decoration of product plays a significant role in this time. Hand-painting takes time (especially with larger volumes) and transfers need to be ordered, applied and even fired an extra time. A painting robot could drastically reduce the lead time of decorating products as a robot can work outside of work hours as well. By loading up a painting robot with biscuit at the end of the day and let it run through the night, Royal Delft could win a large amount of time by decorating between workdays, reducing lead times significantly.

ATTRACT A NEW TARGET GROUP

By bringing innovative production technologies into Royal Delft, opportunities open up to a new target group. Roel: "Especially in business to business, clients that currently approach Royal Delft for products are companies that value the traditional techniques and imagery of Delft Blue. When we could sell Delft Blue that is painted with a robot, we could reach out to more modern, technology oriented companies. This would be a whole new target group."

SHOWCASE IN THE MUSEUM

As shown in the demonstration test done in the museum, the robot could add an entertaining element to the museum and tours. Especially if Royal Delft eventually could combine this with visitors watching their product being made. The entertaining factor of watching the robot paint adds not only value to Royal Delft but also the museum.
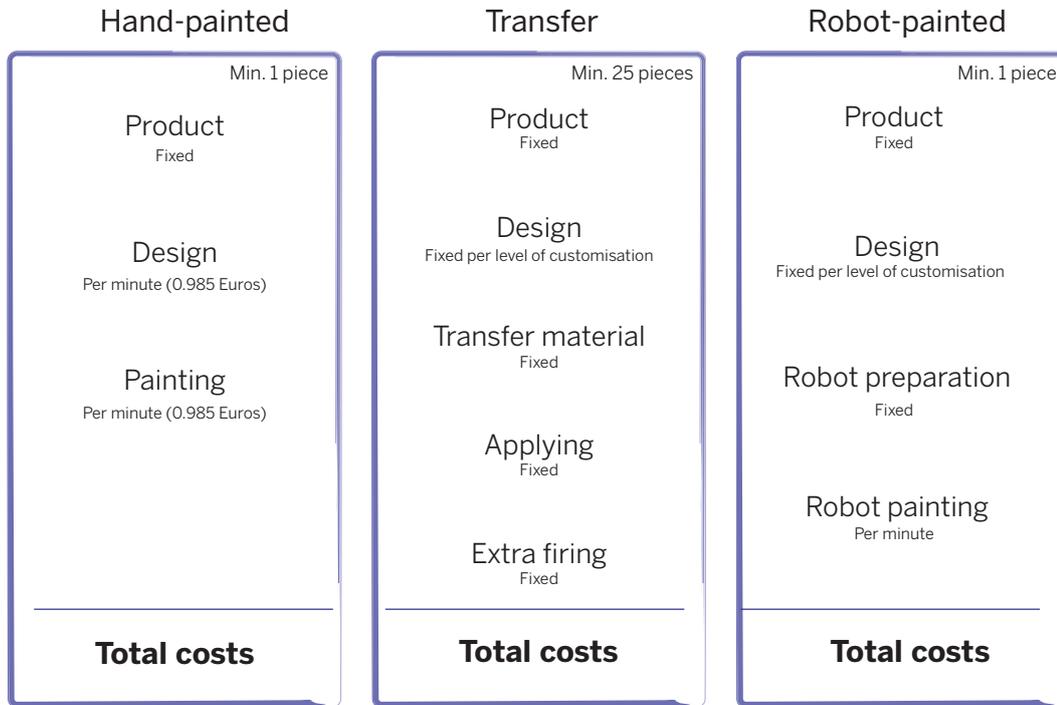
Figure 72: Breakdown of the price calculation of hand-painted, transfer, and robot-painted bespoke products.

PAINTING AT A LOWER PRICE

One of the biggest values of robotic painting, is that it provides a cheaper alternative for painted Delft Blue. If Royal Delft can offer this technique as a new option for bespoke products, they could fill the gap between affordable transfer and high-end hand-painted products. Roel mentioned that "Companies that would like a bespoke products often want a painted product but find hand-painted too expensive. The transfer alternative was not preferred. It would be great if I could offer them a painted bespoke product at a lower price."

To calculate the price differences for these products, an overview is made with the estimates of how much a bespoke product would cost. Normally the price for a hand-painted personalised product is calculated by materials costs, design costs and painted minutes.

A transfer is calculated per piece with a minimal order of 25 products for a logo or 100 products for a higher level of personalisation. A added logo would add 4 Euros per product to the normal cost. The costs are mostly from preparing the file, ordering the transfer sheets, applying them on the product and the extra time that the products are fired in the kiln. The recently added digital transfers reduce the price by being able to print the transfers on smaller sheets and doing this in-house.

Price breakdown for robot painter

Estimating the precise price calculation for the painting robot is hard to do, as it depends on the investments costs (see figure 72) of the final robot.

Figure 73 shows an overview of how the price could be calculated compared to hand-painted and transfer products.

A robot has a high investment cost that needs to be covered in the price. An easy way to do this is to calculate painting minutes with the robot, the same method used for hand-painting. This way, complex decors will be more expensive as they take longer.

Next to that, the design costs of preparing the digital file are significant to the final costs. This is the part that required a designer to prepare the file. Adding a text to a predefined design would only take a minute. It could even be automated in the future. For fully custom designs, the preparation would take much longer and therefore are more expensive. Higher levels of customisation would be more viable for larger tableaus or larger batches, as this would compensate for the development of the digital design.

Demonstrator parts	Price	
Cartesian movement system	€	300.00
Motherboard	€	50.00
Touchscreen	€	90.00
Single Board Computer	€	50.00
Z sensor	€	50.00
cables	€	25.00
Paint area		
Tool station	€	100.00
brush holder	€	20.00
dc motor	€	10.00
Relais	€	5.00
gears	€	30.00
bearings	€	20.00
containers	€	12.00
Total	**€**	**762.00**

Industrial robot parts	Price	
Festo motion system	€	10.000.00
Sheet metal plating	€	500.00
Laser sensor	€	450.00
Sheet metal dipstation	€	100.00
Conveyor Belt system	€	5.000.00
Tools	€	200.00
Total	**€**	**16.250.00**

Figure 73: Price estimates of the demonstrator and a professional version for industrial use.

INSIGHTS

FEASIBILITY

The results from the demonstrator were very promising. The painted tiles were accurate with a high repeatability. There were still small artefacts, but these are desired, as they show the behaviour of the brush, similar in traditional craft.

The showcase product, a tableau of R2D2, displays the possibilities of the robot. Although infill painting is still something that is hard to do well, the overall result with different colours, line thickness and alignment over multiple tiles, looks very promising.

DESIRABILITY

After demonstrating the prototype in its operational environment to fulfil the 7th technology readiness level, the reactions of visitors turned out to be very promising.

Robotic painting seems to be accepted by most of the visitors. They understood the step towards automating the decoration process besides the traditional hand-painted process.

During the day, visitors kept staring at the painting robot, mentioning that they found it fascinating and relaxing to watch.

The most important affordance for potential customers was the easy personalisation. They were excited for customising a tile with a picture or text, while still being affordable.

VIABILITY

Together with the account managers of Royal Delft, the viability was evaluated. The robot can add a lot of value on different aspects. The flexibility of the robot to be able to paint tiles, tableaus and gold lustre, makes it a valuable prototype to further discover the potential of robotic painting.

The lower price and lead time that this robot could give for personalised products, would fill a gap in Royal Delfts portfolio. A price overview shows how Royal Delft could define the price of robotic painted products.

Figure 74: Close-up of the demonstrator.

PART V: CONCLUSION

The conclusion part describes a final design proposal for implementing the painting robot into the Delft blue production process. This is followed by a final conclusion, recommendation and reflection.
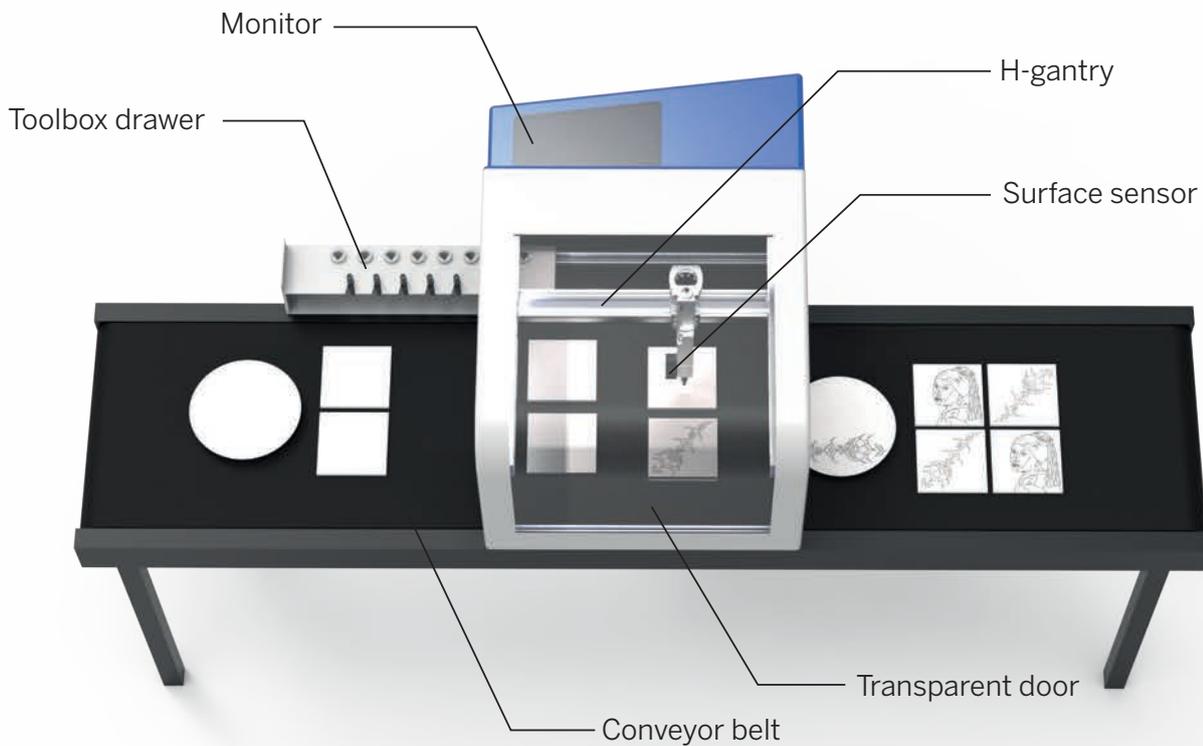
Monitor —
Toolbox drawer —
H-gantry
Surface sensor
Transparent door
Conveyor belt

CHAPTER 18
IMPLEMENTATION

With the demonstrator validated and evaluated, a final implementation step is made as a vision on the product and a recommendation for Royal Delft for future development.

The demonstrator was a way to portray the technology and production method of painting Delft Blue digitally. An important step to take is to convert the insights from the validation and evaluation of this demonstrator to a design and roadmap that would be used effectively in the Royal Delft production process. This implementation shows a design proposal, the work flow for different products and alternative routes for future products.

DESIGN PROPOSAL

This new design is based on a more integrated approach of the robot in the production process of Royal Delft. In contrast to the demonstrator that needs to be loaded with a new product every time it finishes a painting, this design is able to handle a large batch of products with the use of a conveyor belt that can be loaded with the desired products.

Motion system

The robot is built with professional hardware with an industry standard. The motion system is made with a Festo H-gantry system, a lightweight, small footprint cartesian motion system with work area of 450 x 600 x 200 mm. (width, length, height). This enlarged work area has the ability to paint most 2D and 2.5D products of Royal Delft, from a tile tableau of 3 by 4 tiles to a decorative plate of 400 millimetres in diameter.

Laser sensor

The paint head is equipped with a laser sensor probe to increase the probing speed, accuracy and reliability while also having the durability of an industrial standard sensor. This sensor is used as a Z end-stop, a probe to measure surface variations and to detect objects on the conveyor belt. When the robot starts painting, it scans the surface for objects and determines the centre of each object before painting the required decoration on this object.

2.5D painting

With this same laser, a simplified scan can be made of a 2.5D object. By moving in a spiral pattern, measuring on the way, a point cloud can be made from the data points which can be used as input for painting 2.5D objects.

Interface

The robot is equipped with a touch-screen interface where the robot can be controlled by a Royal Delft employee. From this interface, paint jobs are managed and monitored. The interface shows which products need to be loaded onto the conveyor belt and which decoration is being drawn.

Tool drawer

Next to the control screen is a drawer that holds the equipment station. This station is filled with the tools (brushes) and paint containers. These can be refilled and replaced during maintenance or depending on the upcoming paint jobs.

The robot is enclosed with a sheet metal casing to protect visitors and employees from moving parts and keep the system dust-free.

Figure 76: Detail render showing the transparent casing and tool drawer.
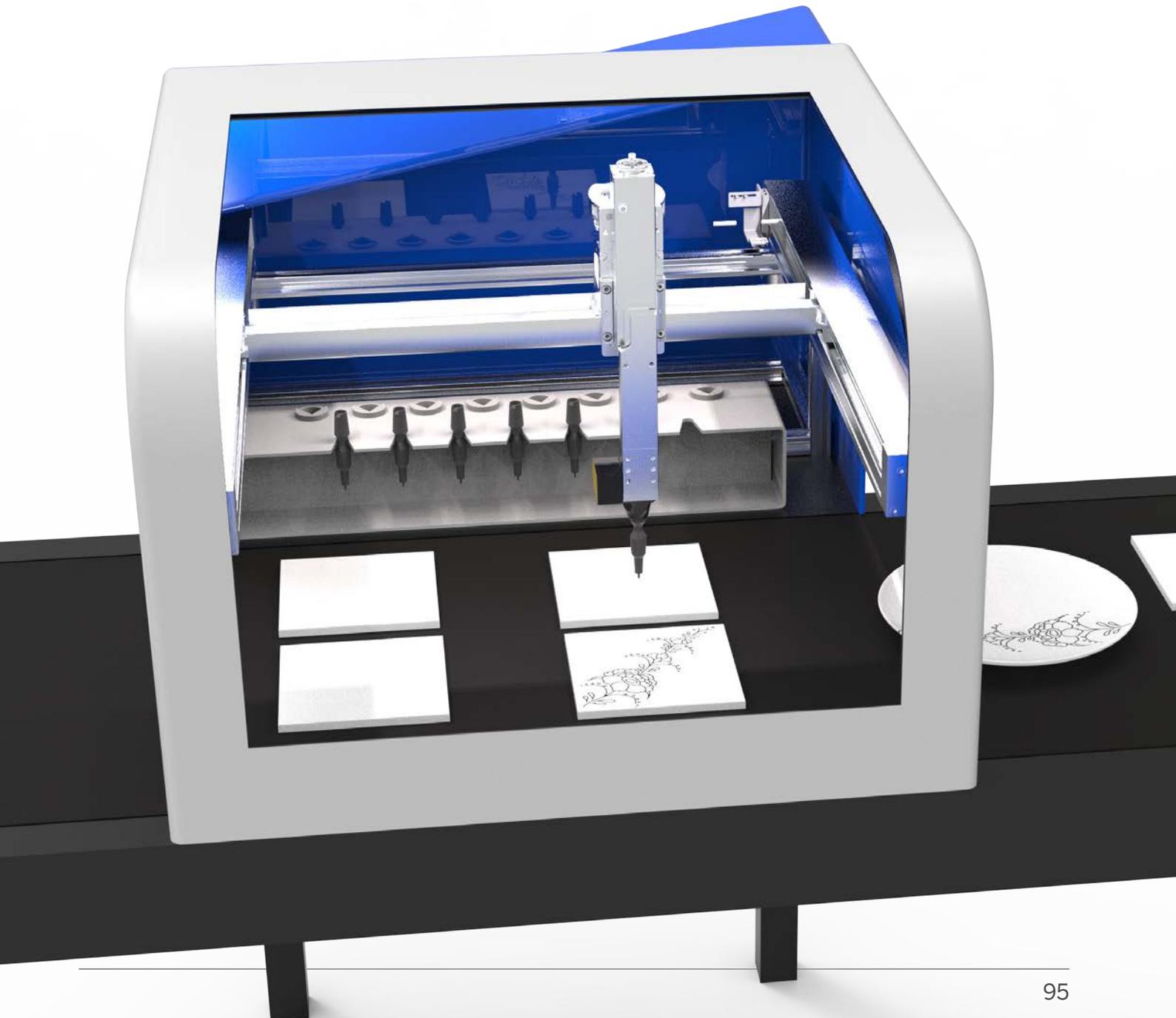
WORKFLOW

The robot can be used for different varieties of products. From bespoke products to collections and collaborations with external designers. Creating a collection would involve the design team creating digital versions of new decorations. The style would fit a new design language that the painting robot would excel in, differentiating itself from the other decoration methods. The design team is free to use different styles, including lines, filling and even gold lustering. The product development of a new collection is streamlined with fast prototyping and iterations as changes in the digital design can directly be made with the painting robot.

Bespoke

Bespoke products require a more in-depth work flow, where the consumer is, in different levels, part of the design process. Figure 77 shows a work flow where different stakeholders are involved in creating a bespoke product.

The work flow for bespoke products is a combination of the consumer, the designer at Royal Delft and the employee handling the robot. By automating processes such as converting text to G-code, low level personalisation can be achieved with minimal workload for Royal Delft. When a standard image is ordered with custom text, an employee only controls if the text is correctly aligned and then sends the job to the robot.

Higher levels of customisation require more input from the designer, where the image is configured in a vector file that can be painted by the robot. This does require feedback from the consumer to approve the final design. When approved, it can be send to the robot for production.
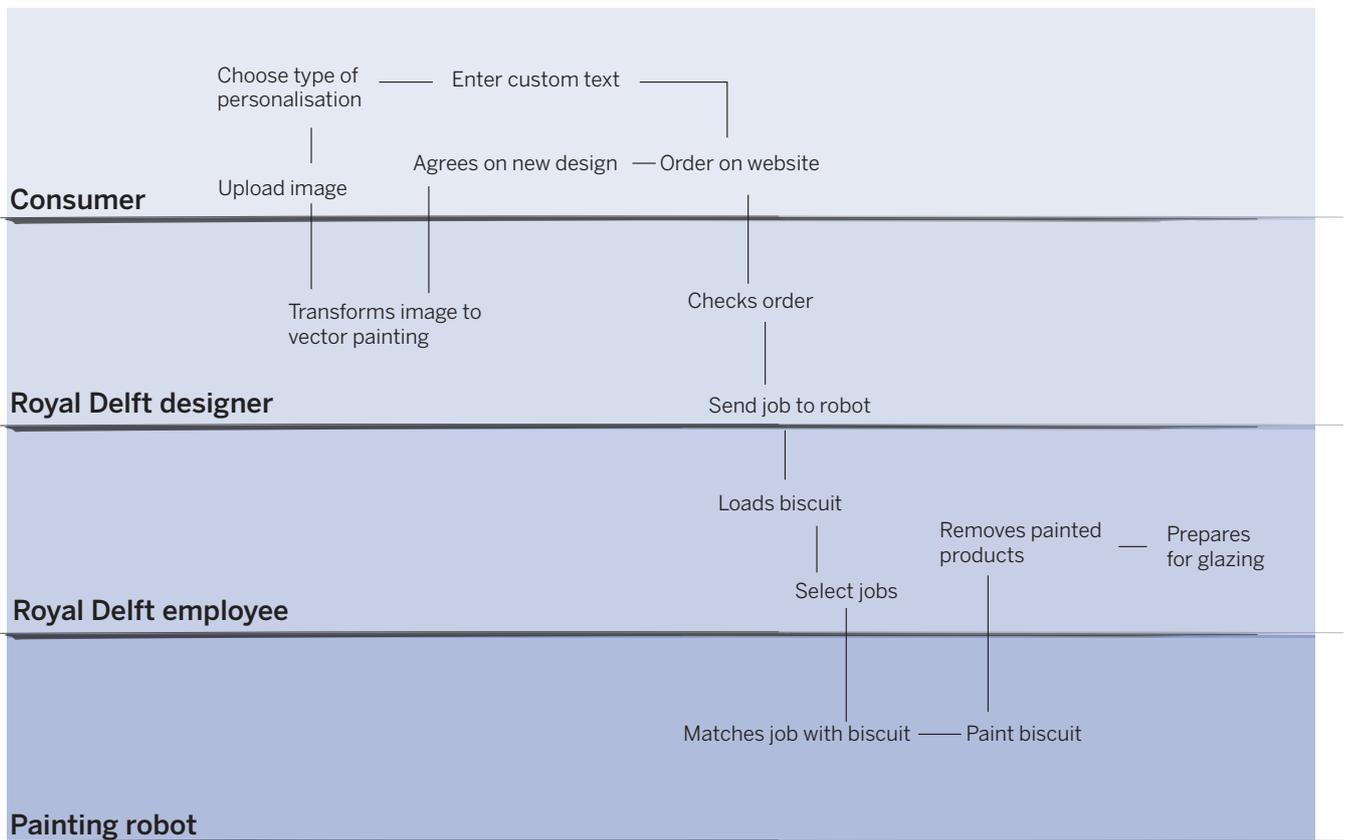

Figure 77: Workflow of a bespoke product painted by the Delft Blue painting robot.
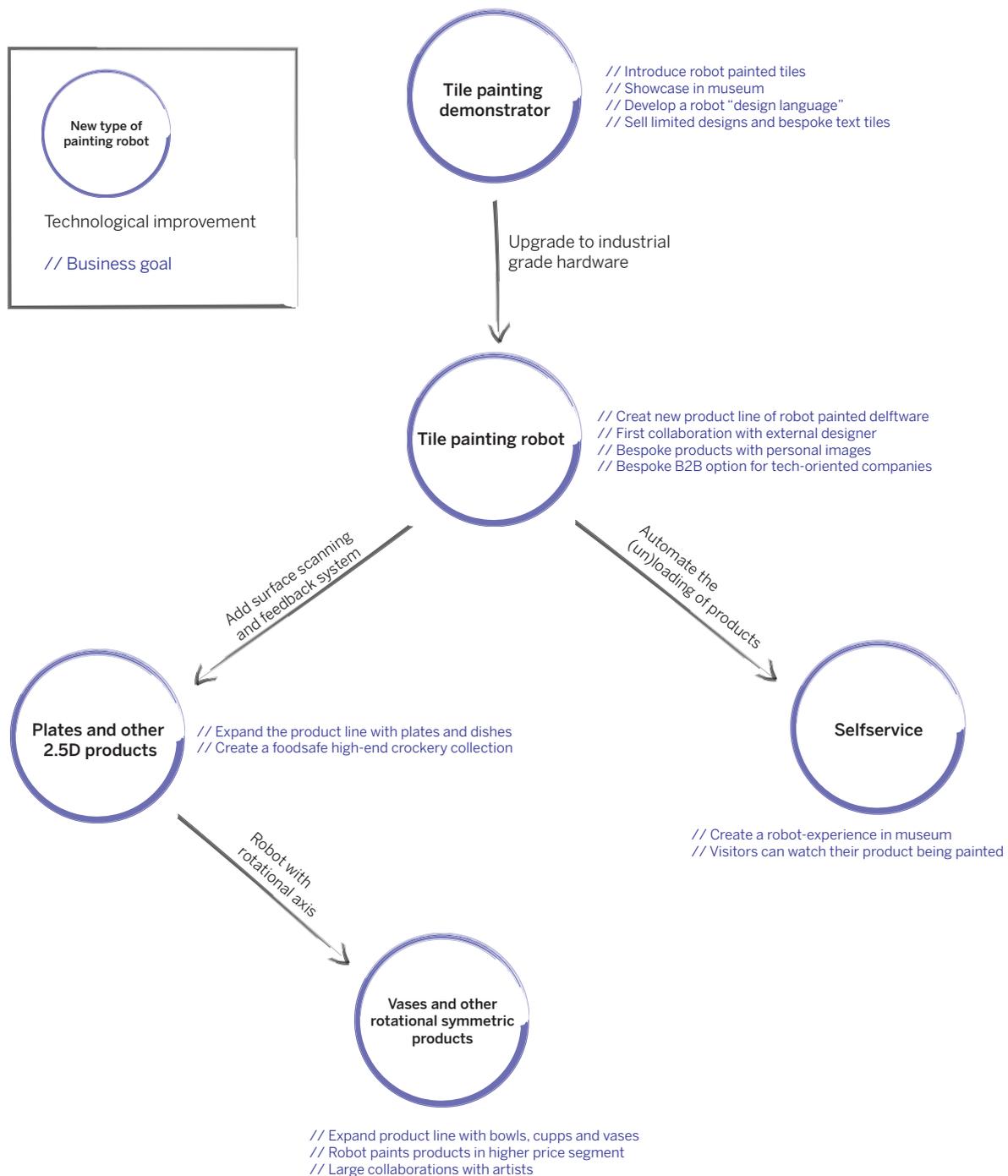
New type of painting robot

Technological improvement

// Business goal

Tile painting demonstrator

// Introduce robot painted tiles
// Showcase in museum
// Develop a robot "design language"
// Sell limited designs and bespoke text tiles

Upgrade to industrial grade hardware

Tile painting robot

// Creat new product line of robot painted delftware
// First collaboration with external designer
// Bespoke products with personal images
// Bespoke B2B option for tech-oriented companies

Add surface scanning and feedback system

Automate the (un)loading of products

Plates and other 2.5D products

// Expand the product line with plates and dishes
// Create a foodsafe high-end crockery collection

Selfservice

// Create a robot-experience in museum
// Visitors can watch their product being painted

Robot with rotational axis

Vases and other rotational symmetric products

// Expand product line with bowls, cupps and vases
// Robot paints products in higher price segment
// Large collaborations with artists

Figure 78: Road map of the implementation of the painting robot, with different routes.

ROADMAP

This implementation step showcases one outcome for a painting robot in the future at Royal Delft. However, there are several options that could be interesting for the company develop regarding robotic painting. Figure 78 shows an overview of a plan of action that Royal Delft could take to further implement the painting robot into their production line. The over-view shows different versions of a painting robot that could be developed and the business strategy that could be applied to introduce the robot into the company, focussing on integration, promotion and consumer acceptance. It also shows the required technological development for each step.

CHAPTER 19
CONCLUSION

DESIGN RESULTS

This project presented a design proposal for a new production technique for decorating Delft Blue. Currently Royal Delft hand-paints their products or makes use of transfers. This proposal explores a new decorating method by combining digital manufacturing methods with the traditional craftsmanship, called digital craft. After a thorough internal and external analysis, a design a design direction was chosen that entails a multifunctional painting robot capable of processing different tasks, from bespoke products to painting a new collection of crockery.

The developed demonstrator uses the same materials as the master painters to autonomously decorate delftware. This demonstrator can paint a tile from a prepared vectorised image autonomously by changing brushes, dipping automatically and adjusting its position to the surface of the tile. The robot was demonstrated in its operational environment to verify the desired technology readiness level within this project.

Although it can not paint the traditional Delft Blue style, the robot excels in line art, making it interesting to develop a new design language that fits Royal Delft's contemporary product line and accentuates the capabilities of the robot.

FEASIBILITY

The demonstrator was used to validate the design of a painting robot. First, the quality was evaluated with a master painter. The demonstrator is able to create accurate and repeatable imagery at a faster speed than master painters, provided that the image is optimised for digital fabrication. To validate the feasibility, a showcase product was painted. A tableau was made to also show the potential in scaling the size of products for further development.

A proof-of-concept was made for painting 2.5D products. However, due to the added challenges of accurately following a curved surface, the results lacked consistency, making 2.5D painting not feasible with the current hardware.

DESIRABILITY

The robot was demonstrated at the Royal Delft museum to capture the reactions of visitors and see how digital fabrication at Royal Delft is received. After speaking to approximately 270 visitors, it was concluded that potential consumers welcome innovation at Royal Delft as well as robotically painted delftware. They found this new decoration type between transfer and hand-painted, a good alternative, given that it provides benefits such as easier customisation and a lower price than hand-painted products.

VIABILITY

Finally, these outcomes were discussed with Royal Delft to evaluate the value of this concept for Royal Delft. This new decoration method adds value on different areas for Royal Delft. The current demonstrator integrates in the Royal Delft production process on different as-pects. It provides the ability to create new products, enhance old inventory and optimise the current production work flow for bespoke products and tableaus. Being able to create painted personalised products at a lower price than hand-painted variants, creates an opportunity in B2C and B2B production.

VALUE FOR LITERATURE

This project contributes to the development and research of combining digital manufacturing methods with traditional craftsmanship. After analysing the developments on this topic, the choice was made to combine the strengths on both craft and digital manufacturing into the demonstrator. The goal to create a production method that uses digital design and manufacturing as a craft practise was reached. The project added new insights to 2.5D painting with a robot, which was an underdeveloped topic. For painting curved surfaces with a brush, more advanced hardware and software is needed to accurately follow the curvature of the surface.
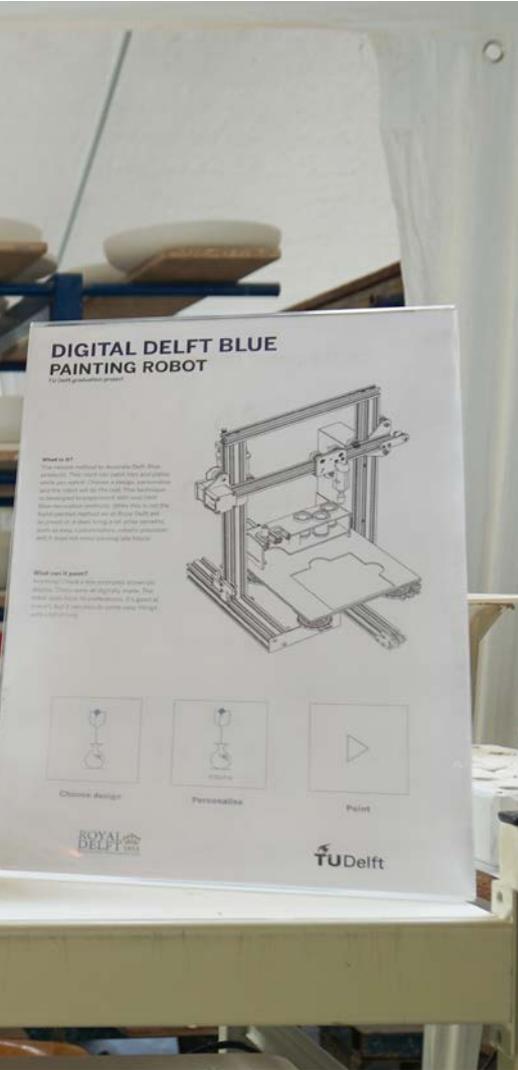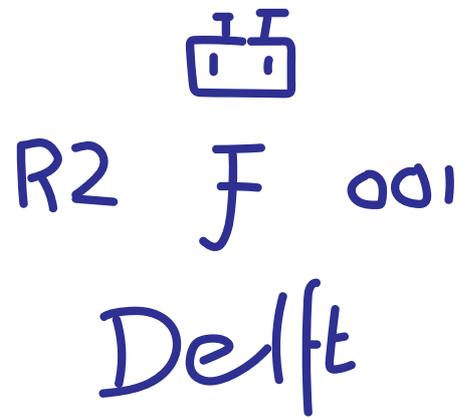
Figure 79: Ready for demonstration day

Figure 80: A robot signature, just like the other decoration techniques, creates recognition and value for robotic painting.

CHAPTER 20
RECOMMENDATIONS

ROBOT DEVELOPMENT

As mentioned in the roadmap of the implementation plan showed in chapter 18, there are multiple routes to further develop this robot. To continue with implementing this decorating technique, Royal Delft should focus on further optimising the technology. A robot such as the demonstrator requires a relatively low investment, making it suitable for more testing regarding the quality as well as designs that could be sold.

To improve the quality, the goal would be to remove more of the uncertainties this project tackled. The brush is one of the fundamental parts that could solve these uncertainties. By designing a new brush for the robot using the same traditional materials, but with shorter hairs and a precisely cut tip, it would be possible to paint more accurately. This would be especially desirable when combining line art with infill.

After improving the current demonstrator, Royal Delft could move towards the first industrial painting robot, made from professional equipment, to start integrating the machine into the production process. It is suggested to focus on 2D painting and expanding in providing different options of personalisation, rather than developing a 2.5D painting robot. There is still too much development needed for that to be a feasible and viable option.

PRODUCT DEVELOPMENT

Apart from the development of the painting robot, Royal Delft should also focus on the products that would be produced with this robot. Part of implementing the robot into the production work flow, is designing the products it is going to make. As mentioned in the validation, customers were most excited about personalisation. The first products to develop would be a line of customisable tiles that focus on life events such as the Miffy birth tiles.

Identity

Next to product development, the robot needs to create an identity in the Royal Delft collection. The visual style used with the robot needs to be recognisable and accepted by the consumers. Just like the other decoration options, the robot should have a signature to paint on every product it makes, so that consumers recognise that their product is painted by the robot. Figure 80 is an example. As these signature are painted on the back of a product and flipping the tile is not efficient, it is suggested to first use the same technique as with transfer products. With a unique stamp, Royal Delft can extinguish their new decoration method from the others to the public.

DIGITAL DELFT BLUE, A NEW APPROACH

REFLECTION

In this section, I reflect on the project outcomes and the things that I learned during this project.

REFLECTING ON THE OUTCOME

Throughout this project, I kept facing with the same issue where my expectations were beyond what was capable during this project. As excited as I was to start designing and building a painting robot, reality faced me many times and showed me that I can not do everything I wanted within the given time frame of a graduation project. With a lot of drawbacks during this project, I was forced to alter my expectations and make drastic decisions. Nonetheless, I am very satisfied with the final results of this project. I was able to achieve the two main goals of this project, new insights in the value for a robot painter at Royal Delft and a working demonstrator that can paint tiles consistently. If more time was available, I would have done more tests for 2.5D painting with better hardware, as I still see potential is this technique. Solving this issue would fill a large gap in the development of painting robots. For now, 2D painting gives enough value for Royal Delft, which was the goal of this project.

MAKING DECISIONS

A personal learning goal during this project was to improve my decision-making. I am a real procrastinator when it comes to making difficult decisions in a design project. This reflected throughout my studies and my internship as well. Luckily, this project forced me to make a lot of difficult decisions in a short amount of time.

PROJECT MANAGEMENT

Doing this graduation project was a unique experience where you had to manage a large design project all by yourself. I was well aware that project management is not one of my strongest points, as I can get obsessed with solving one issue while losing sight of the bigger picture. I have always been more of a team player, mean-ing that this project would be a challenge to manage by myself. Apart from some chaotic meetings and support from my committee keeping track of the end goal, for which I am grateful, I managed to structure and finish this thesis. The project was delayed for 4 weeks, mostly due to the shortage of materials for the prototype and expectation management. By trying to solve it independently, I learned a lot from the experience, which I can use for future projects.

Figure 80: The stand in Royal Delft Museum

CHAPTER 22
FINAL NOTE

The final section of this thesis is a personal note about the things I experienced during this project. First, I am very grateful that I had the opportunity to do my Master thesis on such a unique graduation project. When discussing my project with peers, I was met with curiosity and excitement. These reactions motivated me even in the most stressful times during this project.

Working at Royal Delft was the key to success during this project. Walking through the museum and work place was always inspiring and motivating. The employees at Royal Delft always showed curiosity towards my project and gave suggestions and their insights, which was always helpful. From me entering the painting room with yet another question or suggestion, to the office where I disturbed almost everybody with questions which they were all happy to answer. I want to thank Royal Delft for opening their doors during this project and providing me with all the tiles that I have used for testing, even when the stock was running out.

Lastly, I want to thank Willemijn, Sander and Joffrey for the guidance, the very sincere feedback and informal communication throughout the project.

DIGITAL DELFT BLUE, A NEW APPROACH

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PART VI: APPENDICES

2D PAINTING
Functions
- The system must be able to paint a tile of 13×13 cm
- The system must be able to know when to dip the brush
- The system must be able to change brushes autonomously
- The system must be able to paint with a minimum of three different colours
- The system must be able to paint lines of different thicknesses, text, and gold lustre

Shape
- The system must have a minimal movement area of 20x23x15 cm
- The system must be able to move with three degrees of freedom

Preprocessing
- The system must be able to recreate a vectorized file only containing paths
- The system must be able to convert this image into G-code
- The system must provide the option to select different colours, brushes, and paint types
- The user should be able to upload the generated G-code to the system

Interaction
- The system must allow for easy (un)loading of a biscuit
- The biscuit must be easy to align in the robot
- The system must be operational by a Royal Delft employee
- The user must be able to easily customize designs

Maintenance
- The system must allow for easy refilling of the paint
- The system must keep the paint mixture homogeneous while painting

2.5D PAINTING
- The system must be able to follow the surface of a plate with a slope angle up to 45 degrees with a 1 mm accuracy.
- The system must be able to fit a plate manufactured at Royal Delft
- The user must be able to perfectly align the plate on the work surface

APPENDIX B
FIRMWARE CONFIGURATION

```
   # use this config, during "make menuconfig" select the STM32F103 with
# a "28KiB bootloader" and with "Use USB for communication" disabled.

# If you prefer a direct serial connection, in "make menuconfig"
# select "Enable extra low-level configuration options" and select the
# USART3 serial port, which is broken out on the 10 pin IDC cable used
# for the LCD module as follows:
# 3: Tx, 4: Rx, 9: GND, 10: VCC

# Flash this firmware by copying "out/klipper.bin" to a SD card and
# turning on the printer with the card inserted. The firmware
# filename must end in ".bin" and must not match the last filename
# that was flashed.

# ////////////////////////////////////////////////////////////////////
# //////////////////////    motors       /////////////////////////////
# ////////////////////////////////////////////////////////////////////

[stepper_x]
step_pin: PB9
dir_pin: PC2
enable_pin: !PC3
microsteps: 16
rotation_distance: 40
endstop_pin: ^PA5
position_endstop: 0
position_max: 235
homing_speed: 80

[stepper_y]
step_pin: PB7
dir_pin: PB8
enable_pin: !PC3
microsteps: 16
rotation_distance: 40
endstop_pin: ^PA6
position_endstop: 0
position_max: 235
homing_speed: 50

[stepper_z]
step_pin: PB5
dir_pin: !PB6
enable_pin: !PC3
microsteps: 16
rotation_distance: 8
endstop_pin: probe:z_virtual_endstop
position_min: -3
position_max: 250
homing_speed: 20
```

```
[fan]
pin: PA0

[mcu]
serial: /dev/serial/by-id/usb-1a86_USB_Serial-if00-port0
restart_method: command

[printer]
kinematics: cartesian
max_velocity: 1000
max_accel: 3000
max_z_velocity: 100
max_z_accel: 100

[virtual_sdcard]
path: ~/gcode_files

[display_status]

[pause_resume]



# ///////////////////////////////////////////////////////////////////
# ///////////////////////       PROBE       /////////////////////////
# ///////////////////////////////////////////////////////////////////

[bltouch]
sensor_pin: ^PA7
z_offset: 0
control_pin: PB0
pin_up_touch_mode_reports_triggered: False
probe_with_touch_mode: True
x_offset: 10
y_offset: 19.25
stow_on_each_sample: true
#pin_move_time: 0.0

[display]
lcd_type: st7920
cs_pin: PB12
sclk_pin: PB13
sid_pin: PB15
encoder_pins: ^PB14, ^PB10
click_pin: ^!PB2

[safe_z_home]
home_xy_position: 100,75
speed: 100
z_hop: 5
z_hop_speed: 5

[bed_mesh]
speed: 100
horizontal_move_z: 3
mesh_min: 57, 19.25  # add the x and y offsets for both mesh_min and max. This is set for mine.
mesh_max: 164, 132
probe_count: 6,6
move_check_distance: 3.0
mesh_pps: 2,2
```

```
# //////////////////////////////////////////////////////////////////////
# /////////////////////   MACROS    /////////////////////////////
# //////////////////////////////////////////////////////////////////////

[gcode_macro STARTING_GCODE]
gcode:
    # Use absolute coordinates
    G90
    # Reset the G-Code Z offset (adjust Z offset if needed)
    SET_GCODE_OFFSET Z=0
    G28
    # Home the printer
    G29
    # Move the nozzle near the bed


[gcode_macro PAUSE]
description: Pause the actual running print
rename_existing: PAUSE_BASE
# change this if you need more or less extrusion
variable_extrude: 1.0
gcode:
  ##### read E from pause macro #####
  {% set E = printer["gcode_macro PAUSE"].extrude|float %}
  ##### set park positon for x and y #####
  # default is your max posion from your printer.cfg
  {% set x_park = printer.toolhead.axis_maximum.x|float - 5.0 %}
  {% set y_park = printer.toolhead.axis_maximum.y|float - 5.0 %}
  ##### calculate save lift position #####
  {% set max_z = printer.toolhead.axis_maximum.z|float %}
  {% set act_z = printer.toolhead.position.z|float %}
  {% if act_z < (max_z - 2.0) %}
      {% set z_safe = 2.0 %}
  {% else %}
      {% set z_safe = max_z - act_z %}
  {% endif %}
  ##### end of definitions #####
  PAUSE_BASE
  G91
  {% if printer.extruder.can_extrude|lower == 'true' %}
    G1 E-{E} F2100
  {% else %}
    {action_respond_info("Extruder not hot enough")}
  {% endif %}
  {% if "xyz" in printer.toolhead.homed_axes %}
    G1 Z{z_safe} F900
    G90
    G1 X{x_park} Y{y_park} F6000
  {% else %}
    {action_respond_info("Printer not homed")}
  {% endif %}


[gcode_macro END_GCODE]
gcode:
  G1 Z100
  G1 Y200
  M117 Print finished
  M18

[gcode_macro CANCEL_PRINT]
description: Cancel the actual running print
```

```
    rename_existing: CANCEL_PRINT_BASE
    gcode:
      TURN_OFF_HEATERS
      CANCEL_PRINT_BASE

[gcode_macro G29]
gcode:
 BED_MESH_CLEAR
 G28
 BED_MESH_CALIBRATE
 BED_MESH_PROFILE SAVE=x1

[gcode_macro global]
variable_tool1x: 37
variable_tooly: 204
variable_tool2x: 64.5
variable_colour1x: 128
variable_colour1y: 222
variable_colour2x: 157
variable_colour2y: 204
variable_colour3x: 187
variable_colour3y: 224
gcode:
  M115 ; must provide something


[gcode_macro LOAD1]
gcode:
    {% set toolX = printer["gcode_macro global"].
tool1x %}
    SET_GCODE_OFFSET z=0
    G90
    G1 Z80
    G1 X{toolX} Y205 Z90 F4000
    G4 S1
    G1 Z63 F300
    G4 S2
    G1 Y166 F800
    SET_GCODE_OFFSET Z=66.135
    G1 Z40 F1000

[gcode_macro LOAD_plate]
gcode:
    {% set toolX = printer["gcode_macro global"].
tool1x %}
    SET_GCODE_OFFSET z=0
    G90
    G1 Z89
    G1 X{toolX} Y205 Z99 F4000
    G4 S1
    G1 Z72 F300
    G4 S2
    G1 Y166 F800
    SET_GCODE_OFFSET Z=62.63
    G1 Z49 F1000

[gcode_macro UNLOAD1]
description: Cancel the actual running print
gcode:
    {% set toolX = printer["gcode_macro global"].
tool1x %}
    SET_GCODE_OFFSET Z=0
    G91
    G1 Z29.5 F500
    G90
    G1 X{toolX} Y170
```

```
    G1 Z64
    G4 S2
    G1 Y205 F200
    G4 S2
    G1 Z90 F300
    G4 S2
    G1 Y177 F1000


[gcode_macro LOAD2]
description: load the second brush
gcode:
    {% set toolX = printer["gcode_macro glob-
al"].tool2x %}
    SET_GCODE_OFFSET z=0
    G90
    G1 Z80
    G1 X{toolX} Y205 Z90 F4000
    G4 S1
    G1 Z63 F300
    G4 S2
    G1 Y166 F800
    SET_GCODE_OFFSET Z=59.45
    G1 Z40 F1000

[gcode_macro UNLOAD2]
description: Unload the second brush
gcode:
    {% set toolX = printer["gcode_macro glob-
al"].tool2x %}
    SET_GCODE_OFFSET Z=0
    G91
    G1 Z29.5 F500
    G90
    G1 X{toolX} Y170 F1000
    G1 Z63 F500
    G4 S2
    G1 Y205 F200
    G4 S2
    G1 Z90 F300
    G4 S2
    G1 Y177 F1000


[gcode_macro DIP1]
description: dip brush in first colour
gcode:
    {% set colourX = printer["gcode_macro glob-
al"].colour1x %}
    {% set colourY = printer["gcode_macro glob-
al"].colour1y %}
    G1 Z80 Y125 F1000
    G1 X{colourX} Y{colourY} F3000
    G91
    G1 Z-60 F800
    G4 P3000
    G1 Z20
    G1 Y-10
    G1 Z23
    G1 Y-20
    G90
    G1 Y150 F1000
    G1 X182 Z20
    G1 Y171 F500
    G1 Y150 F1000
    G1 X128 Y92
```

```
                                                    G1 Y-20
    [gcode_macro DIP2]                              G90
    description: dip brush in first colour          G1 Y150 F1000
    gcode:                                          G1 Y100 Z20
        {% set colourX = printer["gcode_macro
global"].colour2x %}
        {% set colourY = printer["gcode_macro
global"].colour2y %}
    G1 Z80 Y125 F1000
    G1 X{colourX} Y{colourY} F3000
    G91
    G1 Z-60 F800
    G4 P3000
    G1 Z20
    G1 Y-10
    G1 Z23
    G1 Y-20
    G90
    G1 Y150 F1000
    G1 X185 Z20
    G1 Y171 F500
    G1 Y150 F1000
    G1 X128 Y92


    [gcode_macro DIP3]
    description: dip brush in first colour
    gcode:
        {% set colourX = printer["gcode_macro
global"].colour3x %}
        {% set colourY = printer["gcode_macro
global"].colour3y %}
    G1 Z80 Y125 F1000
    G1 X{colourX} Y{colourY} F3000
    G91
    G1 Z-60 F800
    G4 P3000
    G1 Z20
    G1 Y-10
    G1 Z23
    G1 Y-20
    G90
    G1 Y150 F1000
    G1 X188 Z20
    G1 Y171 F500
    G1 Y150 F1000
    G1 X128 Y92




    [gcode_macro DIPplate]
    description: dip brush in first colour
    gcode:
        {% set colourX = printer["gcode_macro
global"].colour1x %}
        {% set colourY = printer["gcode_macro
global"].colour1y %}
    G1 Z89 Y125 F1000
    G1 X{colourX} Y{colourY} F3000
    G91
    G1 Z-60 F800
    G4 P3000
    G1 Z16
    G1 Y-10
    G1 Z23
```

```python
# Written by Mischa de Haan
# Based on the Digital Delft Blue Python script written by Lennart Krieg
# Royal Delft - Digital Delft Blue Painting Robot G-code generator v5
# My gratitude goes to lennart for explaining his code and writing the foundation for this version


# LIBRARIES
from pygcode import *
from euclid3 import Vector3
from matplotlib import pyplot as plt
from svgpathtools import *
from datetime import datetime
# import math
import os
import cmath
import numpy as np
import vectors

# INITIALISATION

layerBrush = [1, 2, 2, 2, 2, 2, 2, 1, 1, 1]
layerColour = [1, 2, 2, 2, 2, 2, 2, 1, 1, 1]
#line fill text or luster
layerType = [“fill”, “fill”, “fill”, “fill”, “fill”, “fill”, “fill”, “text”, “text”, “fill”]

autodipping = True
toolchanging = True
infillWait = False

# global variables
currentBrush = 0
currentColour = 0
currentType = “none”

paintingType = [“fill”, “fill”, “text”, “fill”]

lineSpeed = 3500
textSpeed = 2000
fillSpeed = 1500
lusterSpeed = 800


def selectSpeed(currentType):
    if currentType == “text”:
        return textSpeed
    if currentType == “line”:
        return lineSpeed
    if currentType == “fill”:
        return fillSpeed
    if currentType == “luster”:
        return lusterSpeed


Wait = 1  # s
WaitMoveUpZ = 20  # [mm]
OutlineDipLength = 80  # [mm]
to_coordinates = lambda v: {‘X’: v.x, ‘Y’: v.y, ‘Z’: v.z}
undippedlength = 0
```

```python
# get file
SVGName = 'svgname' # Name of the svg file that must be loaded
GCODEName = 'gcodename'  # Desired name of the output Gcode file
TempName = 'temp'
SVGDirectory = 'C:\\Users\\31637\\Documents\\Afstuderen\\3Dprinter\\SVG\\correcte ratios'  # Di-
rectory (folder) to load the svg file
    GcodeDirectory = 'C:\\Users\\31637\\Documents\\Afstuderen\\3Dprinter\\SVG\\correcte ratios'  # Di-
rectory (folder) to save the Gcode file

# SETUP
GcodeSavePath = '{}/{}.gcode'.format(GcodeDirectory, TempName)
paths, attributes = svg2paths('{}/{}.svg'.format(SVGDirectory, SVGName))
# If the Gcode file does not exist already, an empty one is created
if not os.path.exists(GcodeSavePath):
    with open(GcodeSavePath, 'w'):
        pass

# Writing standard starting Gcode to the file
GCODE_out = open(GcodeSavePath, "w")
GCODE_out.write('STARTING_GCODE')
GCODE_out.write('\n')

# SVG Canvas settings:
CanvasHeight = 100  # [mm]
PixelCoordinates = False
PPI = 72  # [pixel/in]
Inch = 25.4  # [mm]
if PixelCoordinates:
    CanvasHeight = (CanvasHeight / Inch) * PPI
# Offset values to specify brush tip position w.r.t. nozzle:
ofsetX = 49  # [mm] was 49
ofsetY = 38   # [mm] was 31

ofsetZ = 0  # [mm] was 4
# Clearance tile/brush for when moving and not painting:
Clearence = 4  # [mm]
SlopeZ = Clearence
InterMoveZ = ofsetZ + Clearence
# Margins from the left bottom corner (zero coordinates)
# where the drawing will start:
MarginLeft = 0  # [mm] was 85
MarginBot = 0  # [mm] was 40
# "Home" xy coordinates:
HomeX = 0  # [mm]
HomeY = 0  # [mm]

# Node spacing settings:
ChopLength = 1  # [mm] [2]
ChopParameterStart = 0  # [0.02]
ChopParameterEnd = 1  # [0.98]
EnsureMinimalSpacing = False
MinChopFraction = 0.7  # [-] Minimum fraction of the ChopLength that the nodes should ACTUALLY be
linearly spaced
# Slope settings:
SlopeAngle = 75  # [degree]
SlopeSpeed = 3500  # [mm/min]
vectors = []


# functions
def toolchanger(current_brush, new_brush):
    if current_brush ≠ 0:
        unload_current = "UNLOAD%s" % (current_brush)
        GCODE_out.write(unload_current)
        GCODE_out.write("\n")
    load_new = "LOAD%s" % (new_brush)
```

```python
        GCODE_out.write(load_new)
        GCODE_out.write("\n")


    def dipper(current_colour):
        if current_colour == 1:
            GCODE_out.write("DIP1")
            GCODE_out.write("\n")
        elif current_colour == 2:
            GCODE_out.write("DIP2")
            GCODE_out.write("\n")
        elif current_colour == 3:
            GCODE_out.write("DIP3")
            GCODE_out.write("\n")
        undippedlength = 0
print ( 'Total number of layers: ' , len (paths))

for LayerIndex, Layer in enumerate(paths):
    print('Layer no.: ', LayerIndex)
    print(Layer)
    print(paths)
    nodes = []
    # reset line length counter
    sublengthsum = 0

    # check for speedchange dependent on the type of lines
    if layerType[LayerIndex] != currentType:
        currentType = layerType[LayerIndex]
        speedXY = selectSpeed(currentType)

    # check for toolchange and change currentBrush variable to the correct brush
    if layerBrush[LayerIndex] != currentBrush:
        toolchanger(currentBrush, layerBrush[LayerIndex])
    currentBrush = layerBrush[LayerIndex]

    # check for colourchange and change currentColour variable to the correct colour
    if layerColour[LayerIndex] != currentColour:
        currentColour = layerColour[LayerIndex]
        dipper(currentColour)

    cnt = 0
    vectors.append([])
    for segment in Layer.continuous_subpaths():
        nodes.append([])
        nodes[cnt].append(f"Segment {cnt} ")
        nodes[cnt].append([])

        for index, sub in enumerate(segment):
            length = sub.length(error=1e-3)
            sublengthsum = length
            print("Length of stroke is: ")
            print(length)
            if not length == 0:
                n = int(length / ChopLength)
              step_t = min(ChopLength / length, 0.5)  # one point every step_len but at least two points

                for i in np.arange(ChopParameterStart, ChopParameterEnd, step_t):
                    # Extract all point data for node at parameter i
                    p = sub.point(i)
                    xp = p.real
                    yp = p.imag
                    zp = 0.0  # als je scan maakt welke hoogte ie moet hebben op die coordinaten
                    # Extract all tangent vector data at parameter i
                    tangent = sub.unit_tangent(i)
                    dx = tangent.real
```

```
                    dy = tangent.imag
                    # If file in pixels, adapt to mm
                    if PixelCoordinates:
                        xp = (xp / PPI) * Inch
                        yp = (yp / PPI) * Inch
                        dx = (dx / PPI) * Inch
                        dy = (dy / PPI) * Inch
                        vec_length = np.sqrt(dx ** 2 + dy ** 2)
                        dx = dx / vec_length
                        dy = dy / vec_length
                    # Adapt y coordinates from svg to 'regular' coordinate frame
                    yp = - 1 * yp + CanvasHeight
                    dy = - 1 * dy
                    # Angle of the tangent in radians between -Pi to Pi
                    # rot_z_rad = math.atan2(dy, dx)
                    nodes[cnt][1].append([xp, yp, zp, dx, dy, sublengthsum])
                    print('point added')
                    print('sublength sum:', sublengthsum)
        cnt = cnt + 1
print("printing nodes")
print(nodes)
# If EnsureMinimalSpacing is True, the distance between the nodes is calculated and if smaller than
# the MinChopFraction of the ChopLength, the node is deleted
# This is done to ensure that moves are not too small such that the robot will skip them
# of less value to a 3D printer/cnc machine, but feature still is included
if EnsureMinimalSpacing:
    for node_seg_idx, node_seg in enumerate(nodes):
        for node_idx, node in enumerate(node_seg[1]):
            if not node == node_seg[1][0]:
                x = node[0]
                y = node[1]
                x_old = node_seg[1][node_idx - 1][0]
                y_old = node_seg[1][node_idx - 1][1]
                d = np.sqrt((x - x_old) ** 2 + (y - y_old) ** 2)
                if d < MinChopFraction * ChopLength:
                    del nodes[node_seg_idx][1][node_idx]
        # print (nodes)


# plot the outcome
for node_seg_idx, node_seg in enumerate(nodes):
    for node_idx, node in enumerate(node_seg[1]):
        if not node == node_seg[1][0]:
            x = node[0]
            y = node[1]
            x_old = node_seg[1][node_idx - 1][0]
            y_old = node_seg[1][node_idx - 1][1]
            plt.plot([x_old, x], [y_old, y], f"C{LayerIndex}", label=f"Layer {LayerIndex + 1}")

# create the vector list of all the lines within this layer
for node_seg_idx, node_seg in enumerate(nodes):
    for node_idx, node in enumerate(node_seg[1]):

        # If the node is the first of a segment, first check if dipping is needed, then a slope start waypoint is
        # added in addition to the node itself

        if node == node_seg[1][0]:
            if autodipping:
                print(node)
                print("node length?:   ")
                print(node[5])
                print('check dipping')
                # add the length of the next segment to the total length

                try:
                    undippedlength = undippedlength + node[5]
                    print('undippedlength =')
                    print(undippedlength)
                except IndexError:
```

```python
                            undippedlength = undippedlength + 20
                        # check if the length exceeds the diplength
                        if undippedlength > OutlineDipLength:
                            # Add dipping sequence to the vector list
                            vectors[LayerIndex].append('dip')
                            print('add dipping sequence')
                            # reset the undipped length
                            undippedlength = 0

                    print('Adding start slope')
                    # Adding additional move/waypoint for the start of the slope down to the tile
                    dx_wrtx1 = - 1 * node[3] * SlopeZ * np.sin(np.radians(SlopeAngle))
                    dy_wrty1 = - 1 * node[4] * SlopeZ * np.sin(np.radians(SlopeAngle))
                    slopex = node[0] + dx_wrtx1
                    slopey = node[1] + dy_wrty1
                    vectors[LayerIndex].append(
                        [Vector3(slopex + MarginLeft + ofsetX, slopey + MarginBot + ofsetY, InterMoveZ),
speedXY])
                    # Adding the first node of a continuous segment
                    vectors[LayerIndex].append(
                        [Vector3(node[0] + MarginLeft + ofsetX, node[1] + MarginBot + ofsetY, ofsetZ),
SlopeSpeed])
                # Adding all other nodes of the continuous segment
                else:
                    vectors[LayerIndex].append(
                        [Vector3(node[0] + MarginLeft + ofsetX, node[1] + MarginBot + ofsetY, ofsetZ),
speedXY])

                # If the node is the last of a segment, slope end waypoint is added
                if node == node_seg[1][- 1]:
                    # Adding additional move/waypoint for the start of the slope down to the tile
                    dx_wrtx1 = node[3] * SlopeZ * np.sin(np.radians(SlopeAngle))
                    dy_wrty1 = node[4] * SlopeZ * np.sin(np.radians(SlopeAngle))
                    slopex = node[0] + dx_wrtx1
                    slopey = node[1] + dy_wrty1
                    vectors[LayerIndex].append(
                        [Vector3(slopex + MarginLeft + ofsetX, slopey + MarginBot + ofsetY, InterMoveZ),
SlopeSpeed])
                    if infillWait:
                        vectors[LayerIndex].append('wait')

                    print("adding end slope")

        for vec in vectors[LayerIndex]:

            if not vec == 'wait':
                if vec == 'dip':
                    dipper(layerColour[LayerIndex])

                else:
                    v = vec[0]
                    # print ("%s F%d" % (GCodeLinearMove(**to_coordinates(v)) , vec[ 1 ]))
                    GCODE_out.write("%s F%d" % (GCodeLinearMove(**to_coordinates(v)), vec[1]))
                    GCODE_out.write("\n")
            else:
                GCODE_out.write(f"Z {InterMoveZ + WaitMoveUpZ} ")
                GCODE_out.write("\n")
                GCODE_out.write(f"S {Wait} ")
                GCODE_out.write("\n")
                GCODE_out.write('G4 S{}'.format(Wait))
                GCODE_out.write("\n")
    GCODE_out.write("UNLOAD%d" % (currentBrush))
    GCODE_out.write("\n")
    GCODE_out.write("END_GCODE")
    GCODE_out.close()
```

```
# search and replace G01 to G1

# input file
fin = open(GcodeSavePath, "rt")
# output file to write the result to
OutputSavePath = '{}/{}.gcode'.format(GcodeDirectory, GCODEName)
fout = open(OutputSavePath, "wt")
# for each line in the input file
for line in fin:
    # read replace the string and write to output file
    fout.write(line.replace('G01', 'G1'))
# close input and output files
fin.close()
fout.close()

# Plotting the buildup of layers
plt.axis('equal')
handles, labels = plt.gca().get_legend_handles_labels()
handle_list, label_list = [], []
for handle, label in zip(handles, labels):
    if label not in label_list:
        handle_list.append(handle)
        label_list.append(label)

plt.legend(handle_list, label_list)
plt.show()
```

DESIGN FOR our future

T̶UDelft

IDE Master Graduation
Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

🛈 **USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT**
Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME
Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 ! 🛈

family name	de Haan
initials	M. B. given name Mischa
student number	4456890

Your master programme (only select the options that apply to you):

IDE master(s): ★ IPD   ◯ Dfl   ◯ SPD

2nd non-IDE master: _____

individual programme: ___ - ___ - ___ (give date of approval)

honours programme: ◯ Honours Programme Master

specialisation / annotation:
◯ Medisign
◯ Tech. in Sustainable Design
◯ Entrepeneurship

SUPERVISORY TEAM **
Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair	Sander Minnoye	dept. / section:	Materialising Futures
** mentor	Willemijn Elkhuizen	dept. / section:	Materialising Futures
2nd mentor	Joffrey Walonker		
	organisation:	Royal Delft	
	city:	Delft country:	The Netherlands

comments (optional): Although from the same department, Sander has expertise in Digital fabrication and Willemijn in 3D scanning.

❗ Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

❗ Second mentor only applies in case the assignment is hosted by an external organisation.

❗ Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.
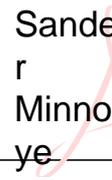
APPROVAL PROJECT BRIEF
To be filled in by the chair of the supervisory team.

chair   Sander Minnoye   date   13 - 09 - 2021   signature

Sander Minnoye
Digitally signed by Sander Minnoye Date: 2021.09.21 12:16:04 +02'00'

CHECK STUDY PROGRESS
To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 27   EC

Of which, taking the conditional requirements into account, can be part of the exam programme   27   EC

List of electives obtained before the third semester without approval of the BoE

(★) YES   all 1st year master courses passed

( ) NO   missing 1st year master courses are:

name   C. van der Bunt   date   21 - 09 - 2021   signature
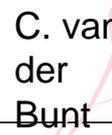
C. van der Bunt
Digitally signed by C. van der Bunt Date: 2021.09.21 14:46:22 +02'00'

FORMAL APPROVAL GRADUATION PROJECT
To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: (★) APPROVED   ( ) NOT APPROVED

Procedure: (★) APPROVED   ( ) NOT APPROVED

comments

name   Monique von Morgen   date   28 - 09 - 2021   signature

Digital Delft Blue, a new approach
project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date   13 - 09 - 2021   18 - 03 - 2022   end date

INTRODUCTION **
Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Royal Delft is a manufacturer of delftware, a traditional luxury product. Since 1653, they are still actively designing and producing products, with a lot of traditional manufacturing techniques. They are most famous for their hand-painted pottery. However, over the last century, the interest in delftware declined and it became more a product of tourism. Royal Delft wants to change this development by innovating on products and their manufacturing processes. By collaborating with famous brands and artists they try to reach a younger audience and create a better position for their products. Other examples they are working on are personalisation, innovating the mold making process and painting by implementing digital manufacturing methods.

Painting Delft Blue
At Royal Delft, there are two different techniques to paint the delftware: hand painting and screen printing. The first technique is the traditional way to paint Delft blue. After eight years of training, painters are able to paint Delft blue. The latter technique, screen printing, is a faster technique that requires a hand-painted design that is replicated and easier to mass-produce.

As Royal Delft wants to innovate on their production process, they collaborated with TU Delft to automate this labour intensive work, searching for new opportunities. After a successful project, a proof-of-concept was built that could paint delftware in a unique way. This project continues on that proof-of-concept, further developing it into a demonstrator. Festo will be supporting this project by providing the necessary hardware and knowledge on gantry systems. The final prototype will be made with their products.

space available for images / figures on next page

120

Personal Project Brief - IDE Master Graduation

TUDelft

introduction (continued): space for images

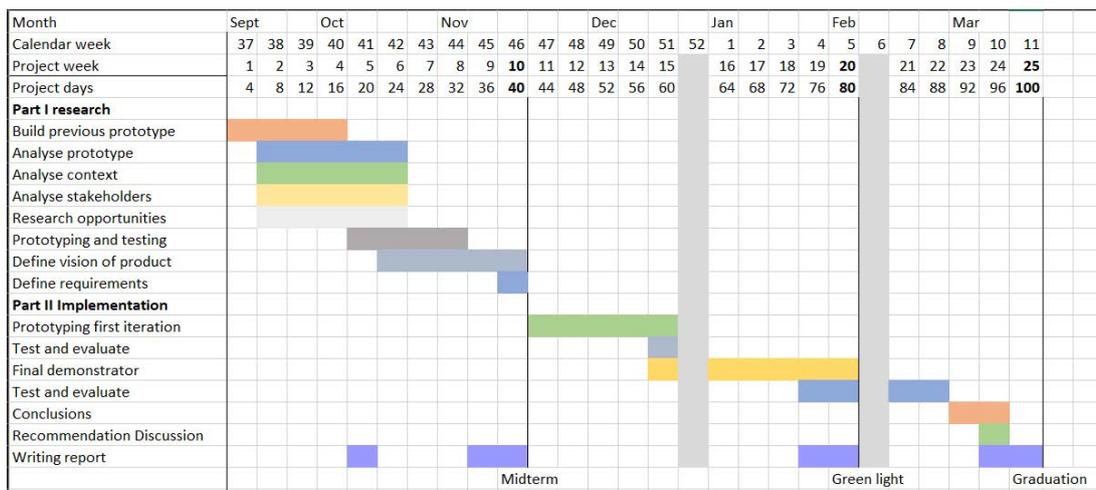image / figure 1:   Goldfinch painted by the 3D printer. Image from report Digital Delft Blue

Month	Sept			Oct				Nov				Dec				Jan				Feb			Mar				
Calendar week	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	1	2	3	4	5	6	7	8	9	10	11	
Project week	1	2	3	4	5	6	7	8	9	**10**	11	12	13	14	15		16	17	18	19	**20**		21	22	23	24	**25**	
Project days	4	8	12	16	20	24	28	32	36	**40**	44	48	52	56	60		64	68	72	76	**80**		84	88	92	96	**100**	
Part I research																												
Build previous prototype																												
Analyse prototype																												
Analyse context																												
Analyse stakeholders																												
Research opportunities																												
Prototyping and testing																												
Define vision of product																												
Define requirements																												
Part II Implementation																												
Prototyping first iteration																												
Test and evaluate																												
Final demonstrator																												
Test and evaluate																												
Conclusions																												
Recommendation Discussion																												
Writing report																												
									Midterm										Green light					Graduation			

image / figure 2:   Gantt chart planning of project: 4 days a week

Initials & Name   M. B.   de Haan   Student number   4456890

Title of Project   Digital Delft Blue, a new approach

**PROBLEM DEFINITION **
Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Royal Delft collaborated with TU Delft to develop a painting robot to create digitally painted Delft blue. The prototype developed during that project was a rebuild 3D printer (Ender 3) that could paint line drawings of typical Delft Blue illustrations. The rough steps to paint delftware consisted of preparing an SVG file, placing the delftware on the print bed, starting the paint sequence and removing the painted piece. Though the paintings were very promising, the result was still inconsistent. There are several challenges to be solved before the printer is able to paint Delft Blue reliably, such as the difference in height between tiles and within the tile, surface influencing the line thickness and the placement of tiles (loading/unloading).

Furthermore, this prototype was developed from a technology-driven approach. To further develop this into an actual product, the viability and desirability of the product need to be researched. So within this project, the context and stakeholders have to be considered when developing the demonstrator.

This project will continue with the development of the painting robot for Royal Delft by focusing on defining a product vision and validating the technology through prototyping. A new demonstrator is designed that can consistently paint delftware by researching, implementing and validating a solution for digitally painting Delft Blue tiles.

Conclusions from the previous project helped to scope down this project:
- The robot should be able to paint on 2D and 2.5D objects. 3D objects, such as vases, are out of scope.
- The design of the robot will continue with the line drawings, as seen in figure 1, as this was the most promising direction.
- When designing the demonstrator, the focus lies on improving the quality and consistency of the painted product.

**ASSIGNMENT **
State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

This project will develop a vision for Digital Delft Blue, a Delft blue painting robot, by researching the technology, context and stakeholders. To improve the feasibility of the robot, the technology should be implemented and validated with a demonstrator.

The first part of this project consists of exploring and testing different techniques to improve the consistency of the current prototype. Firstly, the prototype of the previous project is rebuilt and examined to get acquainted with the working principles and find parts for improvement. Alongside these examinations and tests, research is done on the purpose of this product. The first part will end with a vision and a set of requirements for the demonstrator, finalising the research phase.

The second part of the project focuses on the development of the final demonstrator. Through multiple iterations, tests and prototypes, an improved demonstrator showcasing the potential of this technology is designed and built. The demonstrator should be able to consistently paint Delft Blue and will be validated and evaluated in the final phase of this project.

The final deliverables:
- A demonstrator showcasing the digital fabrication of painting Delft Blue
- A report explaining the product vision and the validation of the technology.
- A video/poster

Personal Project Brief - IDE Master Graduation

**PLANNING AND APPROACH **
Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date   13 - 9 - 2021   18 - 3 - 2022   end date
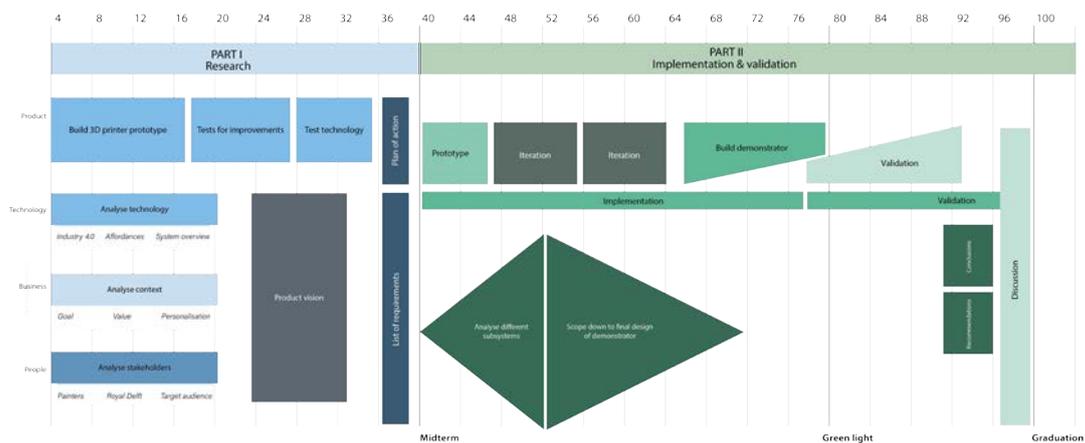
The project will be divided into two phases. The goal of the first phase is to define a vision for the product based on technology, stakeholders and context, together with a plan to improve the feasibility of the product. The phase is concluded with the product vision, a list of requirements and a plan for prototyping and validating the final demonstrator.

The second phase consists of building the improved demonstrator. Through an iterative process with physical prototypes, a new demonstrator is designed based on the requirements set before. This phase focuses more on the feasibility of the product than viability and desirability, as the goal is to deliver a final demonstrator that can showcase the technology of digital Delft Blue..

Note that this graduation project is 4 days a week, meaning that the whole project will be 25 weeks long.

Personal Project Brief - IDE Master Graduation

MOTIVATION AND PERSONAL AMBITIONS
Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

1. Mechatronics and software
I always had an interest in electronics and software within product design. I gained quite some experience during my minor and my year at a Dreamteam which I want to apply during my graduation project. That is why this project is focused on the mechatronics of the demonstrator.

2. A unique collaboration
The collaboration between Royal Delft, TU Delft and Festo is an unique combination of old-fashioned artisanal production with a highly innovative company. I think that this combination makes this project so interesting.

Personal learning goals:

- Learn more about mechatronics and software with commercial grade hardware
- Learn how to manage an individual embodiment design project
-
- Choosing the right approach for technical research

- Learning more about the challenges between digital manufacturing and artisanal crafts
- Doing an embodiment project for a large production company.

FINAL COMMENTS
In case your project brief needs final comments, please add any information you think is relevant.