RE-PRINT

Aesthetically repurposing architectural elements with nanocellulose hydrogels

REBECKA RUDIN

Chalmers School of Architecture
Department of Architecture and Civil Engineering

Supervisor: Malgorzata Zboinska
Examiner: Daniel Norell

RE-PRINT

Aesthetically Repurposing Architectural Elements with Nanocellulose Hydrogels

Rebecka Rudin

MPARC ACEX35

Matter Space Structure 2022

Chalmers School of Architecture
Department of Architecture and Civil Engineering

Supervisor: Malgorzata Zboinska

Examiner: Daniel Norell

CHALMERS

ACKNOWLEDGMENT

This Master thesis project was a part of a contribution to a research project "Nanocellulose in architecture – esthetic applications through 3D printing", led by prof. Malgorzata Zboinska from the Department of Architecture and Civil Engineering at Chalmers University of Technology, in collaboration with prof. Paul Gatenholm and dr. Sanna Sämfors from the Department of Chemistry and Chemical Engineering at Chalmers and the Wallenberg Wood Science Center, with funding support from Chalmers Area of Advance Materials Science and Adlerbertska Research Foundation.

THANK YOU

Thank you Malgorzata Zboinska for giving me the opportunity to work with your research on biofabrication in architecture and for being the most supportive and inspiring tutor I could have asked for.

Thank you Karl Åhlund for generously sharing your grasshopper script for 3D printing with the KUKA robot arm.

Thank you Marie Edman Franzén at Statens Fastighetsverk for taking the time to guide me around Götiska Tornet and for sharing your knowledge about the building's historical background.

Thank you Michael Andersson-Sarning at Chalmers Chemical Engineering Department for sharing knowledge and tools that enabled me to explore the potential of mixing the nanocellulose hydrogel with additives.

And thank you Oscar and my family for all your encouragement and support throughout this process.

ABSTRACT

Working with the naturally occurring biomaterial cellulose, the thesis aims to explore how degraded elements can be preserved and creatively re-imagined by 3D-printing new surfaces with a nanocellulose-based hydrogel. Embracing the unpredictable agency of the material while prioritizing process-driven ornament and tactility. Particular emphasis is placed on the exploration of nanocellulose coatings on wood fiber-based materials, as early experiments indicated that the nanocellulose hydrogel naturally adheres to the material.

The nanocellulose material explored in the thesis is provided by Chalmers Chemical Engineering Department, Boregaard and RISE Innventia in the form of nanocellulose hydrogels. The cellulose derives from the common wood pulp which can be extracted from trees and plant matter and is constituted of hydrophilic polymer networks with unique qualities in regards to softness, wetness and compatibility with living tissue. The material has previously mainly been utilized within the field of tissue engineering and biomedical research to print scaffoldings for cell attachment and growth. In the recent past, nanocellulose hydrogels have started to gain wider popularity in various applications due to their biocompatibility, mechanical properties and high abundance.

The thesis presents a design proposal of three interventions to be implemented internally at Götiska Tornet in Stockholm. Exemplifying through prototypes how the nanocellulose hydrogel can be 3D-printed on degraded wood as an aesthetically enhancing coating to preserve and restore an existing interior. The design implementation of research findings through large-scale application aims to increase awareness and cultivate familiarity with bio-fabrication in the architectural discipline, examining both the potential and issues that are raised by introducing new materials to an existing architectural context.

Keywords: nanocellulose, bioprinting, robotic additive manufacturing, water-based materials, creative reuse

CONTENT

GLOSSARY OF TERMS

HYDROGEL	water-based material consisting of polymer networks and water which form chemical crosslinks via ionic and hydrophobic interactions (Malik et al. 2019, p.2).
NANOCELLULOSE	material derived from wood fibers consisting of long (1-2 micrometers) microfibrils with the appearance of a transparent gel (RISE, 2020).
DIGITAL FABRICATION	production method using digital data to control computer-driven machine tools for building or cutting elements (Iwamot. 2020, p.5).
PHOTOGRAMMETRY	scanning method to determine the position and shape of an object from photographs utilizing a principle of stereoscopic viewing from two or more photos of an object from different angles (Febro, 2020, p. 154).

QR codes are used to link to video content and will be located in the corner of the relevant page. A list of URL links for the files is also located in the Appendix. This QR code takes you to the homepage where all videos in the thesis are located.

INTRODUCTION

BACKGROUND

Nanomaterials extracted from sustainable and naturally occurring sources have recently started to gain increasing attention in ambitions to subvert the currently linear state of building with limited natural resources. Extracted from renewable biomasses, these nanomaterials hold great promise in various applications owing to their biocompatibility, mechanical properties, ease of functionalization, and high abundance (Ying Ee & Fong Yau Li, 2021, p. 3). Amongst these nanomaterials cellulose is classified as the most abundant polymer on earth that can be sourced from plants, bacterial pellicles, and agricultural wastes (Ibid, p. 4). To further reduce wastage and the carbon footprint in the materialization of these biomaterials, additive manufacturing strategies offer great potential in terms of minimum-waste fabrication.

Among evolving design approaches toward more circular fabrication methods, there are not only those that focus on the incorporation of new or vernacular materials but also design approaches that explore the potential of restoring and re-using already materialized components. Within this trajectory digital tools are becoming more widely explored both in the documentation and fabrication of retrofitting solutions. One prominent actor in the development of such digital restoration workflows is the Institute of Digital Archaeology. Through projects such as the re-manufacturing of the Arch of Triumph in Palmyra, the association is working to develop technological solutions within photogrammetric scannings and digital manufacturing techniques that enables the recording and reproduction of historical artifacts (Tarmy, 2018).

The thesis aims to explore both trajectories of digital manufacturing with biomaterials and creative reuse through the retrofitting and re-imagination of an existing architectural environment. In collaboration with ongoing research driven by Malgorzata Zboinska on bioprinting with nanocellulose hydrogels, the thesis investigates the overlapping disciplines of material science, digital fabrication and explorative restoration to elucidate the design potential that can emerge from the interdisciplinary synthesis.

HOW CAN A DESIGN APPROACH BASED IN THE IDEA OF RE-APPROPRIATING MATTER WITH NANOCELLULOSE HYDROGEL SURFACES BE IMPLEMENTED THROUGH THE USE OF DIGITAL FABRICATION TECHNOLOGIES?

WHICH QUALITIES CAN NANOCELLULOSE HYDROGELS BRING TO THE ARCHITECTURAL EXPRESSION?

AIM

The aim of the thesis was to explore the potential of 3d-printing architectural elements with nanocellulose hydrogels to re-imagine and restore an existing architectural interior. Exploring the potential and issues that are raised by introducing new materials to an existing architectural context.

DELIMITATIONS

Although the thesis operates within the interdisciplinary context of digital fabrication, material science and chemistry, the research is centered around the design outcome. Material experiments were executed with a bio-based hydrogel produced by Chalmers Chemistry and Chemical Engineering department, RISE Innventia and Boregaard, and the thesis has not focused on in-depth material aspects which require specialist knowledge about the chemical structures of the material.

METHOD

The method for the thesis is based on a research by design approach and the development of the thesis is divided into three phases; Experimentation, Prototyping and Design Implementation which were conducted in parallel, informing each other throughout the process. During the Experimentation phase investigations were made regarding how printing with a liquid hydrogel can be achieved using KUKA robotic arm with a custom printer tool. During the Prototyping phase, the properties of the printed elements were tested to receive indications of the limitations and potentials of large-scale applications. The phase consisted of 3D-printing prototypes to investigate the material. Documentation through the phases consisted of photographs of the printed elements and the material development after printing as well as videos of the printing periods. In the Design implementation phase, the findings regarding biofabrication utilizing hydrogels were evaluated and translated into a design proposal.

THEORETICAL BACKGROUND

NEW MATERIALITIES

The field of design has since the industrial revolution predominantly been affected by mass production and manufacturing, resulting in designs constituted by the assembly of separate units. These production flows are today starting to change, as the confluence of computational design, additive manufacturing and material engineering are providing us with the opportunity to design and manufacture growth rather than assemblage. In combination with bio-based materials, these new digital design strategies offer a shift towards a more circular way of constructing our built environment where renewable material resources can be extruded through additive manufacturing strategies with minimal material waste. A fabrication process exemplified by the Water-based Digital Fabrication project "Aguahoja" developed by MIT Mediated Matter Group, illustrating how structures can be 3D-printed entirely from biocompatible cellulose (Oxman, 2020, p.84).

Diana Coole & Samantha Frost state in their publication New Materialisms, Ontology, Agency, and Politics that as a result of the scientific and technological advances regarding new materials and their materialization processes, material phenomenas are more frequently being conceptualized as open systems with flexible boundaries rather than closed and predictable entities. Thereby replacing previous Aristotelian views of materials as inactive matter that derives its forms from external forces; ”the fact that a virtual structure can be actualized by different material systems provides us with a way to think about recurring regularities in the birth of form without having to invoke eternal natural laws.” (DeLanda, 2015, p. 5).

As further stated by Paola Antonelli, Senior Design Curator of the Museum of Modern Art Senior: ”Designers stand between revolutions and everyday life” (Ginsberg, 2014, p. 63). When blending design with unaccustomed material science and technology it also challenges our conventional understanding of how our built environment should be perceived through our senses, raising questions about how our behaviors, interactions and lifestyles are affected by our material surroundings. The thesis aims to reflect on some of the philosophical and aesthetic issues that are raised in the intermediate act of applying nanocellulose-based hydrogels into an already designed context, while also exploring the functional opportunities of 3d-printing with a bio-based material.

BIOMATERIAL EXPLORATION
Nanocellulose hydrogel 30 minutes post printing

BIOMATERIAL EXPLORATION
Nanocellulose hydrogel 24 hours post printing

DIGITAL MANUFACTURING

3D printing with nanocellulose hydrogel

DIGITAL MANUFACTURING

Digital manufacturing is an emerging field of production methods that is classified into two main categories; subtractive and additive manufacturing strategies (Arbaceet al., 2013, p. 332). Subtractive techniques involves the development of a physical model through the removal of matter from a solid block of material, often conducted by the use of "milling machines" or "lathes". The machines are run based on computer-aided manufacturing softwares which translate the digital model into a series of commands interpreted by the machine (Ibid, 332).

Additive techniques are methods for materializing digital models through successive additions of material layers, also known as 3-dimensional printing. The production of the printed model requires the application of a slicing software to a digital model, which divides the model object into sequences that are then translated into a series of machine commands through the creation of a specific numerical G-Code. The resolution of the details depends both on the thickness of the layer and the dimensions of the movement imposed on the tool: the smaller the movement of the printer's motors, the greater the degree of detail (Arbace et al., 2013, p. 335).

Since the end of the 80s, the emergence of additive manufacturing has further increased the opportunities for designers to materialize structures with material efficiency, and is gaining popularity within creative industries for the ability to materialize complex structures while generally reducing production costs and production time.

NANOCELLULOSE HYDROGELS

Nanocellulose derives from the common wood pulp which can be extracted from trees or plants in the form of linear polymers consisting of glucose molecules (Lavoine et al. 2012, Kangas et al. 2014). Nanocellulose hydrogels are polymer networks infiltrated with large amounts of water, often comprising more than 90% of their weight (Tibbits 2017, p. 98). Due to the material’s unique qualities in regards to softness, wetness and biocompatibility, it has previously mainly been utilized within the field of tissue engineering and biomedical research to print scaffoldings for cell attachment and growth (Malik et al. 2020, p. 3).

Research has also been made regarding the material's biodegradable potential, studying how hydrogel structures can be decomposed to their original form once they have fulfilled their purpose. The studies prove that the material dissolves into its constituent elements when exposed to water, resulting in a short decay cycle which makes the material biodegradable and fully recyclable (Malik et al. 2020, p. 5).

NANOCELLULOSE HYDROGEL
Produced by Borregaard

BIOMATERIAL FOR THESIS

The hydrogel explored within the thesis was provided by Chalmers Chemistry and Chemical Engineering department, RISE Innventia and Borregaard. The hydrogel consists of approximately 98% water and 2% nanofibres of wood cellulose which is upcycled from forestry and paper mill waste.

Due to the material composition consisting of water and plant-based fibers, the material is a sustainable product that is fully biodegradable when exposed to water. The hydrogel is suitable for 3D printing due to its thixotropic qualities, meaning that the material is viscous enough to be extruded from a container with air pressure, yet firm enough to maintain its structure after being printed (Markstedt et al. 2015, p. 1489).

DIGITAL TOOLS FOR RESTORATION

The relationship between new technologies and craftsmanship is currently entering a new era where the craft of restoration is re-introduced as a cost-effective option through digital tools and manufacturing techniques. The process of digitally re-manufacturing objects for restorative purposes initially relies on the access of 3D virtual models through photogrammetric scanning of the artifact (Higueras et al., 2021, p. 9). The object can then either be reconstructed through additive and/or subtractive manufacturing tools or through the making of molds for reproductions in materials that cannot be printed or milled (Bonora et al., 2021, p. 5).

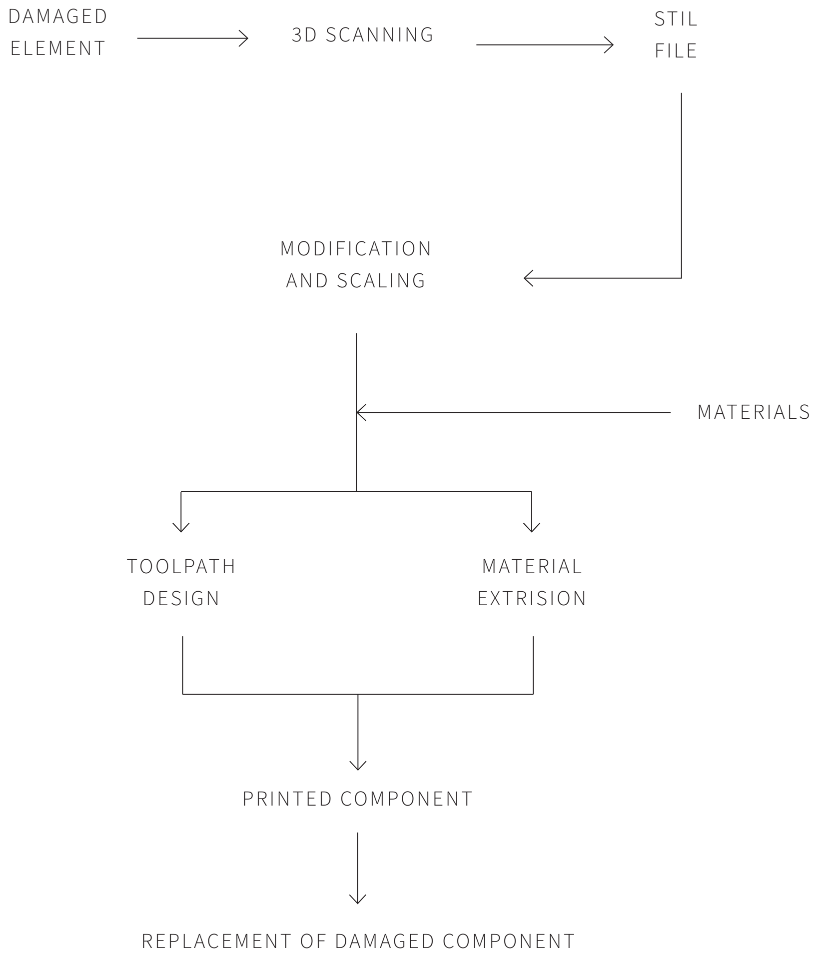
The art conservation company Factum Arte is one of the main precursors within the field of digital restoration through their Factum Foundation and has developed a number of technologies in order to better promote the digital recording and production of objects. One of their most acclaimed projects is the re-creation of the tomb of Tutankhamon, which was executed in collaboration with the Egyptian Ministry of Antiquities and the University of Basel to promote awareness about the importance of sustainable tourism (Tarmy, 2018).

The company's workflow starts with a digital recording of the artifact using a Lucida 3D Laser Scanner which is a non-contact 3D recording system with the ability to capture data with a resolution up to 100µm of the surface. The scanner records 3D data in tiles with dimensions of 48 x 48 cm, which is combined with the recording of two video cameras positioned at 45 degrees in relation to the laser to capture light distortions and thereby define the thickness of surface textures.

The company then reproduces the artifact in-house utilizing 3d-printers and milling machines to create a base layer with the textured profile of the original element. A "skin" is then printed and placed in alignment with the modeled base before being placed in vacuumed pressure so that a contact adhesive between the two elements can create a permanent bond. The resulting facsimile is currently on display in the Valley of the Kings in Egypt to provide tourists an alternative to the deteriorating original. (Tarmy, 2018)

Another prominent project within the development of a digitalized restoration workflow is the collaborative project "The Million Image Database Project" initiated by the Institute for Digital Archaeology (IDA). Their aim is to preserve ancient monuments destroyed in the Syrian civil war and document objects that are at risk of being sieged by ISIS. The project currently provides citizens of Syria with 3D cameras to generate photogrammetric documentation of historical artifacts and thereby enable later recreation of the data in case of the object's destruction (Hadingham, 2016).

Their most debated example of digital recreation is the reproduction of the Arch of Triumph in Palmyra which was destroyed by ISIS in October 2015 (Denker 2017, p.565). The arch was originally built during the period of Emperor Septimius Severus as the entryway to the Temple of Baal and was added to the UNESCO list of world heritage sites in 1880 (Ibid). After the destruction of the arch, the Institute for Digital Archaeology collaborated with the Syrian Governments director of Antiquities to reproduce the arch in Carrara, Italy, using a seven-axis robotic arm that milled the arch from yellow Egyptian marble (The Guardian, 2016).



DIGITAL RESTORATION WORKFLOW
Based on work by Factum Arte and IDA

EXPERIMENTATION

BIOPRINTER SET-UP

ALL EXPERIMENT

FABRICATION LAB

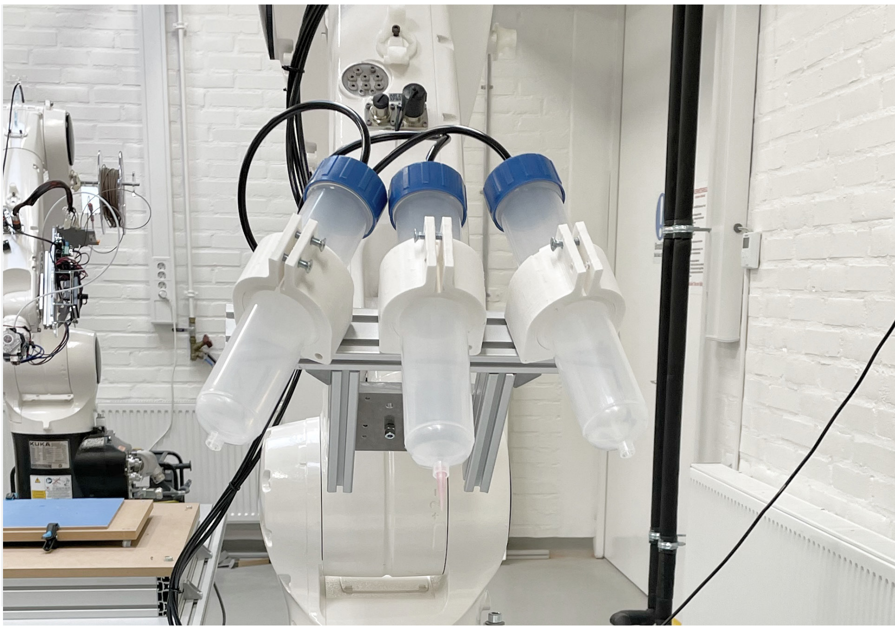
CIVIL ENGINEERIN

KUKA AGILUS KR10

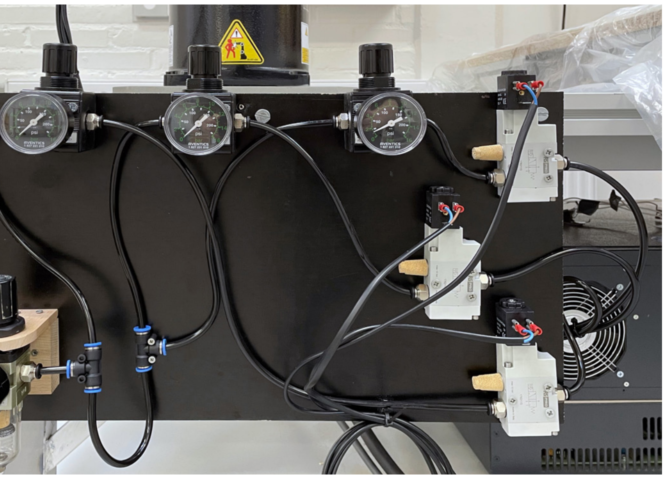
The custom tool for 3D-printing with fluid materials was built and assembled by Malgorzata Zboinska and Karl Åhlund. The printer consists of a printer head with three material containers and extruders from which the material is extruded with air pressure that is activated through scripted commands to solenoid valves connected to each container. The printing board is covered with silicone cladding to simplify the removal of prints with the nanocellulose hydrogel.

PRINTER HEAD

The printer head consisted of three 200 ml containers to enable prints to be conducted with hydrogels in varying colors. The angle between the containers was set to 15 ° to avoid collisions with printed matter and the diameter of the nozzles ranged between 0.6 - 2.9 mm.

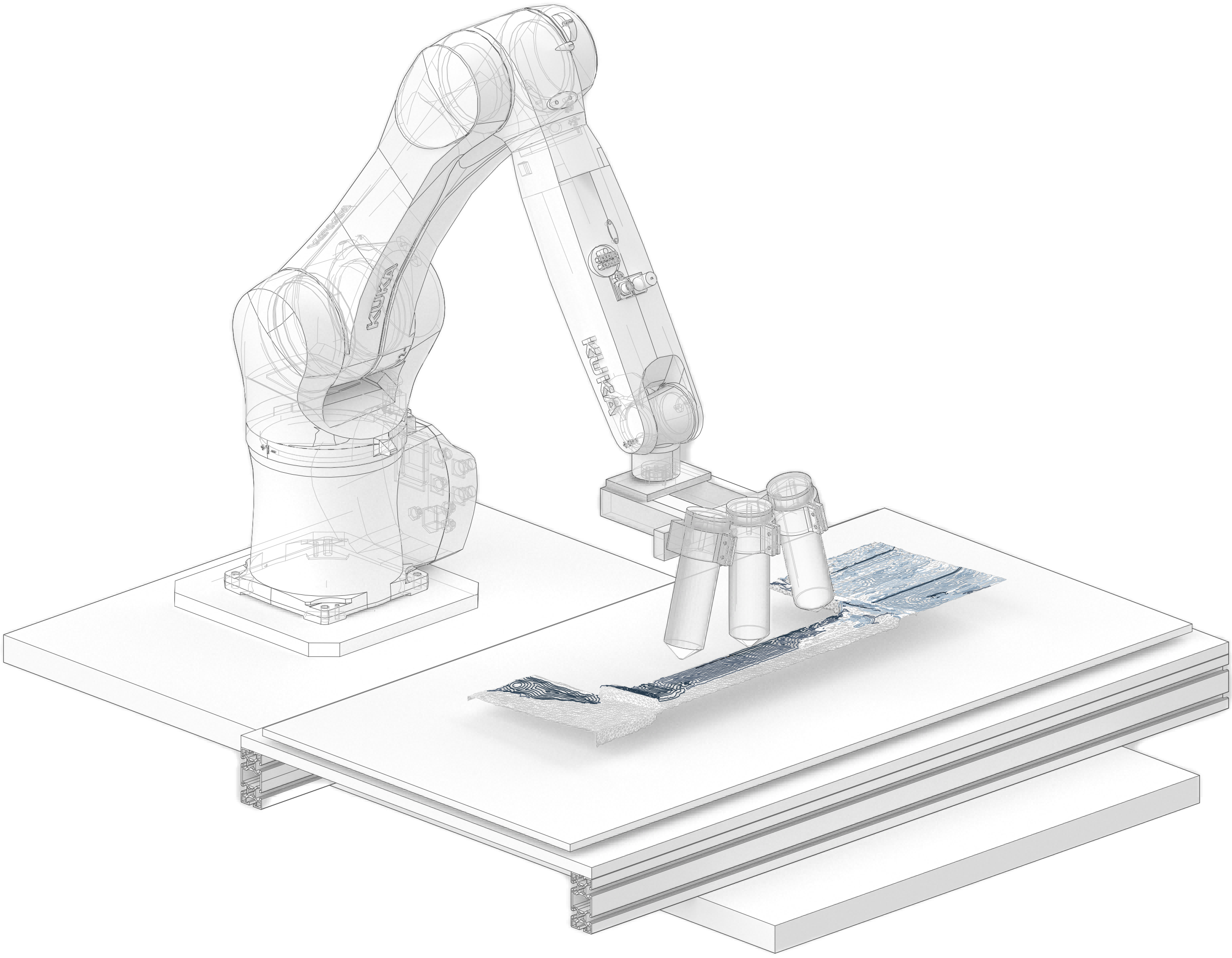


S WERE CONDUCTED IN THE ROBOTIC
ORATORY AT CHALMERS ARCHITECTURE AND
G DEPARTMENT



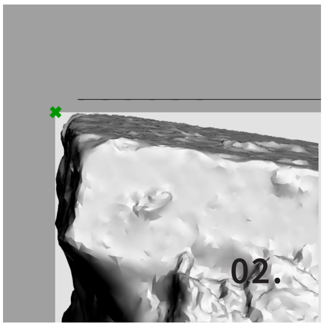
COMPRESSORS & SOLENOID VALVES

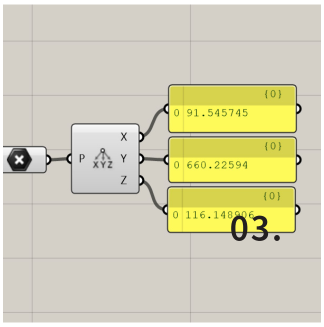
Air compression was manually adjusted for each container through faucets and measured using pressure gauges (maximum pressure being 8 bar). The pressure was activated through scripted commands to solenoid valves connecting to each faucet.



PRINTING WORKFLOW

The element to be printed on was first 3d-scanned to generate a digital model that could be placed in a modelled environment of the robot set-up. The pattern to be printed on the object was then designed either in illustrator or in rhino together with grasshopper before finally generating an SRC-code for the robot to interpret and print.





```
{0}
0 91.545745
{0}
0 660.22594
{0}
0 116.148906
```

OBJECT SCAN

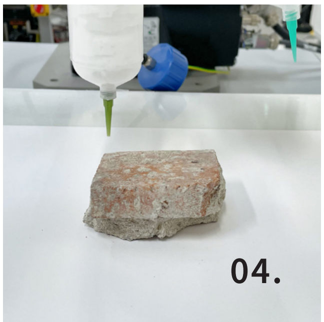
The object was scanned from 360° in the app Polycam. A 3D-mesh was generated which was then exported as an STL-file. The mesh was edited and scaled in Rhino 6. A toolpath was designed and placed 2 mm above the object.

CONTROL POINTS

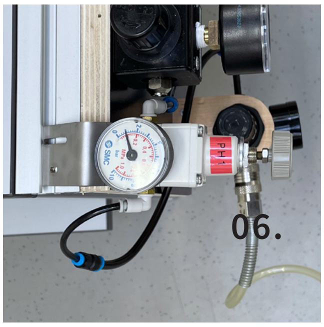
A bounding-box was created around the object from which control points were generated.

CHECK COORDINATES

The control point was baked and then deconstructed to reveal the coordinates in the x-, y- and z-axis. This process was repeated for 2-3 points to ensure that the object was placed correctly.



```
LIN {X -78.044, Y 805.998, Z 116.154, A 0, B 90, C 0, E1 0, E2 0, E3
0, E4 0} C_DIS

LIN {X -78.527, Y 804.78, Z 116.154, A 0, B 90, C 0, E1 0, E2 0, E3
0, E4 0} C_DIS

LIN {X -79.426, Y 800.107, Z 116.154, A 0, B 90, C 0, E1 0, E2 0, E3
0, E4 0} C_DIS

LIN {X -79.915, Y 796.797, Z 116.154, A 0, B 90, C 0, E1 0, E2 0, E3
0, E4 0} C_DIS

LIN {X -79.876, Y 794.706, Z 116.154, A 0, B 90, C 0, E1 0, E2 0, E3
0, E4 0} C_DIS

LIN {X -78.89, Y 792.354, Z 116.154, A 0, B 90, C 0, E1 0, E2 0, E3
0, E4 0} C_DIS

LIN {X -77.6, Y 789.894, Z 116.154, A 0, B 90, C 0, E1 0, E2 0, E3
0, E4 0} C_DIS
```



OBJECT PLACEMENT

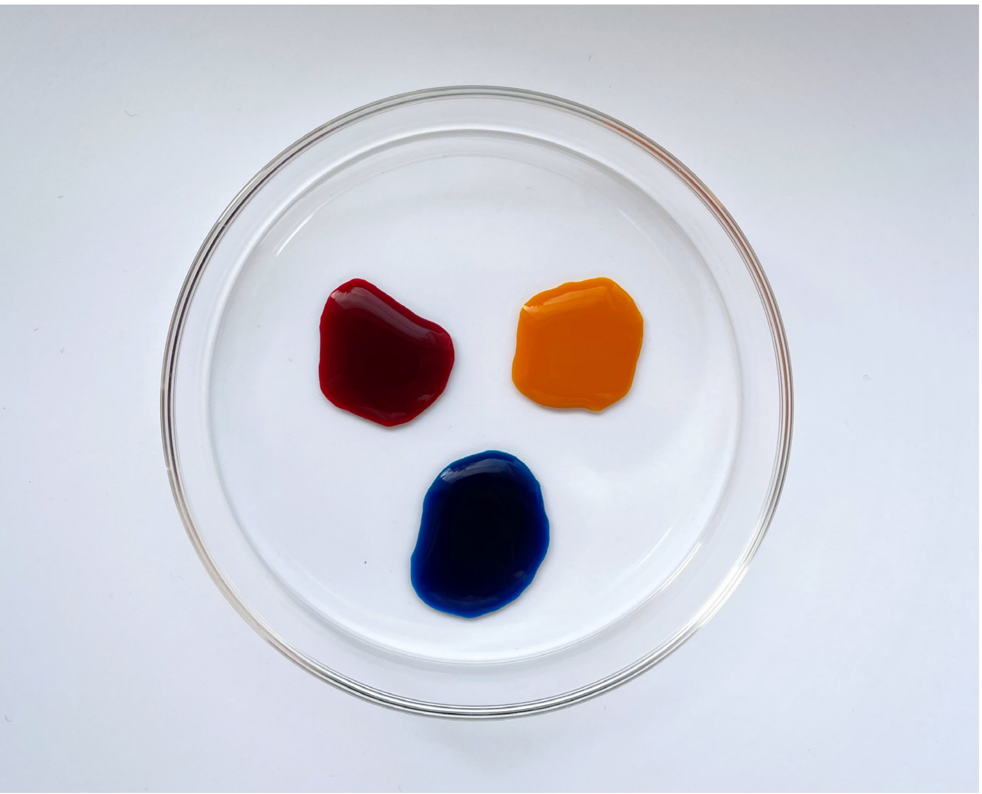
The object was placed according to the coordinates from the digital file.

UPLOAD SRC-CODE

The grasshopper-script was exported as an SRC-code to the robot's computer system and selected on the KUKA smartPAD for printing.

3D PRINT

When printing the air pressure was manually adjusted through regulators with barometer indicators.



EXPERIMENT #1.1

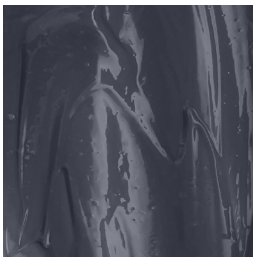
COLORATION OF MATERIAL

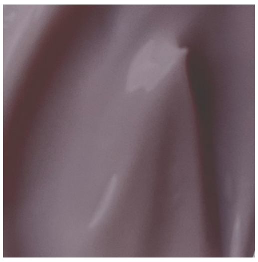
The hydrogel was dyed with food coloring in primary colors to explore aesthetic features with the material. Due to the high opacity of the hand cream in relation to the nanocellulose hydrogel, a more somber color scheme was developed to soften the contrasts between color transitions.

ORIGINAL COLOR

LIGHT BLU

20 ml hydro
0.2 ml blue
0.1 ml black





E

gel
pigment
pigment

MEDIUM BLUE

20 ml hydrogel
1.5 ml blue pigment
1.0 ml black pigment

GREY/BLUE

20 ml hydrogel
1.5 ml blue pigment
1.0 ml black pigment

PINK

20 ml hydrogel
0.5 ml red pigment

LILAC

20 ml hydrogel
1.0 ml red pigment
0.25 ml blue pigment
0.10 ml black pigment

BURGUNDY

20 ml hydrogel
1.5 ml red pigment
0.5 ml blue pigment
1.0 black pigment

EXPERIMENT #1.2

3D PRINTING POTENTIAL

OBJECTIVE

The experiment investigates the potential of printing three-dimensional geometries with the infill material. Studying the impact during printing and 48 hours later.

METHOD AND PROCEDURES

Colored hand cream was extruded five times in a circular toolpath from a bottle with a nozzle diameter of 2 mm.

RESULT AND DISCUSSION

The hydrogel disseminated from the original form during the printing, increasing the diameter of approximately 0.5 cm.
48 hours later the outer diameter remained intact but the hydrogel had dispersed inwards, significantly decreasing the central radius of negative space.

CONCLUSION

The fluid hydrogel is not ideal for printing three-dimensional geometries as the hydrogel spreads and changes the printed shape while drying. There is a possibility to improve the results by speeding up the drying process while printing occurs. Future design iterations will therefore explore the potential of printing two-dimensional surfaces without the obligation to maintain structural integrity after printing.

PRINTING
The hydrogel dispersed immediately within the already printed geometry while printing, not resulting in distinguished toolpaths.

AFTER 5 EXTRUSIONS
The print sunk while drying, both expanding the outer diameter and decreasing the inner radius.

48 HOURS LATER
After two days the hydrogel had developed a hardened skin which maintained the form.

EXPERIMENT #2.1

HYDROGEL ADHESION

OBJECTIVES

The aim of the experiments was to study how the nanocellulose hydrogel dries on various materials in terms of adhesion, to elucidate the potential and compatibility of coating materials with the nanocellulose hydrogel.

METHOD

Approximately 1.5 ml of cellulose hydrogel was manually extruded on each object from a plastic syringe with a nozzle diameter of 0.5 mm.

RESULTS

#4.1 METAL

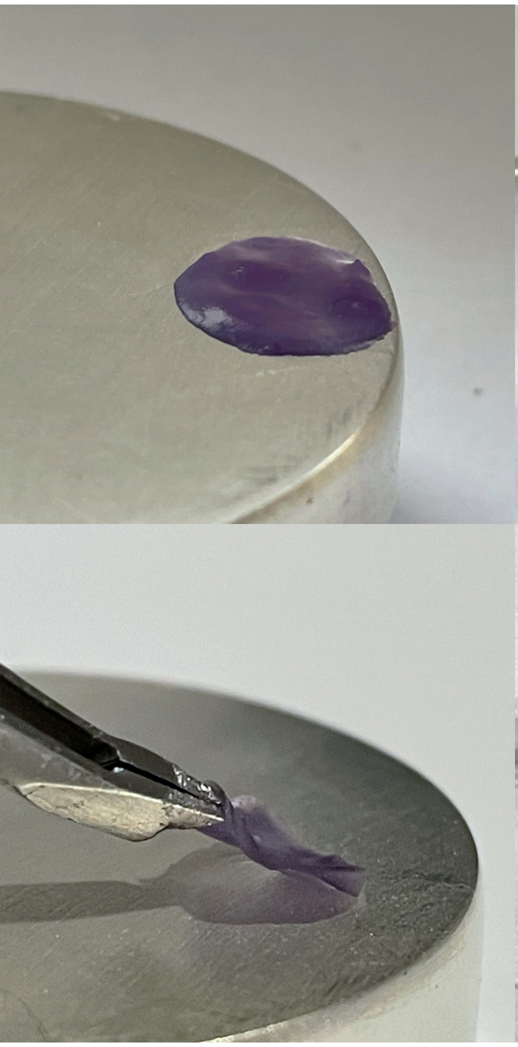
The cellulose was attached to the surface and dried within approximately 20 minutes. The cellulose completely detached from the metal througout the drying process, resulting in a separate membrane that could be removed from the surface.

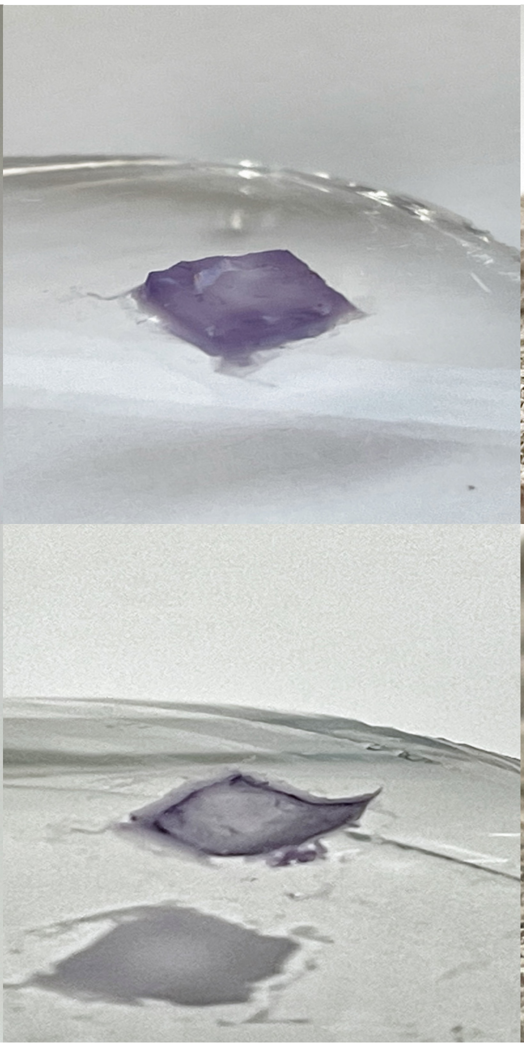
#4.2 GLASS

The cellulose adhered to the surface and dried within approximately 20 minutes. Once it had dried completely the cellulose however started to peel off from the glass in two of the corners, resulting in a slightly curved cellulose surface.

#4.3 CONCRETE

The cellulose attached to the concrete surface and dried quickly after approximately 10 minutes. Once it had dried completely it however started to peel off from the material, creating a small gap where the object was most irregular in texture.





#4.1 METAL

#4.2 GLASS

#4.3 CONCRETE

#4.4 CHIPBOARD

The cellulose dried quite slowly in relation to the other elements, taking about two hours before being completely dry. Once dry the cellulose adhered well to the chipboard, generating a thin, smooth surface that followed the texture of the material.

#4.5 OILED OAK

The cellulose dried over one hour, resulting in a cracked membrane once it had dried completely. The cellulose's connection to the wood was stronger than the internal bond, resulting in that the edges of the extruded material remained connected to the wooden surface.

#4.6 WOODEN APERTURE

The cellulose dried quickly within 20 minutes and needed to be dried vertically to prevent the cellulose from separating from the aperture or sticking to underlying surfaces. The cellulose cracked in the center while drying, generating an aperture that grew throughout the drying process.

CONCLUSIONS

The material studies indicated that the nanocellulose hydrogel adhered significantly better to the wooden finishes in comparison to the other material surfaces. Based on this study the prototyping and design implementation was chosen to be applied on wooden surfaces.

#4.4 CHIPBOARD

#4.5 OILED OAK

#4.6 WOODEN APERTURE

EXPERIMENT #2.1

AIR PRESSURE CALIBRATION

OBJECTIVES

The main aim of the experiment was to receive indications of the optimal air pressure required to achieve a consistent extrusion of fluid hydrogel while printing.

METHODS AND PROCEDURES

Printing was accomplished on a KUKA robot model KR6-10R1100 with a custom extruder system consisting of a container connected to an air compressor which is controlled through a faucet. The pressure gauge ranges between 0 - 16 bar and the maximum pressure from the connecting air compressor was 8 bar. The substitute hydrogel was from the brand Locobase, which was colored with food coloring pigments in primary colors. The process was documented through videos and photographs. The robot was moved to its position by running an already uploaded script for adjusting the nozzle height. the hydrogel in the containers. A plastic sheet was placed under the nozzle before turning on the faucet by activating the solenoid valve on a KUKA smartPAD. Air pressure was manually adjusted throughout the printing period, ranging between 0 - 2 bar during the printing period.

RESULTS AND DISCUSSION

The hydrogel started to extrude from the container at a high velocity at approximately 2.0 bar, resulting in a blob of material on the plastic sheet. The pressure was difficult to regulate due to slight delays in the response from the faucet, resulting in the hydrogel being extruded in uneven intervals.

CONCLUSIONS

The main issue for the print was to maintain a precise pressure with the faucet, and also maintaining a steady flow once the hydrogel started to extrude from the nozzle. The hydrogel started to extrude at slightly under 2 bar at a high velocity which was then difficult to control without as there was some delay in response from the faucet. This might be resolved by exchanging the faucet and pressure gauge to another indicator with a smaller range, as most future tests will need 2 bar. The issue of the fast flow of hydrogel might also depend on the viscosity of the material, which was lowered by adding food coloring to the hand cream. Further notions to explore would therefore be the use of a firmer (uncolored) hydrogel, and possibly exchanging the nozzle diameter to a smaller size (1.0 - 1.5 mm) to increase the pressure required to extrude the material.

EXTRUSION
The hydrogel started to extrude uncontrollably at 2.0 bar, after which it was difficult to maintain a steady extrusion flow.

FINAL RESULT
The experiment resulted in a chunk of material without a readable toolpath.

EXPERIMENT #2.2.1

EXTRUSION WITHIN ENCLOSED APERTURE

OBJECTIVES

The experiment aspired to gain more information regarding the optimal air pressure required to achieve a consistent extrusion of fluid hydrogel while printing. The aim of the experiment was also to elucidate the potential of 3D-printing a vector-based toolpath within an enclosed aperture using a fluid hydrogel.

METHODS AND PROCEDURES

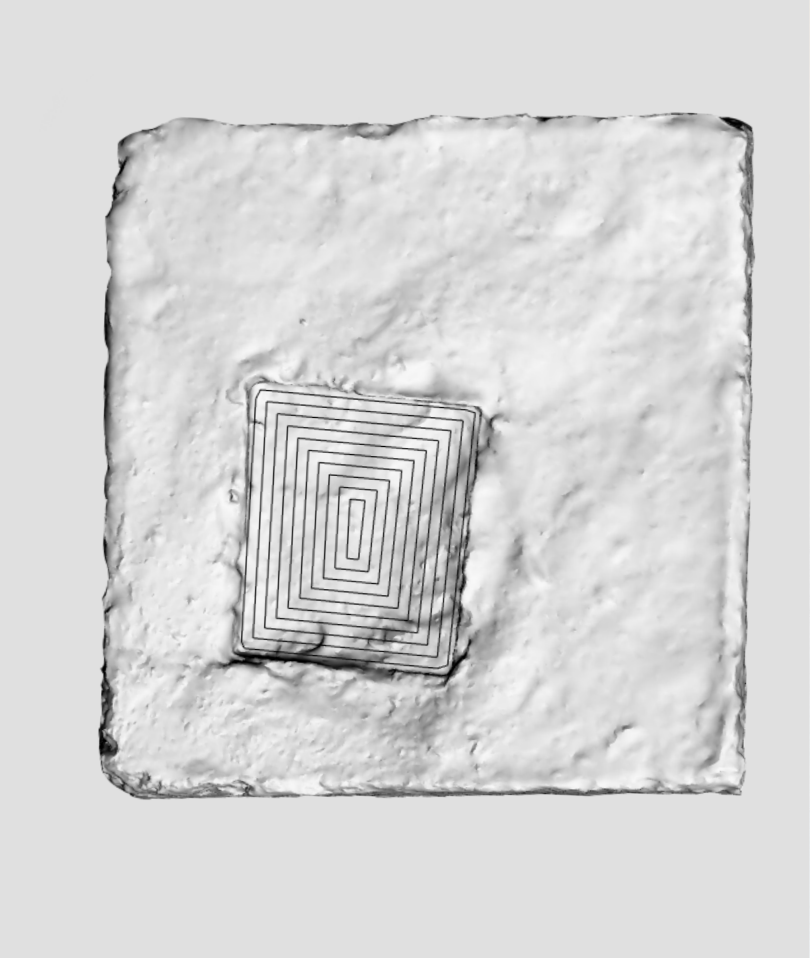
3D scanning was achieved by scanning the object from 360° using the Polycam app. A STL file of the scanned mesh was then edited and scaled in Rhino 6, for which a toolpath was developed consisting of ten circuits with a set distance of 3 mm. The object was placed on the printing board in relation to coordinates from the digital model, generated as control points on the toolpath which were then physically checked by jogging the robot to the x-,y- & z-coordinates. The script was saved as a SRC-code and run on KUKA KR6- 10R1100 with a custom tool for 3D printing with the fluid hydrogel with a nozzle diameter of 1.55 mm. Air pressure was manually adjusted throughout the printing period, ranging between 0 - 2 bar during the printing period. A waiting time of 1 second was set every time the robot moved to the adjacent toolpath and the printing speed was set to 0.015 m/s.

RESULTS AND DISCUSSION

The hydrogel started to pour out of the container at approximately 1.75 bar at a high velocity and was then difficult to regulate due to slight delays in the response from the faucet. This resulted in a big chunk of the hydrogel being extruded into the aperture, creating a blob in the middle of the print. The pressure from the connected air compressor also dropped from 2.0 bar to approximately 1.5 bar during the printing, which could have contributed further to the uneven printing flow.

CONCLUSIONS

The main issue for the print was inaccuracies regarding air pressure during the printing period. Both in terms of manually reaching the precise pressure on the faucet, and also maintaining a steady flow once the hydrogel started to extrude from the nozzle. This might partly be resolved by exchanging the faucet and pressure gauge for another indicator with a smaller range, as it seems improbable that future tests will need pressure higher than 2-3 bar. The issue of the fast flow of hydrogel might similarly to experiment #1 depend on the viscosity of the material. Further notions to explore would therefore be the use of an uncolored hydrogel.



3D SCAN & TOOLPATH
The toolpath consisted of 10 circuits to fill an open aperture.

FINAL RESULT
A big portion of material was extruded without a visible toolpath.

EXPERIMENT #2.3.2

EXTRUSION ON ANGLED BRICK

OBJECTIVES

The aim of the experiment was to gain a deeper understanding of the optimal air pressure required for 3d-printing using a hydrogel with a higher viscosity than previous experiments. The objective was also to study how a printed toolpath falls on an angled object while printing at a horizontal level.

METHODS AND PROCEDURES

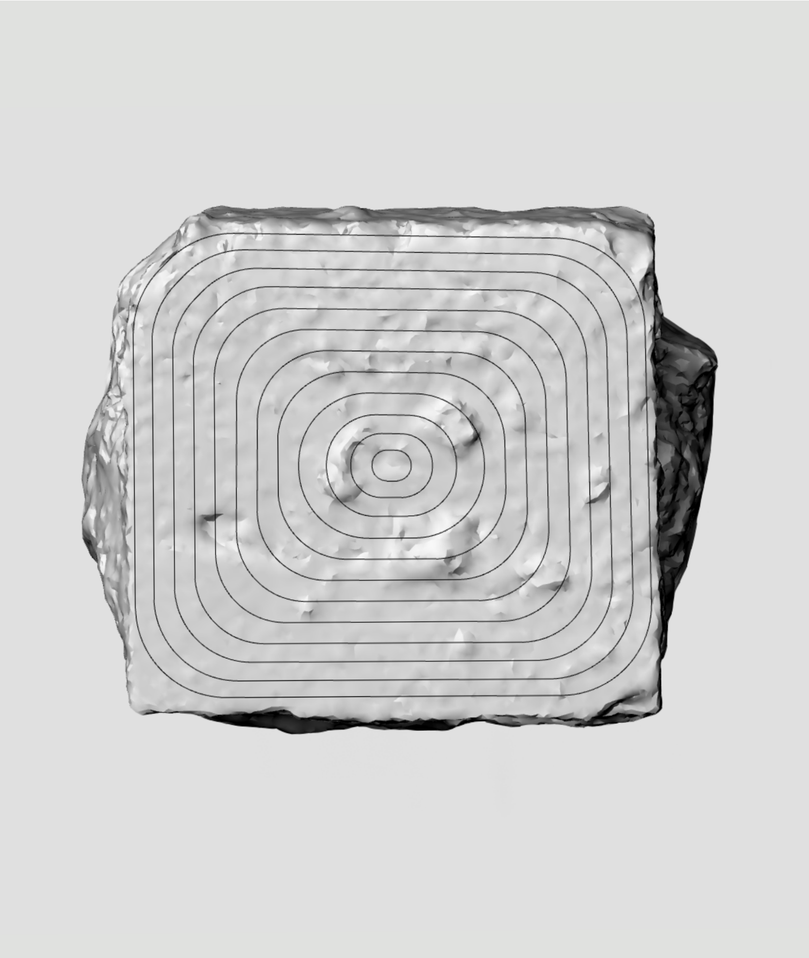
Handcream from the previous experiment was wiped off the brick to be reused for the experiment. A toolpath was developed consisting of ten circuits with a set distance of 2 mm. The script was saved as a SRC-code and run on KUKA KR6- 10R1100 with a custom tool for 3D printing utilizing a nozzle with a diameter of 1.55 mm. Air pressure was manually adjusted throughout the printing period, ranging between 0 - 1.5 bar during the printing period. A waiting time of 3 seconds was set every time the robot moved to the adjacent toolpath and the printing speed was set to 0.015 m/s.

RESULTS AND DISCUSSION

The hydrogel started to extrude from the container when the air pressure was slightly under 1.4 bar. The pressure was maintained between 1.2 - 1.3 bar during the printing period which generated a consistent printing flow during the printing period which was occasionally interrupted by bursts of hydrogel caused by air bubbles in the container. The hydrogel also curled as it was extruded onto the lower parts of the brick, while generating a straighter extrusion on the brick's highest points. The air pressure required for the material to extrude from the container was easier to maintain compared to previous experiments due to the new receptor gauge and the thickness of the material. The printed toolpath remained firm after printing, maintaining its shape and texture.

CONCLUSIONS

The experiment was successful in terms of extruding the hydrogel as a coherent toolpath. Future notions to explore to avoid the curling of the hydrogel would be to adjust the toolpath to follow the increase/decrease in height of the scanned object on the z-axis.



3D SCAN & TOOLPATH
The toolpath consisted of 12 circuits which were positioned horizontally above an angled surface.

FINAL RESULT
The print resulted in a readable toolpath that also indicates the optimal printing distance between the nozzle and surface.

EXPERIMENT #2.4.1

EXTRUSION ON TILE

OBJECTIVES

The objective was to identify the optimal air pressure values for achieving a constant printing flow on a flat surface.

METHODS AND PROCEDURES

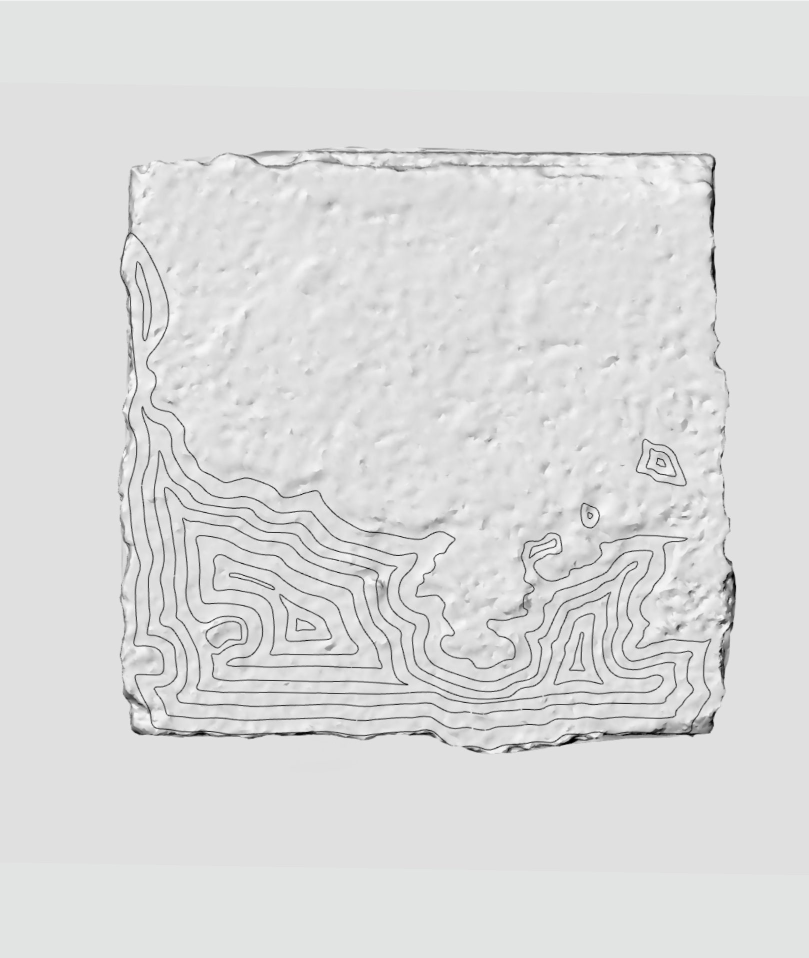
3D scanning was achieved by scanning the tile from 360° using the Polycam app. A STL-file of the scanned mesh was then edited and scaled in Rhino 6, for which a toolpath was developed consisting of ten circuits with a set distance of 3 mm. The object was placed on the printing board in relation to coordinates from the digital model, generated as control points on the toolpath which were physically checked by jogging the robot to the given coordinates. A toolpath was developed consisting of ten circuits with a set distance of 2 mm. The script was saved as a SRC-code and run on KUKA KR6- 10R1100 with a custom tool for 3D printing utilizing a nozzle with a diameter of 1.55 mm. Air pressure was manually adjusted throughout the printing period, ranging between 0 - 1.5 bar during the printing period. A waiting time of 3 seconds was set every time the robot moved to the adjacent toolpath and the printing speed was set to 0.015 m/s.

RESULTS AND DISCUSSION

The hydrogel started to extrude from the container when the air pressure was at 1.3 bar. The pressure then needed to be decreased to 1.1-1.2 bar to print at a steady flow. The pressure needed to be increased to 1.3 bar and then decreased to 1.1-1.2 every time the extruder turned off and on between closed toolpaths, causing irregularities in the print. The hydrogel also curled and looped as it extruded to the tile, which was likely caused by the distance of approximately 5 mm between the nozzle and the object. The regularity of the print was occasionally interrupted by bursts of hydrogel caused by air bubbles in the container, which also showed on the reactor as the indicator moved down approximately 0.5 bar. The printed toolpath remained firm once printed, maintaining its texture and form.

CONCLUSIONS

The experiment managed to print a consistent toolpath with the need for some manual adjustments after the "on" commands where air pressure needed to be increased to 1.3 bar to make the hydrogel extrude from the container, which was then lowered to 1.15 bar for an even extrusion. The curling of the hydrogel could be resolved by lowering the height of the toolpath from 5 mm to 2-3 mm above the printed object.



3D SCAN & TOOLPATH
The toolpath was designed as 20 circuits with the aim to fill in an abraded surface.

FINAL RESULT
The print resulted in a curled toolpath due to the high distance between the nozzle and the surface

DESIGN IMPLEMENTATION

SITE

The chosen site for the design proposal is Götiska Tornet located in the park of Drottningholm in Stockholm. The tower was designed and built between 1788 - 1792 by the French architect Louis Jean Desprez by the commission of Gustav III. The tower was originally designed as a part of a bigger scheme for a "Chateau Gothique" but after the death of Gustav III the plans were limited to the single tower. As a result the interiors and exterior facade also remained partly unfinished, leaving the facade free of previously planned decorations. Parts of the wooden interior were painted with gray linseed oil in 1811, and selected elements of the interior structure were repaired in 1902 where windows, doors and roof trusses were repaired.

The tower was initially intended to be used as backdrop scenery for medieval plays in the garden theatre but has mainly been used as storage for theatre props and gardening tools. During the 20th century it has occasionally been used to host temporary exhibitions, but the current state of the tower no longer allows public events to take place inside the building.


01


02


03

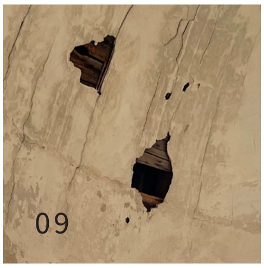

04


05


06


07

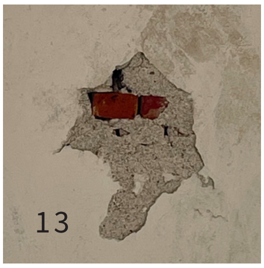

08


09


10


11


12


13

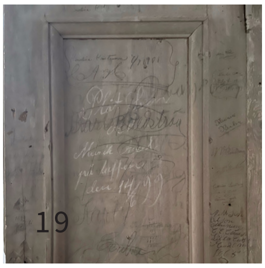

14


15


16


17

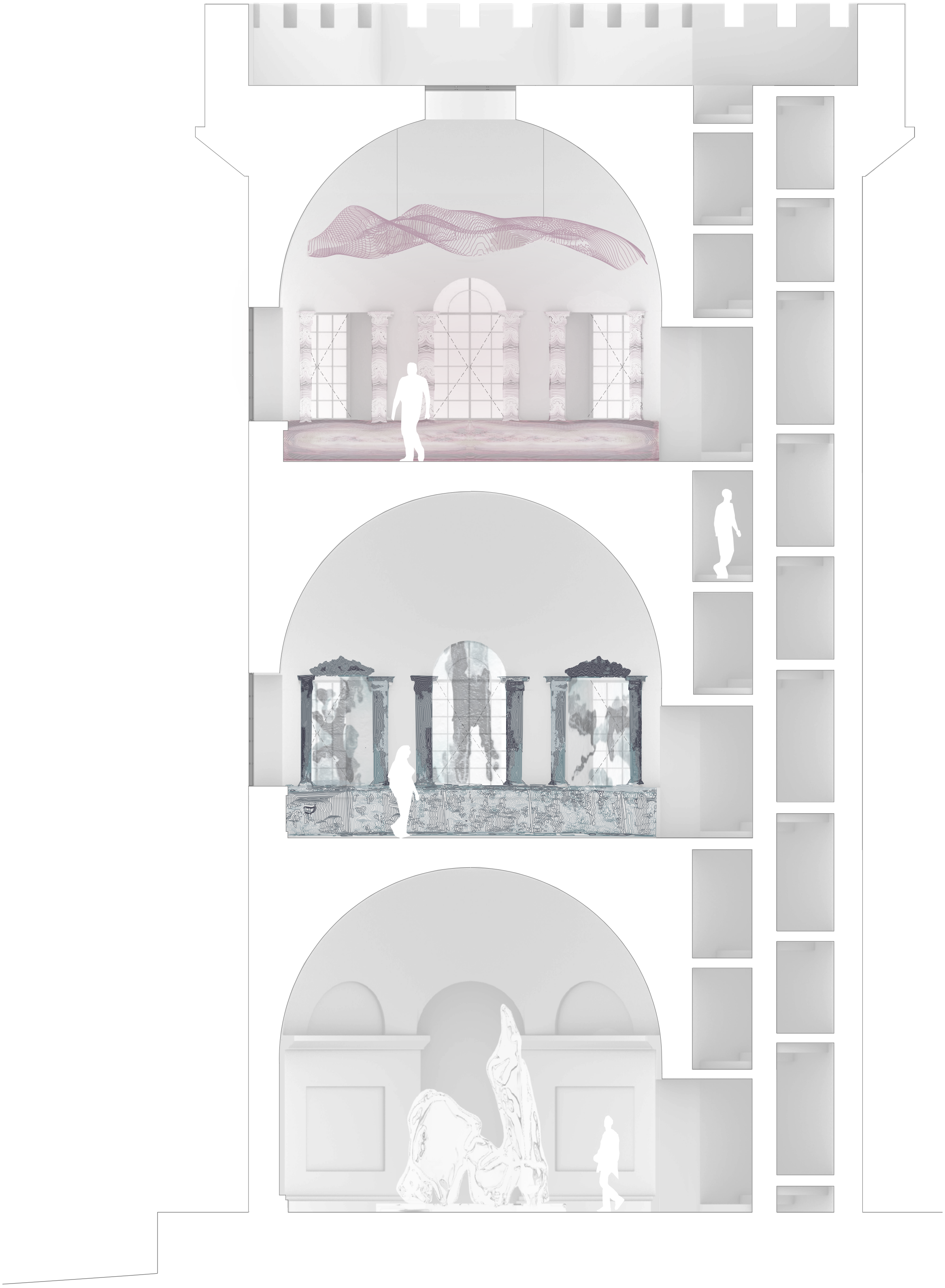

18


19


20

SITE INVENTORY

01. Unknown entrance detail
02. Wooden plinth
03. Undecorated niche
04. Exposed interior brick
05. Painted door
06. Wooden Tuscan pilaster
07. Exposed wooden structure
08. Wooden joint
09. Abraded plaster
10. Undecorated wall panel
11. Pilaster above panel
12. Window cornice
13. Explosed brick behind plaster
14. Abraded plaster in sill
15. Scribble from 1888
16. Wooden panel
17. Original staircase
18. Abraded plaster above window
19. Sheer paint on door
20. Wooden joint



SECTION

Scale 1:150

DESIGN CONCEPT

The design concept was to convert the structure into an exhibition space by restoring and creatively-repurpose the deteriorated wooden elements in the tower. The transition mainly consists of three interventions with the hydrogel that explore different potentials of printing with the bio-material.

1. LIGHT FILTERING MEMBRANE

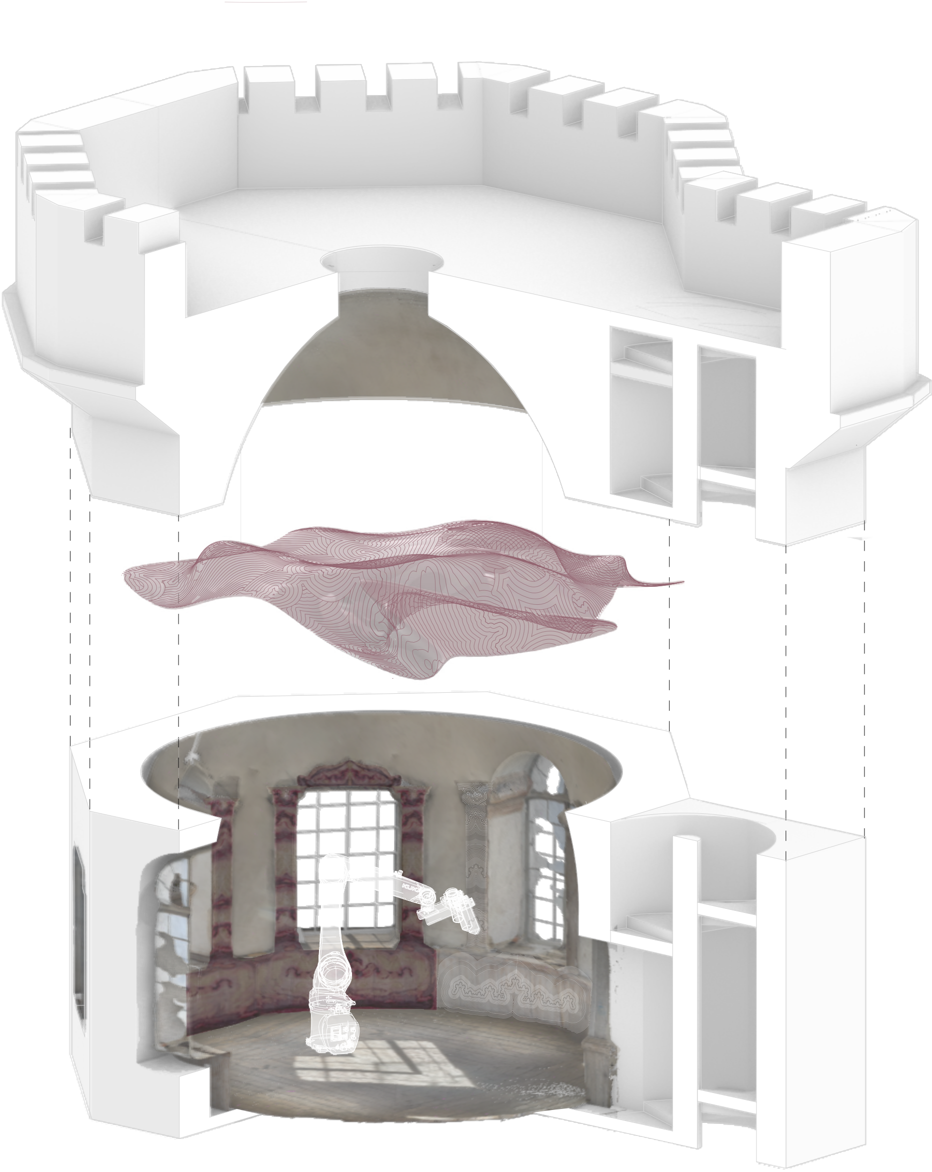
3D-print membranes that are dried without scaffoldings or molds to allow the material to generate it's own organic form while drying. The membrane would be hung in the ceiling on the 3rd floor to spread an ambient light in the room.

2. RESTORATION OF ELEMENTS

Wooden pilasters and panels would be given new surfaces with the cellulose hydrogel that are 3D-printed on the existing surface of the elements through the prototyping of a model.

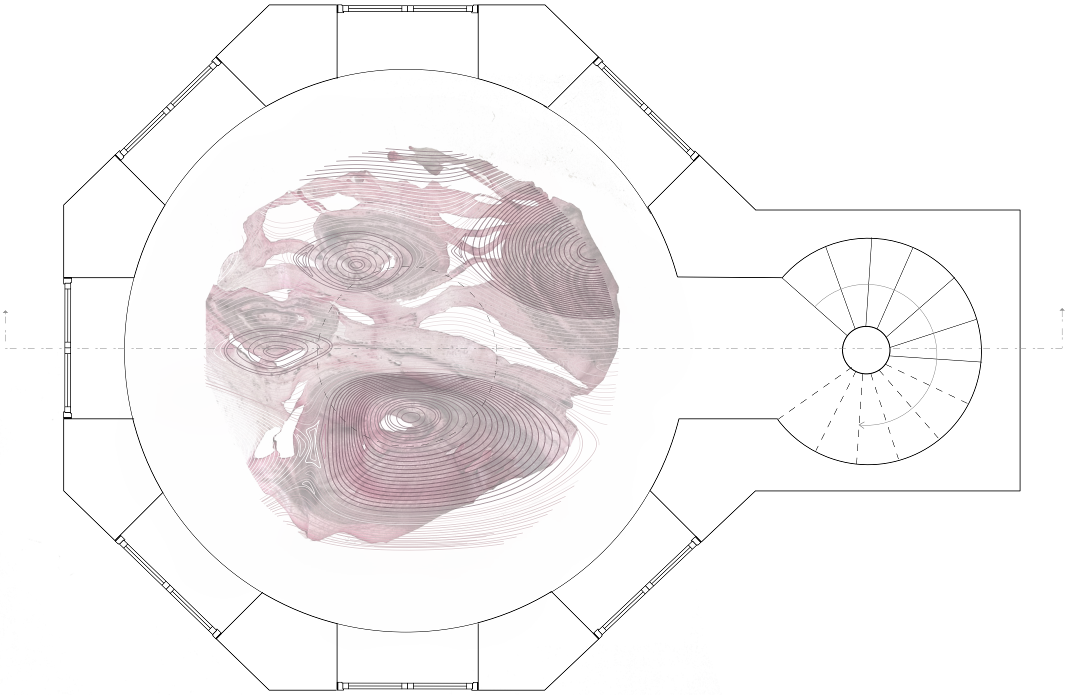
3. WINDOW PANELS

The hydrogel would be printed within wooden frames to generate light-filtering membranes to protect the exhibited objects from direct sunlight. After printing within the wooden frames for the panels, the panels would be dried under compression between two silicone sheets to prevent deformations in the print.



AXONOMETRIC 3RD FLOOR
Scale 1:00

THE FRACTAL CURVE PATTERN WOULD BE IMPLEMENTED ON THE THIRD FLOOR IN THE FORM OF NEW SURFACE LAYERS FOR THE WOODEN ELEMENTS AND A LIGHT FILTERING MEMBRANE

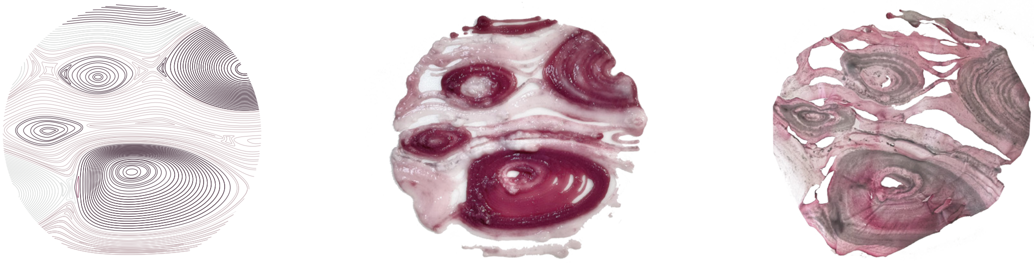


PLAN 3RD FLOOR

Scale 1:100

TOOLPATH & FINAL RESULT

Freeform membrane



WINDOW PANEL, TOOLPATH & FINAL RESULT
Scale 1:20

DIGITAL LAYERS OF PRINTED SURFACE
Scale 1:20

THE COLOR TRACED PATTERN WOULD BE IMPLEMENTED ON THE 2ND FLOOR IN THE FORM OF NEW SURFACE LAYERS AND LIGHT FILTERING WINDOW PANELS

PROTOTYPING

TOOLPATH DESIGN STRATEGIES

Two different strategies were explored in the development of the toolpaths to explore two deviating trajectories for designing new surfaces for an existing environment. The first approach worked with current textures as points of departure to refer to the current character of the original surface. The second strategy explored the potential of introducing new patterns as detailing features, based on a fractal curve pattern that was chosen to conceptually link to the Baroque period in which the tower was built. From a stylistic point of view, the organic aesthetic of the fractal curve was also meant to relate to Baroque's characteristically decorative elements.

COLOR HUE TRACING

The first pattern was developed through color-hue tracing in illustrator of an original photo of the element. This resulted in closed vector paths outlining the discolored patches on the surface. The vector paths were then offset with a 2 mm distance between the lines and projected on a photo scanned model of the CNC-milled prototype model and offset 2 mm above the modeled surface.

FRACTAL PATTERN

The fractal curve pattern was designed parametrically in grasshopper and deliberately applied on the surface to emphasize the various architectural elements in the scanned component. The fractal curves were then offset in illustrator to generate closed vector paths with a distance of 2 mm between the lines. Similar to the color hue tracing pattern the toolpath was finally projected onto the scanned surface of the prototype model and offset 2 mm above the surface.

COLOR PALETTE

The colors for the printed elements were inspired by the color palette found in the baroque room at Drottningholm castle to reference the time period when the tower was built.

[29]

SHADES OF BLUE

Three shades of blue were developed based on the color palette found in Hedvig Eleonora's bed chamber.

[30]

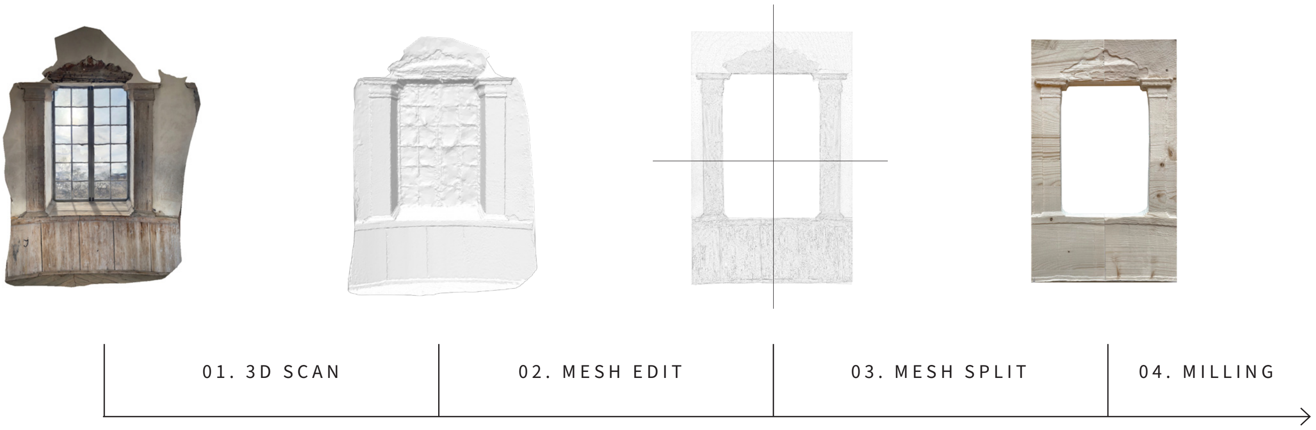
SHADES OF PINK

Nuances of pink were developed in three variations based on the colors found in the main entrance of the castle.

THE ELEMENT WAS PROTOTYPED IN BIRCH WOOD ON A SAINSMART 3018 PROVER CNC-MILL

MODELLING OF ELEMENT

The chosen element consisting of two pilasters and a wooden panel was initially scanned by 216 images using the app Polycam on an iPhone 12 to generate a 3D digital model. The STL file generated from the photogrammetry model was then edited in Blender, Meshlab and Rhino to generate a closed mesh. The edited mesh was then split into four equally sized components in the size of 20 x 15 cm to enable milling on a detailed milling machine. Milling was finally performed on a Sainsmart 3018 PROVer CNC mill after which the elements were glued together as a final step of assembly. The toolpaths were then generated and printed on one half of each of the milled models.



TOOLPATH DEVELOPMENT

PROTOTYPING 4.0

COLOR HUE TRACING

TOOLPATH DEVELOPMENT

The photograph was color traced in Illustrator to generate outlines for the patches of color variations in the element. The outlines were then offset as vector lines with a distance of 2 mm to generate a printable toolpath. The color variations in blue were chosen to mirror the intensity of colors in the original element.

THE PATTERN WAS GENERATED IN ILLUSTRATOR BASED ON THE COLOR TRACING FUNCTION

01. ORIGINAL ELEMENT

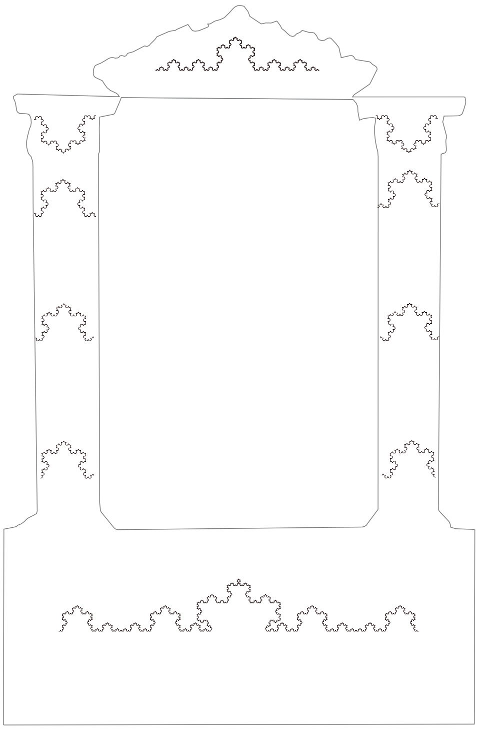
A photo of the element was used as a base to generate outlines of the original color variations.

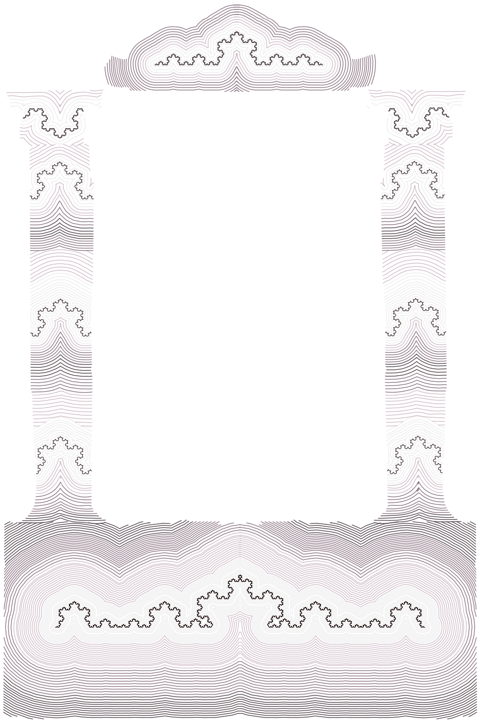
02. COLOR TRACING

The photograph was color traced in Illustrator with a set limit of 6 variations to outline the color shifts in the wooden surface.

TOOLPATH 2

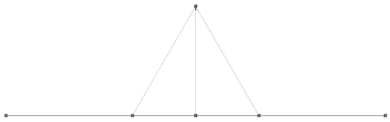
FRACTAL CURVE PATTERN





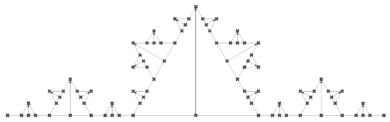
The fractal curve pattern was deliberately chosen to conceptually link to the Baroque period in which the tower was built. From a stylistic point of view, the organic aesthetic of the fractal curve was also meant to relate to Baroque's characteristically decorative elements.

THE PATTERN WAS GENERATED PARAMETRICALLY IN GRASSHOPPER FOLLOWING A KOCH SNOWFLAKE PATTERN



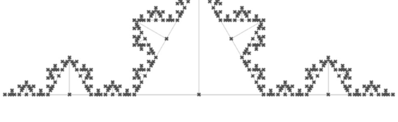
GENERATOR

Length = 4/3



ORDER 2

Length = 16/19



ORDER 3

Lenth = 64/27

MATERIAL RATIO

200 g water

20 g cellulose powder

WOOD PRE-TREATMENT

CELLULOSE HYDROGEL

Tests conducted through the experimentation phase indicated that the material properties of the nanocellulose hydrogel produced by Borregaard differed from the initially explored hydrogel donated by Chalmers Chemical Engineering Department in terms of adhesive qualities. The hydrogel from Borregaard did not adhere naturally to wooden surfaces and therefore needed a pre-treatment for the printed surface to attach. Another cellulose-based material usually used as an additive in the cosmetic industry was therefore initially explored as an alternative printing material, but as the hydrogel dried very quickly it was not a stable option for printing. Instead, the material was used to pre-treat the wooden element to give it a cellulose-based surface that the printed nanocellulose hydrogel could adhere to. The cellulose treatment needed to dry for 24 hours before being dry enough to be printed on with a new layer of the nanocellulose hydrogel.

MATERIAL INGREDIENTS

Hydroxyethylcellulose, sodium acetete and water

Produced by Crearome

3D PRINTING ON PROTOTYPE MODEL

PRINTING METHOD

A 200 ml container was filled with colored hydrogel, which was exchanged throughout the printing period for each newly colored toolpath. The wooden prototype was placed on the printing board and the robot was jogged to three coordinates from the element and two from the toolpath to ensure the correct placement of the object in relation to the digital file. Air pressure was manually adjusted throughout the printing period between 0.5 - 0.7 bar. The printing speed was set to 0.015 m/s and the waiting time set to 0.5 seconds between every printed toolpath.

MATERIAL / **TOOLPATH 1**	NANOCELLULOSE HYDROGEL, RISE INNVENTIA
MATERIAL / **TOOLPATH 2**	NANOCELLULOSE HYDROGEL, BORREGAARD
NOZZLE SIZE	1.6 MM

THE TOOLPATH FOLLOWED THE FORM OF THE WOODEN PROTOTYPE, PRINTING 2 MM ABOVE THE SURFACE ON THE Z-AXIS.

TOOLPATH 2
Fractal curve pattern

POST-PRINTING MATERIAL DEVELOPMENT

TOOLPATH DEVELOPMENT

While drying the pre-treated layer of cellulose started to swell and absorb the water content from the newly printed nanocellulose hydrogel surface. The printed surface adhered well to the surface but started to shrink throughout the drying period, resulting in that the distance between the printed toolpath increased which generated a different pattern than the original design.

COLOR TRANSFORMATIONS

The lighter colors became fully translucent throughout the drying period while the darker pigments remained dark, which further changed the pattern from the original design. The base coat of cellulose and the wooden prototype also absorbed the color pigments which made the end result look more intensely colored compared to the printed freeform elements.

FURTHER RESEARCH POSSIBILITIES

The addition of alginate to the hydrogel could prevent all the water from evaporating through a process called ionic cross-linking, achieved by treating the printed surface with a calcium chloride solution post-printing. This was however not tested in the thesis but could be a possible solution to the current deformation of the printed result.

01

TOOLPATH 1
30 minutes post printing

02

TOOLPATH 1
36 hours post printing

03

TOOLPATH 2
30 minutes post printing

04

TOOLPATH 2
24 hours post printing

FINAL RESULT

THE MATERIAL AGENCY RESULTED IN A FINAL PRODUCT WHICH AESTHETICALLY DIFFERE
REGARDED AS A DESIGN FEATURE TO BE EMBRACED FOR FUTURE DESIGNS OR BE PREVEN
PRINTED SURFACE WITH A CALCIUM CHLORIDE SOLUTION TO PREVENT WATER IN THE HY

D FROM THE ORIGINAL DESIGN. THIS MATERIAL DEVELOPMENT COULD EITHER BE TED BY ADDING ALGINATE TO THE PRINTING HYDROGEL AND POST-TREAT THE DROGEL FROM EVAPORATING.

PROTOTYPING 2.1

FREEFORM 3D-PRINT

PRINTING METHOD	A 200 ml container was filled with 30 ml of material, for which 10 ml was colored with 0.25 ml of black and 0.5 ml of red food coloring pigment. A toolpath was developed with distances between the lines ranging up to 2 mm. A plastic sheet was placed on the printing board and the robot was jogged to one coordinate from the toolpath to find the correct placement of the sheet in relation to the digital file. Air pressure was manually adjusted throughout the printing period between 0.5 - 0.7 bar. The printing speed was set to 0.015 m/s.

THE ELEMENT DRIED WITHOUT SCAFFOLDINGS TO EXPLORE HOW THE MATERIAL DEVELOPS WITHOUT EXTERNAL INFLUENCES

FINAL RESULTS

The hydrogel started to deform throughout the drying period as the water evaporated. The general area of the material decreased while the corners of the printed element started to bend upwards to adjust to the shrinkage. The pink color also started to spread to the previously white areas, while the black pigment in the darker areas of the print became more prominent. The quality of the dried element resembled paper quality in terms of thickness and fragility.

MATERIAL	NANOCELLULOSE HYDROGEL, BORREGAARD
NOZZLE SIZE	1.2 MM

DRYING PROCESS

30 minutes post printing

DRYING PROCESS

48 hours post printing

PROTOTYPING 2.1

WINDOW PANEL 3D-PRINT

THE PROTOTYPE EXPLORED THE POTENTIAL OF DRYING A NANOCELLULOSE MEMBRANE UNDER PRESSURE TO GENERATE A FLAT SURFACE

PRINTING METHOD	A 200 ml container was filled with 70 ml of material, colored in four shades of blue with black and blue food coloring pigments. A toolpath was developed with distances between the lines ranging up to 2 mm. A plastic sheet was placed on the printing board and the robot was jogged to one coordinate from the toolpath to find the correct placement of the sheet in relation to the digital file. Air pressure was manually adjusted throughout the printing period between 0.5 - 0.7 bar. The hydrogel was exchanged for each printing file in a new color. The printing speed was set to 0.015 m/s.

FINAL RESULTS

The printed membrane was dried under two sheets of plastic, which significantly prolonged the drying period compared to other prints. Taking about two weeks to become fully dried, the print started to crinkle slightly while still maintaining a flat form. The general area of material also decreased with 1.5 cm at the border. The black pigment in all of the blue colors became more prominent throughout the drying period, resulting in a membrane that mostly consisted of shades of gray.

MATERIAL	NANOCELLULOSE HYDROGEL, BORREGAARD
NOZZLE SIZE	1.2 MM

PRINTING PROCESS

3D extrusion on plastic sheet

DRYING PROCESS

1 week post printing

CONCLUSION

REFLECTION

The thesis exemplifies an alternative approach for architects to creatively reimagine an existing environment and retrofit elements using digital tools in the form of photogrammetry, computational design and additive manufacturing with a sustainable biomaterial. By developing a workflow to exemplify how a bio-based material can be 3D-printed to fabricate architectural elements, the thesis aimed to cultivate familiarity with bio-materials in combination with digital tools, discussing the potentials and risks of introducing new materials to an already existing architectural context.

It became apparent throughout the development of the workflow that digital tools offer great potential in terms of documenting and rendering an existing setting with custom retrofittings. At the same time, it also became evident that the process of operating digital tools in such a workflow is a contemporary craft that requires the designer to have a thorough understanding of how to manage the data generated in each step of the process. The designer therefore needs to develop an intimate relationship with the machines when exploring new types of workflows in order to be able to make digital, mechanical and analog adjustments throughout the process and maintain momentum in the project.

The actual process of materializing nanocellulose hydrogel surfaces through 3D printing required a great deal of human interaction from the initial material preparations to the final assembly. The robotic printing consisted of a rather small fraction of the overall process of producing and editing the generated material. The robotic printing however contributed decisively to the aesthetic qualities of the final result, which would have differed significantly without a mechanical procedure for extruding the material at an even pressure along a vectorized path.

The material experiments showed that nanocellulose-based biomaterials can be implemented in the field of architecture both as coatings of existing materials and be implemented as more free-standing interventions. In the current state of the material, such interventions could take the form of light filtering membranes, room dividers and other non-loadbearing designs that can aesthetically contribute to the atmosphere of a space.

In terms of controlling the aesthetic outcome, it also became apparent throughout the process that it is crucial to have a thorough understanding of the qualities and behaviors of the new material that is being introduced. Slight alterations in the ratio between cellulose and water proved to have a crucial impact on how the material was printed and dried on a surface. This unpredictability can either be regarded as aesthetic features to be embraced, following the materialist philosophy of Manuel De Landa that the material world has an inherent agenda independent of our intentions. To generate a more predictable design outcome, a closer collaboration with specialists in the fields of material science and industrial engineering would be required to control the various factors in the process.

Beyond the discussion of aesthetic fine-tunings, digital tools in combination with bio-based materials offer elemental opportunities to re-appropriate and care for our built environment with the most recent developments in biomaterial research and new digital fabrication tools. The workflow highlights new opportunities to re-introduce customized craftsmanship as a financially viable option with the use of digital fabrication tools. Thereby contributing to the industry's imperative paradigm shift towards more circular construction processes.

STUDENT BACKGROUND

2020 - 2022	CHALMERS UNIVERSITY OF TECHNOLOGY MSc Architecture and Urban Design Digital Manufacturing Matter, Space, Structure 2 Hybrid Practice Nordic Architecture Material & Detail
2021	UPPSALA UNIVERSITY Art History
2015 - 2018	UMEÅ SCHOOL OF ARCHITECTURE BA Fine Arts in Architecture
2019 - 2020	WHITE ARCHITECTS Internship

CONTACT

TEL: +46 736154468

MAIL: REBECKA.RUDIN@GMAIL.COM

BIBLIOGRAPHY

Literature

Bonora, V; Tucci, G; Meucci, A and Pagnini, B. (2021) Photogrammetry and 3D Printing for Marble Statues Replicas: Critical Issues and Assessment. Civil and Environmental Engineering Department (DICEA), University of Florence, pp. 5-19.

Chirani, N; L'Hocine, Y; Gritsch, L; Leonardo Motta, F; Chirani, S and Faré, S. (2016). History and Applications of Hydrogels. J Biomedical Sci. 4:2.

DeLanda, M. (2015). The New Materiality. Architectural Design. 85. 10.1002 ad.1948.

Duro-Royo, J; Mogas-Soldevila, L; Oxman, N. (2015). Flow-based fabrication: An integrated computational workflow for design and digital additive manufacturing of multifunctional heterogeneously structured objects. Mediated Matter Group, Media Lab, School of Architecture and Urban Planning, Massachusetts Institute of Technology.

Febro, J. (2020). 3D Documentation of Cultural Heritage Sites Using Drone and Photogrammetry: A Case Study of Philippine UNESCO-recognized Baroque Churches.

Higueras, M; Calero, A and Collado-Montero, F. (2021). Digital 3D modelling using photogrammetry and 3D printing applied to the restoration of a Hispano-Roman architectural ornament. Digital Applications in Archaeology and Cultural Heritage, 20(4), pp. 1-9.

Malik, S; Hagopian, J; Mohite, S; Lintong, C; Stoffels, L; Giannakopoulos, S; Beckett, R; Leung, C; Ruiz, J; Cruz; M, and Parker, B. (2019). Materials for Biomedical Engineering Hydrogels and Polymer-Based Scaffolds. Department of Biochemical Engineering, University College London.

Markstedt,K; Mantas, A; Tournier, I; Ávila, H; Hägg, D; and Gatenholm, P. (2015). 3D Bioprinting Human Chondrocytes with Nanocellulose–Alginate Bioink for Cartilage Tissue Engineering Applications. Wallenberg Wood Science Center and Biopolymer Technology, Department of Chemical and Biological Engineering, Chalmers University of Technology.

Markstedt, K; Karl Håkansson, K; Toriza, G; and Gatenholm, P. (2019). Materials from trees assembled by 3D printing – Wood tissue beyond nature limits. Wallenberg Wood Science Center and Biopolymer Technology, Department of Chemical and Biological Engineering, Chalmers University of Technology.

Oxman, N. (2020). Material Exology: The Catalogue. Thames & Hudson Ltd

Tibbits, S. (2017). Active Matter. Massachusetts Institute of Technology.

Images

Image 29-30: Kungliga Slotten. (2012). Hedvig Eleonoras Paradsängkammare. https://www.kungligaslotten.se/artiklar-film-360/drottningholms-slott/2019-08-28-hedvig-eleonoras-paradsangkammare.html (02.04.22)

Videos

Experiment #2.1: https://youtu.be/144x7o9p71M

Experiment #2.2.1 https://youtu.be/zcM1_geot20

Experiment #2.3.2: https://youtu.be/ZIWL-KWJ3Kk

Experiment #2.4.1: https://youtu.be/JUcwSpvlg-k

Prototyping #1.1: https://youtu.be/3d6KP6yjvdI

Prototyping #2.1: https://youtu.be/JiZ-gKfl-IU

Prototyping #2.2: https://youtu.be/BprH0WDhjkw

RE-PRINT

Rebecka Rudin

Chalmers School of Architecture

Department of Architecture and Civil Engineering