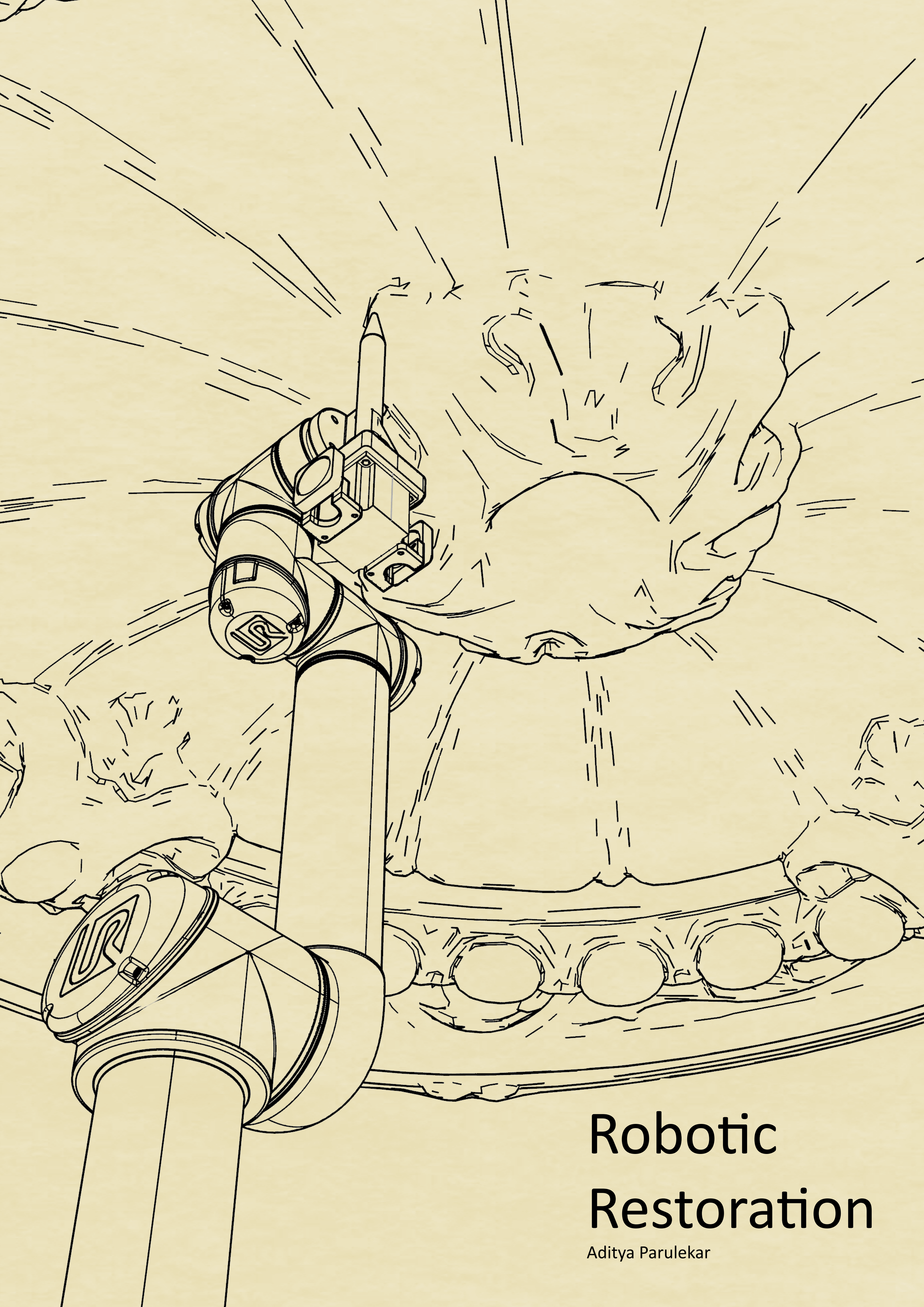
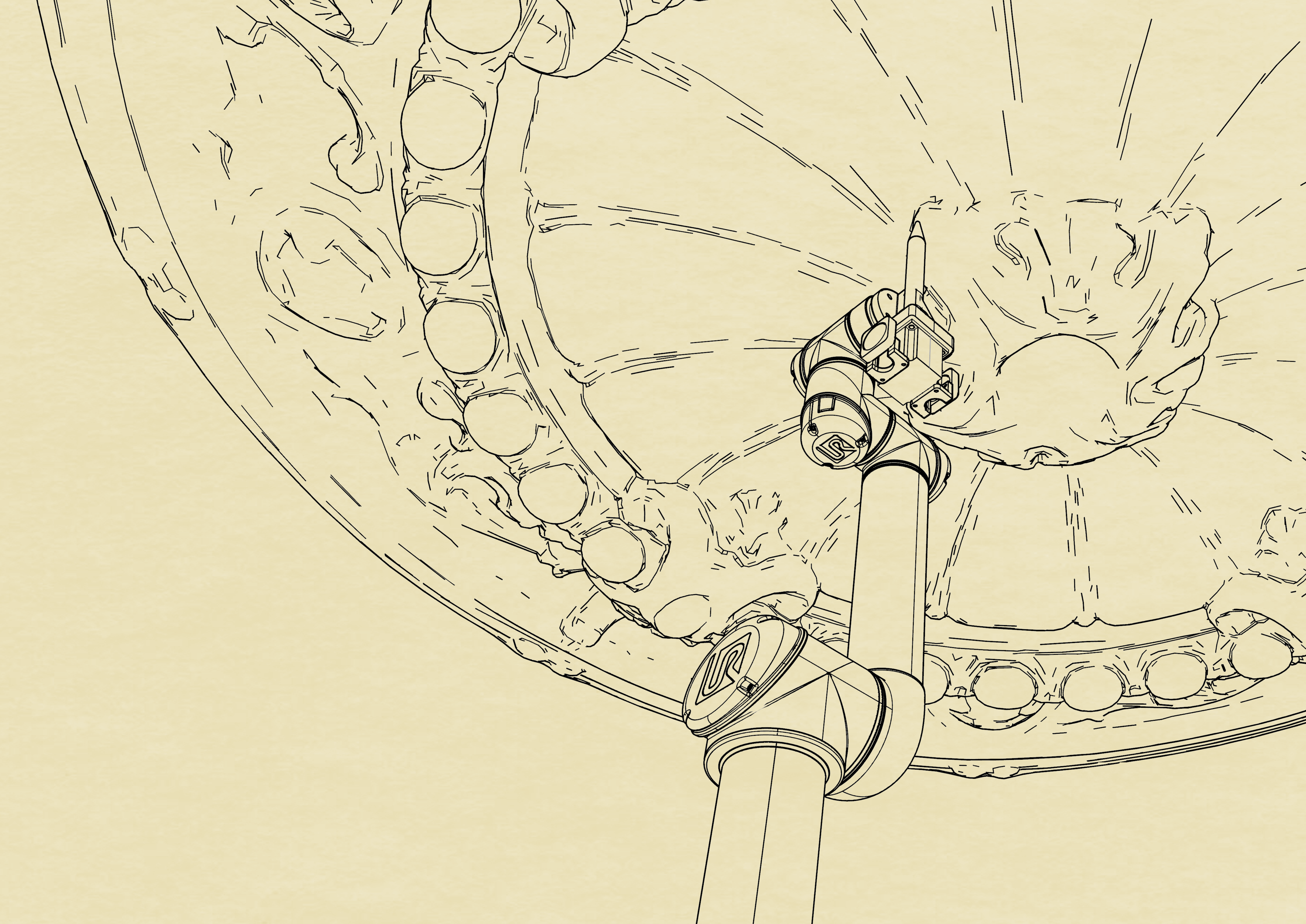


Robotic Restoration

Aditya Parulekar



Robotic Restoration

Restoration of stucco ornaments by means of in-situ Additive Manufacturing.

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Abstract

The preservation and restoration of intricate stucco ornaments, which are part of our collect cultural Heritage, is under threat due to a diminishing number of skilled restoration plasterers. The highly physically demanding- and labour intensive nature of this work makes it unsustainable for the human body and advocates for a more sustainable alternative restoration method for the future. Digital Fabrication has the potential to offer such an alternative method. While 3D scanning, digital repair and 3D printing are all proven technologies, stucco ornament restoration often requires an on site fabrication solution directly onto a ceiling or wall due to the brittle nature of prefab stucco elements. The research explores how an in-situ 3D printing technique can be developed for the restoration of stucco ornaments by focussing on three main topics: 1) developing gypsum-based 3D printing materials, which are compatible to gypsum ceilings and comply with criteria for extrusion based 3D printing; 2) Designing and prototyping 3D printing tools including an extruder and material delivery system; 3) Conceptualizing a Restoration Robot Platform with which the developed printing material can be used with the developed 3D printing tools, for on site stucco ornament restoration. The insights gained from the development of the printing material and printing process are integrated into digital fabrication software used in practise, through a proposed plug-in and workflow.

Key words

Restoration – Stucco Ornaments - Additive Manufacturing – Digital Fabrication – 3D printing – Collaborative Robot

Acknowledgements

During my bachelor Bouwkunde at TU Delft, I noticed that I had a great interest in research and innovation to further the sustainable development of the built environment. By taking up the Building Technology master track, I was able to further explore this interest and digital design- and fabrication became another great interest of mine. During my masters, I was exposed to the amazing and innovative research of researchers from all over the world, which eventually lead me to choose this topic for my graduation project. For my master thesis I have used many skills acquired during my MSc studies. For that I would like to thank in particular: Marcel Bilow - building and prototyping; Serdar Asut - robot programming; Peter Eigenraam – Structural Mechanics; Fred Veer – Material Science; Friso Gouwetor – Grasshopper; Henry Kiksen; Pirouz Nourian; Shervin Azadi.

The worldwide outbreak of Covid-19 initially made a dent in the planning and preparations of this research, as access to the University facilities was lost. However, my mentor Paul de Ruiter spared no effort and time to make sure I, and in fact all his mentor students, could acquire necessary tools and machines to continue our research with as minimal changes to our planning as possible. This marked the start of my lab "Mini-LAMA' at home, from where I conducted almost all of my experiments and built most of my machines. I would like to thank Paul for always taking time in his week to meet with me to share his knowledge, initially at the faculty and later online. I would also like to thank my mentor Barbara Lubelli, for all her valuable guidance in a field which was not that familiar to me before my thesis, and for always asking very sharp and interesting questions at each presentation. I believe that by thinking about these questions, the project could be developed much further than I could have foreseen before.

In early January 2020, I got the opportunity to visit the workshop space of Delstuc Stukadoors in Monster, were Anton van Delden and his colleagues welcomed me with much warmth and interest in my ideas. They spent a lot of time to tell me about their work and they took the time to show me their special craft of stucco ornament restoration in their workshop. This gave a lot of insight into the world of the restoration plasterer and made me realise that it is the craft of the craftsmen that must be preserved, not just the workpiece.
I would like to thank my fellow board members of Praktijkvereniging BouT, with whom I had a fantastic year leading BouT in organizing interesting and fun activities and publications, next to my studies. Finally, I would like to thank my parents, my friends and my housemates for the fun times at home, for cooking meals for me during the very busy days and for allowing me to use our tiny living room in our student house as my mini -lab for several months. I promise, I will clean it up.

01.

INTRODUCTION

1.1 Stucco ornaments

Stucco and plaster are among the most commonly occurring building materials in and on buildings around the world (Koldeweij, 2010). Stucco generally consists of natural components such as gypsum, lime, chalk, marble powder, mixed with water to create a past-like mixture. This paste-like mixture is easy to form into any desired shape. The different type of raw materials needed to make stucco, can be found in abundance around the world and therefore are relatively inexpensive. Due to its global availability and good workability, humans have used various local forms of stucco to create beautiful decorations on buildings and objects across the whole world. Stucco ornaments can be found from the walls of ancient Hindu temples in India and sculptures made by the Mayans in the Americas from the 6th and 8th century A.D. (Dallas-Museum-of-Art, 2017), till intricately decorated ceilings and walls of churches, palaces and villas in Europe around the 18th century. Even today, ornamented stucco ceilings, often made with gypsum as the main ingredient, can be found in many homes dating back to the late 19th and early 20th century in the Netherlands (Prins, 2013). Such ornaments are part of our history and heritage. They tell us something about ourselves from another time. They remind us of who we once were, what was important to us and what our societies looked like. Built heritage, is considered as an extension of the collective cultural heritage of humanity (Tweed & Sutherland, 2007) and therefore can be considered as inherently valuable for all of us. It is important to protect, preserve and when needed, intervene to maintain this value for future generations.

Figure 1 *Mayan wall panel, 790 AD. Source: Wikkimedia.org*

Figure 2 *Sculpture, Meenaksi temple, India, 6th century AD. Source: Wikkimedia.org*

Figure 3 *Ornamented ceiling of Huize Nolet, 1803, Schiedam, Netherlands. Source: https://www.tbafbouw.nl/Mebest/publicatie/Huis-Nolet%2C-een-vroeg-19e-eeuws-fenomenaal-interieur-in-restauratie*

Unfortunately, buildings and building components, such as ornaments, are subject to degradation over time. Stucco ornaments are no exception to this, as the can be subjected to various forms of mechanical-, moisture- and chemical-related damage (Geerken & Freling, 2010). The conservation of these timeless materials turns out to be a very complex procedure, which requires an interdisciplinary approach, as knowledge is required in the value of heritage, restoration techniques, building technologies, material science, and stucco craftmanship (Koldeweij, 2010). An extensive investigation is required into the materials and techniques used to create the original work, to find suitable restoration materials and techniques to consolidate a damaged ornamented stucco ceiling. After such investigations, the stucco ornament must be restored, which is done by so called "restoration plasterers".

1.2. Restoration plasterers

Stucco ornament restoration is considered to be a real craftmanship. In the Netherlands, individuals trained as plasterers aspiring to specialize in this field can follow a 3-year part time restoration plasterers' course to learn about stucco restoration, architectural history and the craft of sculpting geometrically complex stucco

ornaments (NOA, n.d.). This is an additional course, which comes after the regular vocational training to become a plasterer, which means it is a significant investment in time for an individual to indulge into this specialized field.

Figure 4 *Restoration plasterers working above their head. Source: RCE 2010*

Many stucco ornaments tend to have a high geometrical complexity. Accurately recreating such geometrically complex shapes is a labour intensive task and requires a lot of practise. The restoration of the ceiling of a single room of Huize Nolet, an early 19th century villa in Schiedam featuring breath-taking stuccowork by Italian stucco artist Pietro Joseph Tessa , has been under restoration for over a year by various members of Het Neerlandsch Stucgilde (Tba, 2019). Such projects with complex shapes, require many experienced restoration plasterers. Furthermore, restoring an ornamented ceiling requires working for long periods of time above the head, which is extremely physically demanding and strenuous for the body. With the current pension age in the Netherlands at 68 (Pensioenperspectief.nl, 2018) and projected rise of this age of well into the 70's in the future, it is unlikely that a restoration plasterers can keep doing such strenuous work until such late age. Due to these factors, the sustainability of the restoration plasterer's profession and in turn, the sustainability of stucco ornaments and buildings that may need restoration in the future is uncertain.

1.3. A mismatch in demand and supply

After the financial crisis of 2008, the demand for stucco ornament restoration in the Netherlands has risen significantly according to the Dutch restoration plasterer's guild, Het "Neerlandsch Stucgilde", which was set up in an effort to combine forces of various specialized stucco craftsmen in the country ("Samenwerking restauratiestukadoors | Het Neerlandsch Stucgilde," 2017). A high demand in restoration work, means there is a lot to do for restoration plasterers. However, the domain of the restoration plasterers is experiencing a severe shortage in personnel and, in particular, highly skilled and properly trained craftsmen are a rare breed of today ("Samenwerking restauratiestukadoors | Het Neerlandsch Stucgilde," 2017). This is in line with the overall shortages of craftsman and workers which the building industry as a whole is experiencing (Tanum, Olsen & Defnall, 2012). Furthermore, there is also a severe shortage of new students in training to become restoration plasterers as well as a severe shortage in teachers ("Samenwerking restauratiestukadoors | Het Neerlandsch Stucgilde," 2017). Such developments could, in the worst case, lead to no one being able to do stucco ornament restoration anymore in the future and the craft of the restoration plasterer to be lost.

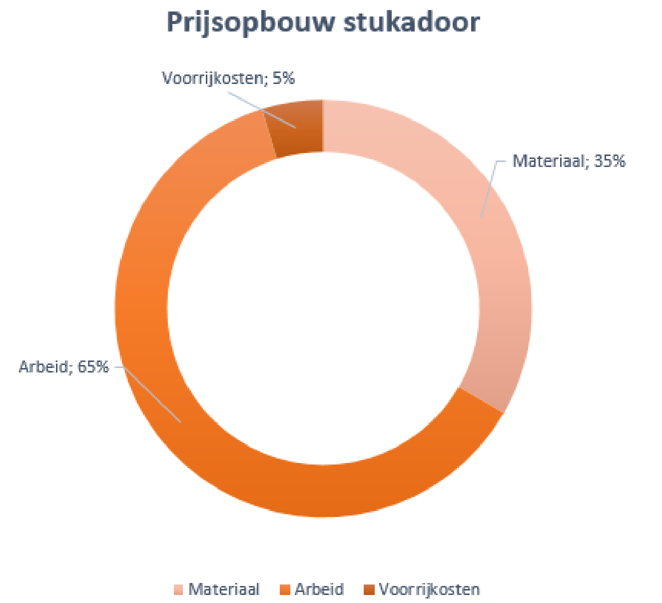


Figure 5 *Price breakdown for plasterers in the Netherlands. Source: https://www.kosten-stukadoor.nl*

1.4. Increasing labour costs

Labour costs are increasing worldwide but are especially high in western countries like the Netherlands. A renowned plasterer in the Netherlands, costs about 30-45 euros per hour (kosten-stukadoor.nl, n.d.). In regular plastering works, labour accounts for about 65%

of the total project costs, while material costs are only 35% (kosten-stukadoor.nl, n.d.) (Figure 5). Restoration plasterers, who are specialists, would likely cost even more in comparison. The combination of the highly specialized and labour intensive nature of stucco restoration, with ever increasing labour cost makes stucco ornament restoration expensive and has a risk of becoming something only available for building owners with a larger budget. The current shortages and projected increasing number of shortages in stucco craftsman threaten our ability to preserve and finance stucco ornament restoration in the future.

1.5. Digital Fabrication in architecture and restoration

The emerging field of digital fabrication has the potential to offer solutions to problems we are currently facing in stucco ornament restoration. A damaged stucco ornament can be scanned with a 3D scanning device and the scanned geometry can be translated into a format which can be manipulated with Computer Aided Design (CAD) software. With the use of such CAD software, the geometry can be "digitally repaired" by extrapolation. For example, by digitally duplicating an element with a similar geometry from another part of the ornamented ceiling. The digitally repaired geometry could then be fabricated by means of 3D-printing, also referred to as Additive Manufacturing (AM), which is a digital fabrication technique in which a geometry is created by depositing material on top of each other layer by layer to build the geometry up in many thin "slices". Due to its layer by layer approach of building up geometries, geometrical complexity does not form a problem or cause any significant increase in cost for AM.

Techniques such as 3D-scanning, digital repairing and Additive Manufacturing have already been adopted in the field of architecture and restoration. La Sagrada Familia, though not a restoration project, has adopted such technologies since 2001 for the construction of the cathedral. By 3D-scanning models of elements from the cathedral Antoni Gaudi had made before his death, the complex shapes are digitized (Stott, 2015). These digital models can then be created with AM techniques (Figure 6).

Figure 6 *Models and parts of La Sagrada Familia prototyped by powder printing. Source: https://www.tctmagazine.com/*

It many scenario's, it is not preferable to create stucco ornaments off-site, as prefab elements. In personal correspondence, Anton van Delden, owner of a restoration plasterers' company and chairman of Het Neerlandsch Stucgilde, says there is a long tradition of restoring hand-made stucco ornaments on site by hand and not with prefab elements. Larger ornaments, especially long and thin ones, have a risk of breaking during transportation and installation on site. Furthermore, prefab elements are not compatible with old warped ceilings. Therefore, in many cases it is necessary to be able to make adjustments on site, because the original ceilings are not made with robotic precision and may have warped over time. To really be able to alleviate pressure from restoration plasterers, a method must be created to apply AM technology on site: In-situ Additive Manufacturing.

1.6. Gap of knowledge in Additive Manufacturing

At present, AM is mainly used for off-site applications, usually in closed and controlled environments where ambient parameters can be controlled. AM almost exclusively relies on depositing material vertically down on a flat printing bed. So technically, most forms of 3D-printing are really just stacking a bunch of 2D printed layers on top of each other on a flat substrate. For most AM applications this method suffices. However, most common AM methods and machines cannot create objects on substrates with an irregular height, or on angled (inclined) substrates, due to gravity. Because of this, current AM methods unsuitable for creating objects on

surfaces that are course and inclined at an angle, such as walls or ceilings (Laarman, Jokic, Novikov, Fraguada, & Markopoulo, 2014). Not much research has been conducted yet in freeing 3D printing from this "2D way of working". Furthermore, materials like stucco and gypsum are not being actively explored for AM applications, as most research in AM for construction applications today is conducted with concrete and clay.

The knowledge and craft of the Master Plaster must not be lost. By embodying this knowledge and craft in new digital tools, the knowledge and craft itself can be conserved and developed further to preserve our collective cultural heritage.

1.7. Goal of research

For AM to be able to be an effective new method for in-situ restoration of stucco ornaments, research must be conducted into the development of the gypsum-based 3D printing material as well as the 3D printing process and tools required for the envisioned application. How do you develop a material that is suitable for restoration of stucco ornaments, but is also suitable for AM? What type of machines would be required to perform such a task? And what is the role of the restoration plasterer in the future? A good starting point for this, can be to study manual restoration techniques used by restoration plasterers. In the next chapters, a research framework is presented to give structure and set clear goals for the research.

02.

RESEARCH FRAMEWORK

2.1. Problem statement
In-situ manual restoration of geometrically complex stucco ornaments on ceilings and walls is physically demanding and labour-intensive work. This requires highly skilled and experienced restoration plasterers, a field which has shortages and more severe shortages are foreseen for the future ("Samenwerking restauratiestukadoors | Het Neerlandsch Stucgilde," 2017). Additive manufacturing with a multi-axis robot is highly suitable for creating such complex geometries on uneven surfaces and has the potential to alleviate the pressure on the restoration plasterers in the future. To adopt such a technology, research is required in creating gypsum-based printing materials which are both compatible with the original historic materials and are 3D printable on inclined planes.

2.1.1. Sub problems

1) Compatibility of printing material with substrate material
New materials must be compatible to the original historic substrate onto which they are being added and must be integrated into the whole.

2) Printability of gypsum-based materials.
The printing mixture should fulfil various criteria associated with creating a new 3D printing material. It must, among other things, be able to flow through a material delivery system, be able to achieve a high resolution, gain enough strength, adhesion to the substrate after extrusion and not crack or shrink too much after printing.

3) Adhesion of printing material onto inclined surfaces.
AM is almost exclusively done by depositing material vertically downwards. When printing in-situ, onto a wall or ceiling, material would have to be extruded on an inclined substrate, instead of vertically down. To achieve this, it is expected special properties would be required for the printing material and printing process.

4) In-situ stucco ornament restoration machine
Additive manufacturing technology is not explored much for in-situ applications for restoration, which means there are no ready-to-use solutions for applying AM on restoration sites.

2.2 Objective
The main objective is to investigate to what extent a Digital Fabrication methodology and 3D printable gypsum-based mixtures can be developed for restoration of stucco ornaments by means of in-situ additive manufacturing.

2.2.1 Sub objectives

1) Determining criteria for compatibility between printing material and gypsum substrate.
Compatibility in this context is defined as aesthetic compatibility (colour, texture, etc.) and physical compatibility (thermal expansion, porosity, etc.). Key parameters will be found for compatibility between the printing material and substrate, which will lead to the selection of suitable raw materials for the printing mixture.

2) Designing a printable gypsum-based mixture
First key parameters for printability of 3D printing materials will be defined, next methods of manipulating these parameters will be identified and finally methods of assessment of the parameters will be identified or developed. After this, printable gypsum-based mixture will be developed.

3) Investigate printing process for good adhesion of printing material onto inclined substrate
Methods to manipulate printing material, substrate and printing process to enhance adhesion of printing material onto substrate will be investigated.

4) Defining guidelines for a Restoration Robot platform
Guidelines for a Restoration Robot platform will be defined based on physical and practical constraints related to the context, as well as constraints for printing process and the hardware required.

2.2.2. Final products
The thesis will be conducted through literature research, consulting specialists, manual & robotic experimenting and designing.
The results will include:

- Evaluation of printing performance of several mixture recipes for in-situ AM.
- Evaluation of various strategies for improving adhesion onto inclined substrates.
- Analysis of printed prototypes.
- Designed & built extruder for AM process.
- Method for integrating research into practise.
- Concept design of in-situ AM process for restoration of stucco ornaments on interior walls and ceilings.
- Recommendations for further development of in-situ AM for stucco ornament restoration.

2.3. Boundary conditions & limitations
Even though restoration of stucco ornaments consists of many steps such as investigation, cleaning etc. the research will only focus on the in-situ fabrication of ornaments. The fabrication will be done on inclined planes in the interior (wall and ceilings) as working context. The printing material will consist of gypsum-based mixtures and pure gypsum will be considered as the substrate material.

The thesis will not analyse durability or compatibility over time between the newly printed elements and the old substrate. This requires a long time for testing, which is unavailable within the scope of this thesis. This is an important aspect to consider before applying such a technique for restoration, however it will not be researched in this thesis. The documentation phase of 3D scanning and converting the raw scan data into a workable 3D model will only be dealt with in the literature review, these steps will not be taken for the experimenting phase.

Since there is a lot of variety in buildings which feature stucco ornaments on their ceilings and walls in terms of size, maintenance state, structural strength etc., the Restoration Robot platform will be designed by defining some basic constraints about ceiling height and structural strength of the floors. This means the platform may not be suitable for all buildings, but the design methodology will indicate how to adjust the platform for use in different type of buildings.

Since the world-wide Covid-19 outbreak from late February 2020 onwards, access to the university was lost. Therefore, access to both the Heritage & Architecture lab (HA lab) and the Laboratory for Additive Manufacturing in Architecture (LAMA) was no longer possible. The planned robotic experiments could not be conducted without access to the UR5 robot inside LAMA. Therefore, alternative manual testing methods were used as explained further in the chapter Extrusion experiments.

2.4. Research question
The research questions consist of background questions to gain more insight into the problems and potentials, the main research question and the sub questions to help answer the main research question.

2.4.1. Background questions
- In which situations of stucco restoration should in situ additive manufacturing be implemented?
- What are current restoration methods for stucco ornaments?
- Which additive manufacturing method is best suitable for in-situ AM for stucco ornament restoration?

2.4.2. Main research question

To what extent can a Digital Fabrication methodology and 3D printable gypsum-based mixtures be developed for restoration of stucco ornaments by means of in-situ additive manufacturing?

2.4.3. Sub questions
This main question leads to dividing the research of the project into four main investigation topics:

1. Compatibility of printing material with original material
2. Printability of printing material
3. Adhesion between printing material and substrate when printing on inclined planes
4. Guidelines for developing a Restoration robot platform

These four investigation topics are translated into sub questions, which will help to answer the main question.

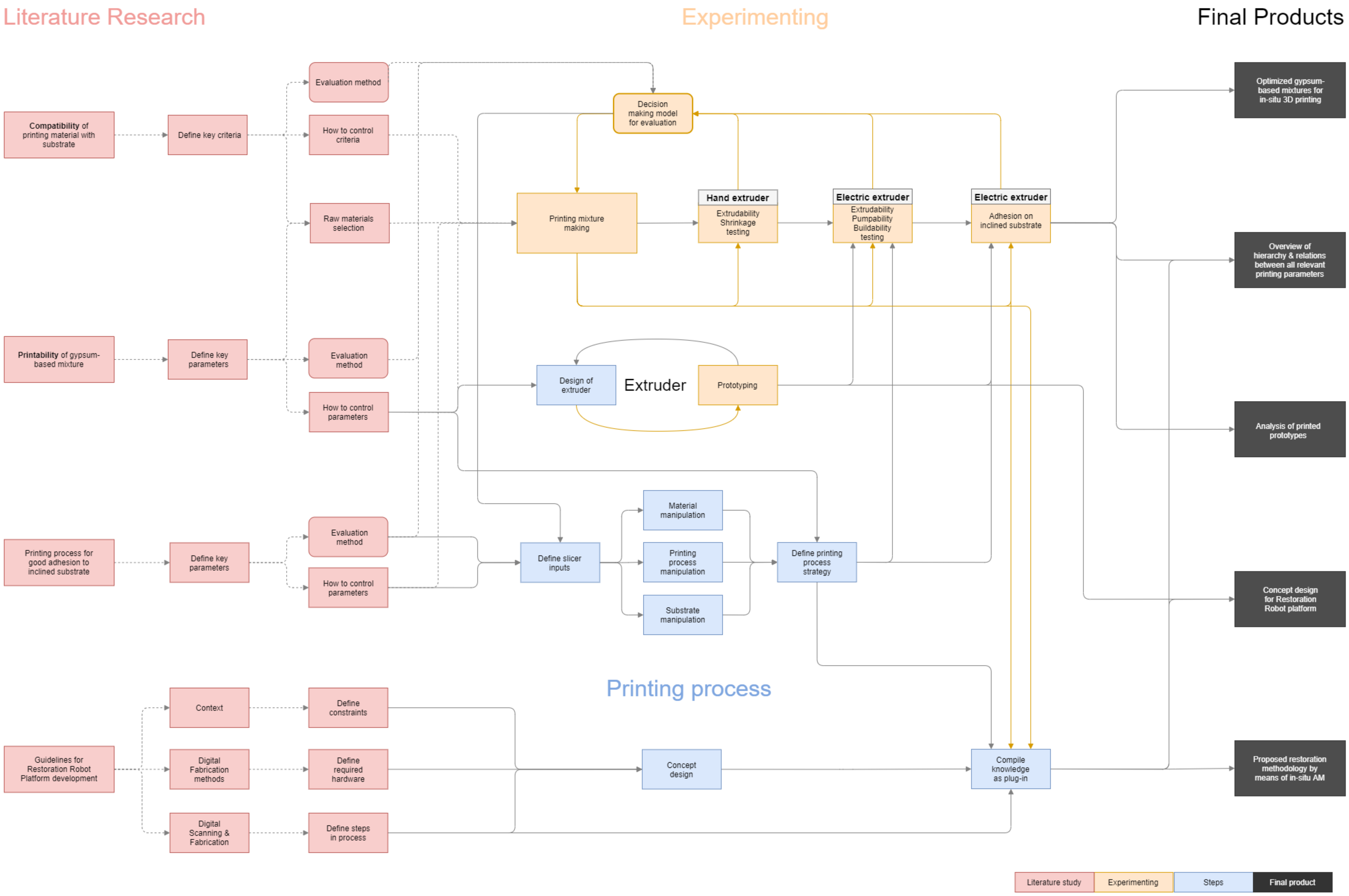
1. To what extent can gypsum-based mixtures be developed for the purpose of Additive Manufacturing, which are compatible to materials used in original gypsum ceiling substrates?
    - What are key criteria for compatibility between the printing material and the gypsum substrate?
    - What are suitable raw materials?
2. To what extent can a gypsum-based mixture be developed for Additive Manufacturing?
    - What are key criteria for developing a printable mixture material?
    - How can key criteria be controlled?
    - How can key criteria be evaluated?
3. To what extent can the printing mixture be extruded on inclined substrates?
    - How can the printing material be manipulated to improve adhesion?
    - How can the printing process be manipulated to improve adhesion?
    - How can the substrate be manipulated to improve adhesion?
4. How can a Restoration Robot Platform be developed, considering constraints related to the context of operation and 3d printing process of stucco ornament restoration?
    - Which context-related physical and practical constraints must be considered?
    - Which practical and technical constraints must be considered regarding the suggested in-situ AM process?

When these research topics are explored and the sub questions are answered, it should be possible to answer the main research question.

2.5. Methodology
The research is divided into different phases. There is a literature review phase, a designing phase, an experimenting phase and a compiling phase. The literature review researches the four topics by identifying key parameters, identifying methods to control and evaluate these parameters. For the research on the compatibility and printability of the printing material, this part of the literature review is summarized into a decision making model, which can help modifying the printing material in the experimenting phase based on observations. Meanwhile, an extruder is designed and prototyped, which can be used in the later printing experiments. In the experimenting phase, various mixtures are created and tested, initially with a manual extruder and later with the extruder which is designed to work with a robot. The evaluation methods and decision making model obtained from the literature review phase help to take informed decisions on changing the material recipe to improve the printing mixture for successive experiments. Once a printable mixture is developed through experimenting, printing tests are conducted on inclined substrates. Knowledge obtained in the literature review phase about manipulation of the printing material, printing process and substrate for improved material adhesion is used to test and improve the adhesion of printed samples. After this, conclusions are drawn on the printability of the created printing mixture.

A proposal for a new restoration with Digital Fabrication workflow is developed throughout thesis. The current stucco restoration practise is researched to contextualize the role of Digital Fabrication within this field. The various steps required for restoration by means of Digital Fabrication are identified and the tools and techniques used in each step are researched. Furthermore, case studies are conducted on current state-of-the-art Digital Fabrication technologies to find key aspects to consider for the development of a novel Restoration Robot platform and in-situ AM technique. This knowledge is compiled to set up guidelines for the development of such a robotic platform. A design for a proposed prototype is also created based on these guidelines to show how the guidelines can be used. Finally, the material properties of the newly created gypsum-based printing mixture, the proposed printer settings and the Restoration Robot platform are integrated in the form of a proposed plug-in for existing 3D printing software and robot simulation software. This plug-in shows how the research of this thesis can be used in practise by integrating the knowledge into the currently used workflow. A detailed scheme showing various steps and relations of the methodology of this thesis can be found in the figure on the next pages.

Methodology



03.

RESTORATION THEORY & PRACTISE

3.1. Introduction

According to renowned conservation architect Sir Bernard Feilden, whose works include the conservation of the Taj Mahal and Great Wall of China, “conservation is the action to prevent decay and manage change dynamically” and “Restoration means the replacement or repair of damaged elements to preserve their essence” (Feilden, 1982). To understand how, where and when new technologies of Digital Fabrication can be implemented into the field of conservation & restoration, it is important to understand some philosophies, guidelines and rules of this field. This can help to create a framework to contextualize the role Digital Fabrication can play within the field of conservation & restoration.

3.2. Contextualizing conservation & restoration

Different international guidelines exist for conservation of Heritage and historic buildings and artefacts. Among them, the Charter of Venice is globally the most widely referenced charter (Quist, 2011). It was based on the earlier Charter of Athens from 1931 and was adopted in 1964 at the 2nd International Congress of Architects and Technicians of Historic Monuments. The charter does not give concrete guidelines which can be used to make choices in materials or conservation techniques, but rather formulates, in an international context, a set of goals and definitions in the form of 15 articles. Three main criteria from various international charters are identified as most relevant in context of this research: compatibility, reversibility and durability.

3.2.1. Compatibility

Three articles from the Charter of Venice are especially noteworthy in the context of stucco ornament restoration and give guidelines about compatibility between the restored elements and original elements:

- **Article 6:** *“…No new construction, demolition or modification which would alter the relations of mass and colour must be allowed.”*
- **Article 10:** *“Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience.”*
- **Article 12:** *“Replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence.”*

Article 6 formulates that no changes must be made to the original relations of mass and the original colour of monuments. In the case of stucco ornament restoration, this can be interpreted as the restored geometry must have the same texture and colour as the original work. Article 12 formulates missing parts must on the one hand be harmoniously integrated with the whole, but on the other hand also be distinguishable from the original work. Article 6 and 12 both advocate for a harmonious integration, but article 12 formulates that the restoration work must not falsify the artistic or historic work by being undistinguishable. This seems like a dilemma, where the restoration experts of a specific restoration task may implement their own interpretation or vision, based on these guidelines. In any case, AM should ideally facilitate achieving any desirable texture and colour.

Article 10 formulates that when traditional techniques prove inadequate, the use of any new modern technique for conservation can be used. The prerequisite for this, however, is that the efficacy of this new modern technique has been proven by scientific data and experience. Given the current trend of a declining number of (highly skilled) restoration plasterers in combination with the labour intensive and physically demanding nature of on-site restoration work, the use of in-situ Additive Manufacturing can be justified as a new restoration technique. This thesis intends to take the first steps in researching whether the efficacy of this new technique can be proven by conducting scientific experiments and research by design.

3.2.2. Reversibility

The term “reversibility” is first mentioned in “Appleton Charter for the Protection and Enhancement of the Built Environment” (1983) (Quist, 2011). The charter states that “The use of reversible processes is always to be preferred to allow the widest options for future development or the correction of unforeseen problems, or where the integrity of the resource could be affected”.

In practise, achieving reversibility in restoration is more often an exception than a rule (Quist, 2011). Generally, manual, on site stucco ornament restoration is not intentionally done to be reversible. There are examples of reversible restorations, such as the restoration of the Pantheon, where missing or damaged pieces of stone are replaced and fixed with steel anchors which can be removed. However, in stucco ornament restoration such techniques are not as common.

According to Sasse and Snethlage (1997), a general consensus exists which states that strict reversibility should be replaced by compatibility and re-treatability (Sasse & Snethlage, 1997). In context of stucco ornament restoration by means of in-situ AM, reversibility could be understood as the ability to remove the 3D printed elements without damaging the original elements and substrate. In order to achieve this, the adhesion strength between the 3D printed elements and the original substrate should be on the one hand strong enough to hold the 3D printed elements without any problems, but on the other hand should also be the weakest link. This can be assessed with experiments in which the adhesion strength between hand-made samples and 3D printed samples can be compared to each other. However, reversibility is not sought after or achievable currently in manual stucco ornament restoration, therefore there is not hard criteria for the AM restoration process to be reversible either.

3.2.3. Durability

An intervention to a historic building should be a quality intervention (Hees, Naldini, & Roos, 2014). This means that from a material point of view, the restoration work should in addition to compatible, also be durable. Durable restoration means the restoration work does not look shabby over time and should contribute to a low maintenance frequency (Hees et al., 2014). Durability is closely linked to compatibility. Using an extremely durable restoration material may be durable by itself but if incompatible with the original substrate material could cause harm to the original substrate material.

In the context of interior stucco ornament restoration, a durable restoration work does not show severe changes in surface quality over time. This includes changing of colour (due to light), cracking, warping and unjoining of elements. Before the introduction of any new restoration materials for restoration work, these material must be tested on compatibility and durability to assess their success for the desired application (Hees et al., 2014). Since a special mixture will be created for 3D printing, the durability of such a mixture would require to be tested before application in practise. This could include assessing any changes in colour, surface texture (cracking) and adhesion strength. In this thesis durability will not be assessed by itself but certain aspects of it will be taken into consideration in the assessment of compatibility.

3.2.4. Conclusions

In accordance to international guidelines in restoration, the key aspect to consider for the development of gypsum-based mixtures and in-situ Additive Manufacturing process for stucco ornament restoration is: Compatibility. As reversibility is not sought after in stucco ornament restoration, this will not be investigated further. Durability will not be assessed separately but will be integrated into the investigation for combability. The guidelines provided by the various international charters give a general direction towards restoration. They do not go into detail about what exact factors must be considered to choose or create a compatible, reversible and durable restoration materials. These factors will be identified and further explored in the section “05. Printing material design”.

3.3. Degrees of intervention

Conservation is a term which encompasses a broad term of actions. To give more structure to this broad term, conservation can be categorized in so called 'degrees of intervention' according to seven categories as proposed by conservation architect Sir Bernard Feilden. Feilden, proposes seven degrees of conservation interventions in his book "Conservation of Historic Buildings", published in 1982:

- Prevention of deterioration: Control of immediate environment.
- Preservation of the existing state: Repairs, direct removal of decay agents.
- Consolidation of the fabric: May include physical intervention, structural supports etc.
- Restoration: Replacement/ Repair of damaged elements to preserve essence.
- Rehabilitation: Adaptive Reuse to make conservation economically sustainable.
- Reproduction: Replacement of entire features to preserve aesthetic harmony.
- Reconstruction: Complete rebuilding of structure but disconnection with context / essence.

In his master thesis, Ali Sarmad Khan, a Building Technology student from TU Delft, contextualizes digital fabrication within these different degrees of conservation (Figure 7). He concludes that "digital fabrication is independent of these degrees of intervention and can be used as a tool by conservationists for any appropriate degree of intervention, but primarily when additional material is required" (Khan, 2016, p. 13). Article 10 of the Treaty of Venice states that the use of any modern techniques is permitted if traditional methods prove inadequate as mentioned earlier. In the case of in situ stucco ornament restoration, the current methods may not necessarily inadequate by nature. However, the decreasing number of restoration plasterers and the physically demanding nature of the work make restoration time consuming and expensive, which means restoration cannot be done in an increasing number of cases. This could result in the further degradation of an ornament or building. Therefore, Additive Manufacturing is suitable to be applied for rehabilitation, reproduction and restoration of stucco ornaments.

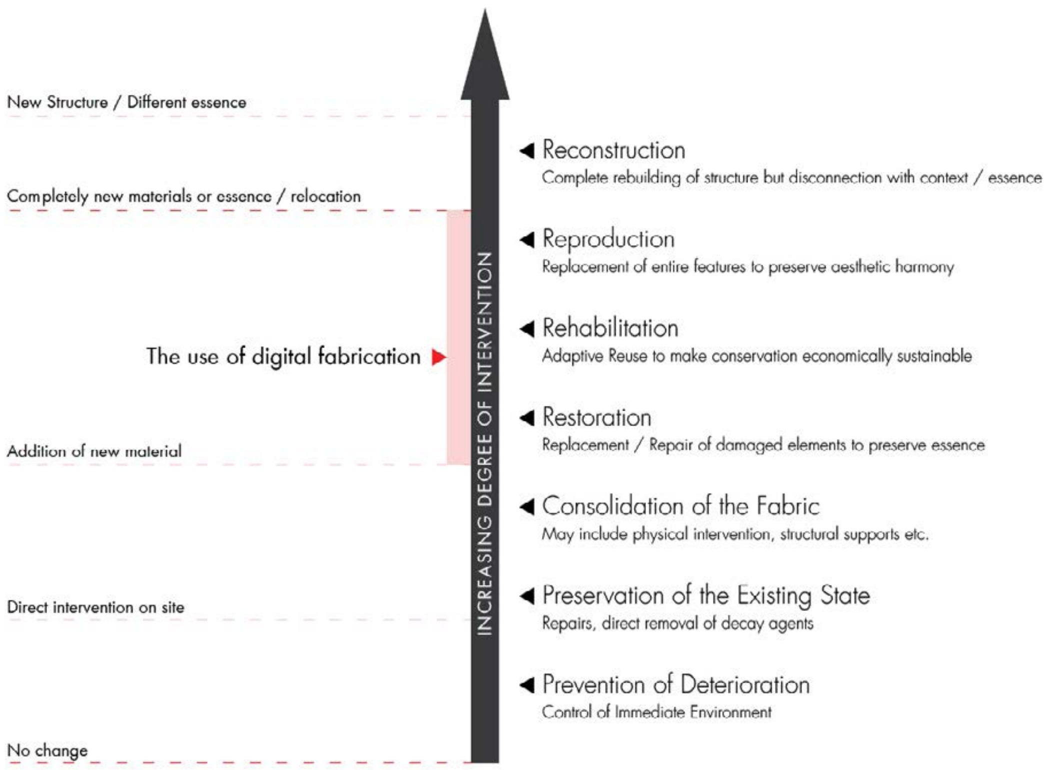


Figure 7 Contextualizing digital fabrication within the degrees of intervention. Source: (Khan, 2016)

Rehabilitation

Rehabilitation focusses on adaptive reuse to make conservation efforts and interventions more economically feasible. An examples of this is Villa Dijkzicht, built in 1852 as a summer villa for the family Van Hoboken (Natuurhistorisch, n.d.), which after the rehabilitation efforts in the 1980's and 1990's, hosts the Natural History Museum of Rotterdam inside. To accommodate this new function, several changes are made to the building, including the addition of a large glass hall.

Figure 8 Natuurhistorisch Museum Rotterdam, hosted in Villa Dijkzicht. Source: https://www.hetnatuurhistorisch.nl/het-museum/architectuur.html

Reproduction

Reproduction focusses on the precise recreation of an artefact which is lost, but its archaeological evidence (documentation in any kind of way) remains (Feilden, 1982). This archaeological evidence can then be used to reproduce a replica of the lost original. Heavily decaying or damaged parts can also be reproduced and replicated, while the original part is removed for safekeeping to protect it from further decay. Michelangelo's 'David' statue in Florence is put inside the Accademia Gallery for safekeeping, while a replica of the statue is kept outside (Feilden, 1982). Digital fabrication can aid in this process of reproduction by employing 3D scanning techniques for accurate recording and documentation as well as AM techniques to produce replicas.

Figure 9 "David" by Michelangelo, kept inside the Accademia Gallery in Florence for safekeeping. Source: https://en.wikipedia.org/wiki/David_(Michelangelo)

Restoration

The main objective behind restoration is "to revive the original concept or legibility of the object" (Feilden, 1982, p. 9). Replacements of decaying parts must integrate harmoniously with the whole, but must be distinguishable on close inspection so the restoration does not falsify historical evidence (Feilden, 1982). Restoration includes the cleaning of a building (part) and replacement of missing decorative elements (Feilden, 1982). Therefore, stucco ornament restoration falls mainly under this degree of intervention. Therefore, from here on, the term "ornament restoration" will be used to describe the conservation efforts of stucco ornaments by means of in-situ AM.

Figure 10 Restoration of stucco ornament in Huize Nolet. Source: https://www.tbafbouw.nl/

3.4. Current stucco restoration practise

Stucco on interior walls and ceilings of a building is subjected to weathering processes related to the interior climate (such as thermal and hygric stresses), possible presence of moisture and salts as well as damage due not compatible conservation and/or renovation interventions. Due to these influences ornamented stucco ceilings and walls can become damaged over time. The value of these ornaments must be considered and based on this assessment, appropriate actions can be taken. Choosing not to intervene may be done for a number of reasons, such as high cost. However, if it is decided to intervene, a careful plan must be formulated. To restore ceiling or wall-mounted ornaments, a multidisciplinary approach is required, as well as an extensive research into the causes of the damage. Furthermore, highly skilled restoration plasterers are required to perform the actual restoration work, especially when dealing with Heritage sites. Only if a proper research is conducted and a sound diagnosis is formulated, can a plan be formulated about how and what all must be restored. This is essential for budgeting, which often is one of the most important factors in restoration projects (Geerken & Freling, 2010). The current stucco ornament restoration method can be roughly divided into four general steps according to Geerken and Freling (2010).

3.4.1. General stucco ornament restoration steps

Step 1. Investigation and diagnosis of damage causes

The damage is investigated by experts. The causes of the observed damage must be found in order to perform proper and durable restoration later. For example, if there is decay due to the presence of moisture, then the source of the water must be found and stopped or controlled, before any restoration work can be done to the damaged ornaments. Along with the causes of the damage, the materials used in the original ceilings, walls and/or ornament used must also be identified and its properties must be assessed. This is essential because during restoration, compatible materials must be chosen carefully. Along with these technical aspects, the cultural and historical qualities must also be investigated, which includes gathering any historic documentation of the artefacts in question. These qualities are the reason the building or ornamentation has a collective importance that transcends the lifetime of the current user (Geerken & Freling, 2010).

Step 2. Solving the causes of the damage.

The second step is to solve the causes of the observed damage. At this point, a dilemma may arise between preservation of the original elements and the need of replacement of some elements. This could mean a rotting timber beam is replaced above the stucco ceiling to prevent the ceiling from sagging. This kind of intervention would be required to maintain the aesthetical appearance and essence of the original stucco ceiling. The further restoration work is described in this step and a quotation is made (Geerken & Freling, 2010).

Step 3. Restoration/repair

The thirds step is accepting the quotation and performing the restoration work. The first two steps have helped to understand the problems and deal with the causes, so the same damage will not occur again. In this third step restoration or repair is done to the artefacts, which in this case would be the damaged stucco ornaments. It is important to document all the steps taken and all materials and techniques used in the restoration process, as this will help future restoration workers to understand the composition of the restored artefacts (Geerken & Freling, 2010). How the restoration work itself is done, will be dealt with in the next subchapter.

Step 4. Aftercare and payment

In the fourth step the restoration work is finished, and the work must be checked with reference to the documentation which was used to create the restoration work. A maintenance plan may be formulated for the upkeep of the artefacts and the parties involved are payed.

3.4.2. Off-site vs. On-site

Fundamentally, there are two different approaches to stucco ornament restoration in the current practice: Off-site and On-site restoration. They both follow the same general steps presented in the previous subchapter, but have some fundamental differences, which will be explained in the next subchapters. Off-site restoration can be further divided into “Mold-based” and “Manual” restoration, while On-site restoration solely consists of “Manual” restoration. These approaches will be discussed briefly and finally, an overview of the various tools & techniques used by restoration plasterers will be given.

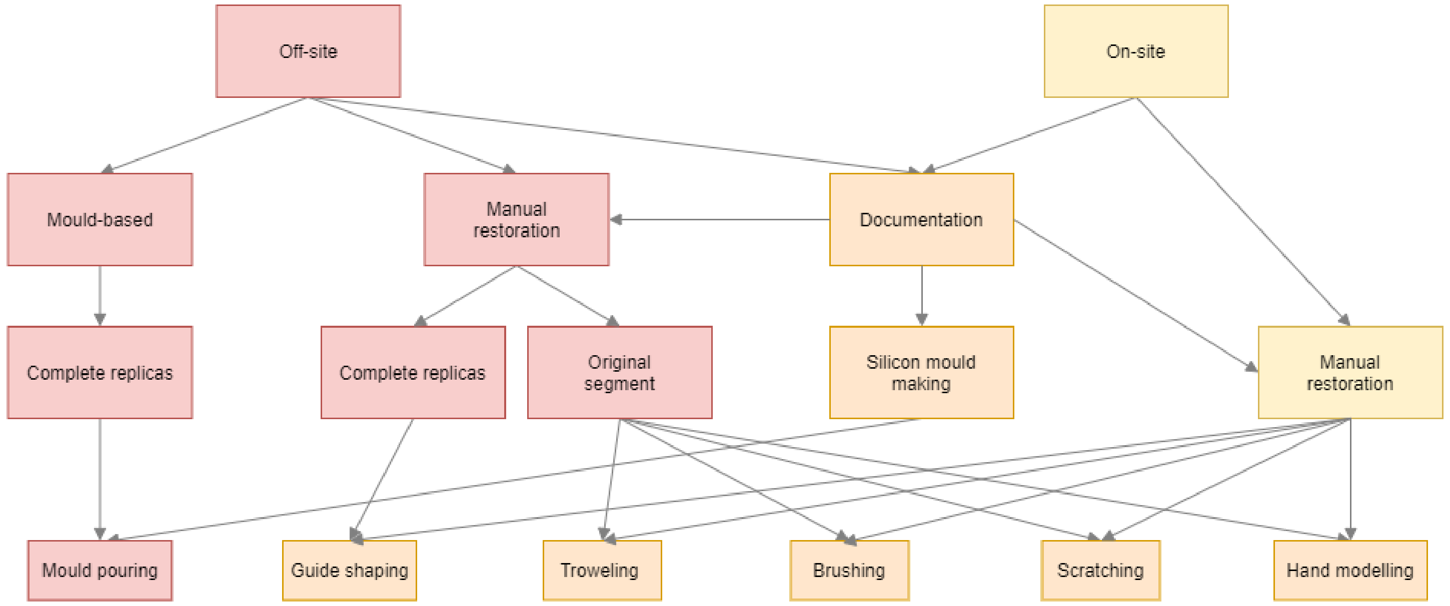


Figure 11 Overview of off-site and on-site methods and techniques. Red = off-site, Yellow = on-site, orange = both. Source: Author

3.4.3. Using moulds for restoration

Perhaps the simplest method for stucco ornament restoration is by creating prefab elements using moulds. If a mould of a damaged or missing ornament, which is essentially the negative of the ornament itself, is available then it is possible to pour a gypsum mixture into the mold to create a copy of the ornament. When this is done, the mold is removed, and the prefab ornament can be transported to the site to be installed. Because the moulds cannot be used more than a certain number of times, so called “mother moulds” are often created. This is an actual gypsum copy (positive) of the ornament made by pouring a gypsum mixture into the mould. This positive is stored and can be used to create moulds (negative) of this ornament. Between 1860 and 1920, J.C.L. Siberling an engineer from TU Delft, had a company called Siberling & Zoons, which made gypsum ornaments for ceilings and walls. The company possessed a very large collection of moulds in various art styles and

Figure 12 Excerpt from an ad of Siberling & Zoons showcasing a mould, support mould and ornament. Source: (Prins, 2013)

practically had a monopoly on the stucco ornament business in the Netherlands (Prins, 2013). That is why, many of the homes in the Netherlands that have stucco ornaments dating from around 1900 are likely to be a Siberling ornament. Het Neerlandsch Stucgilde possesses a substantial part of the Siberling collection and can produce prefab copies of these ornaments. So, in cases where the mold of a damaged ornament is still around, this method is the easiest and cheapest to restore a damaged or missing ornament.

In the case no mould is available, but the damaged or missing element is repeated somewhere else on the ceiling, or in some cases the house next door has a similar ceiling, then a mould can be made on-site. To do this, the part of the ceiling which is to be copied is treated with an anti-sticking agent to prevent the mould to damage the original ornament when removing. After this, a large container made of wood or gypsum is filled with liquid silicon. This container is then pressed from below onto the ornament which must be copied. After the silicon has dried, the mold can be carefully be removed and an imprint of the ornament is created in the mould. This mold can then be used to produce a copy of that ornament. This technique allows to create an accurate copy of the missing element. However, this technique has many disadvantages. The ornament which is used to make the mold can still be damaged in this process and a protective cover has to be placed over the entire floor underneath to protect it against falling silicon, making this process expensive (Anton van Delden, personal communication).

Digital fabrication offers some possibilities in this case. A 3D scanner can be used to create a 3D model of the damaged geometry as well as the geometry which needs to be copied. By extrapolating the two 3D models, the missing geometry can be modelled, and the ornament can be fabricated by 3D printing it or by pouring it into a 3D printed mould. This approach would prevent any risks of damaging the original ornaments when producing moulds.

3.4.4. Off-site manual restoration: complete replicas

Two types of off-site manual restoration can be identified. The first type is manually creating complete replicas. This means that a completely new geometry is created with new materials, by taking measurements, using photographs, drawings or any other kind of documentation of the original ornament as a reference. This can be done in the workshop of the restoration plasterer, so off-site, and the produced ornament can later be transported to site, where it can be attached to the ceiling or wall. It is important the precise measurements are taken before creating the copies off-site, as these copies must precisely fit into the existing ceiling.

During a visit to the workshop of Delstuc Stucadoors in January 2020, the "guide shaping" manual restoration technique was demonstrated. To create simple straight or round cornices for example, a wooden guide is used to shape the gypsum into the desired shape (see Figure 13). First, a gypsum mixture is created by adding gypsum powder (they used Molda 3 Normal) to a bucket of water in a certain ratio. When the gypsum starts to slowly set, some gypsum is put onto a wooden table and the wooden guide is guided along the gypsum to push it into the desired shape. This process is repeated several times over the course of about 15 minutes until the gypsum has set. The wooden guide not only helps to create the desired shape, but it also creates a smooth surface finish as can be seen in Figure 13. When creating simple shapes such as these, using a guide is much faster and easier than creating these shapes with AM.

Figure 13 Creating a smooth texture by using a guide. Image source: Author

3.4.5. Off-site manual restoration: Cut-out ornaments

In some cases, parts of an original stucco ceiling are removed by cutting them out and are brought into the workshop for off-site manual restoration. According to Van Delden, it is an unspoken rule that a stucco ceiling which was created by hand must be restored by hand, it cannot be restored with prefab elements. If it is not possible for any reason to perform the restoration works on-site, parts of the ceiling can be cut out for off-site restoration. This is a risky process, as elements can be further damaged when cutting them out of the ceiling or during transportation. The entire ceiling must be very accurately documented as well before cutting it out, to make sure all the pieces can be put back in the right place later (Geerken & Freling, 2010).

Figure 14 Cut out ceiling of the Beuningkamer brought to a workshop. Source: R. Klein Gotink.

Once a cut-out element is brought to the workshop, the restoration plasterer can work on it in a more comfortable position, rather than working above their head on-site. There are several tools and techniques used by the restoration plasterer for the manual restoration process in this type of situation. Thomas Salveter, a Stucco Restorer who has worked on restoring the iconic stucco ornaments of renowned stucco artist Antonio Bossi, explains that he uses sketches and photographs as a reference when working on a damaged ornament. He first applies stucco with a trowel to create the rough shape that he wants to make. Next, he uses wooden sticks or steel scratching tools to scratch fine details into the gypsum after the rough shape is made (Simon Russell, 2014). Finally, he uses a wet brush to stroke parts of the ornament to give them a smooth texture.

Figure 15 Salvater applying the rough shape of the missing part of a damaged ornament with a trowel. Notice the photographs and sketches he is using as reference. Adopted from https://www.youtube.com/watch?v=8_dwEbF-NiI

3.4.6. On-site manual restoration

On-site manual restoration is another common method of stucco ornament restoration. It does not require as extensive measurements of the original geometry as with off-site manual restoration. By restoring ornaments on-site, the ornaments do not require to be transported, which is risky especially when dealing with large and fragile ornaments. According to Van Delden, old stucco ceilings often tend to warp over time, making it extremely hard to create ornaments off-site that fit perfectly into this warped ceiling. This is because this new ornament may be straight, while the old ceiling is not, due to warping overtime. He argues that especially in these cases it is better to do on-site manual restoration. This is however extremely physically demanding work, as it requires plasterers to work above their head for long periods of time.

Figure 16 *On-site stucco ornament restoration work. Sources: tbafbouw.nl, (Geerken & Freling, 2010)*

The tools and techniques used in on-site manual restoration are similar to that of off-site manual restoration of the cut-out ceiling elements, discussed in the previous subchapter. Restoration plasterers require scaffolding or ladders to stand on in order to reach the damaged areas on the ceilings or walls. They use trowels to apply stucco onto the ceiling or wall, wooden sticks or steel scratching tools to create details and wet brushes to smoothen parts out. Very intricate shapes are sometimes also modelled by hand directly onto the ceiling, or modelled on a table first, after which the ornament is stuck onto the ceiling. In these situations, AM has the potential to help. Complex and intricate geometries are not a problem for manufacturing by means of AM. In these situations, instead of building elaborate scaffolding and spending a huge number of man-hours on doing the physically demanding work above the head by the diminishing number of restoration plasterers, in-situ AM could be an alternative.

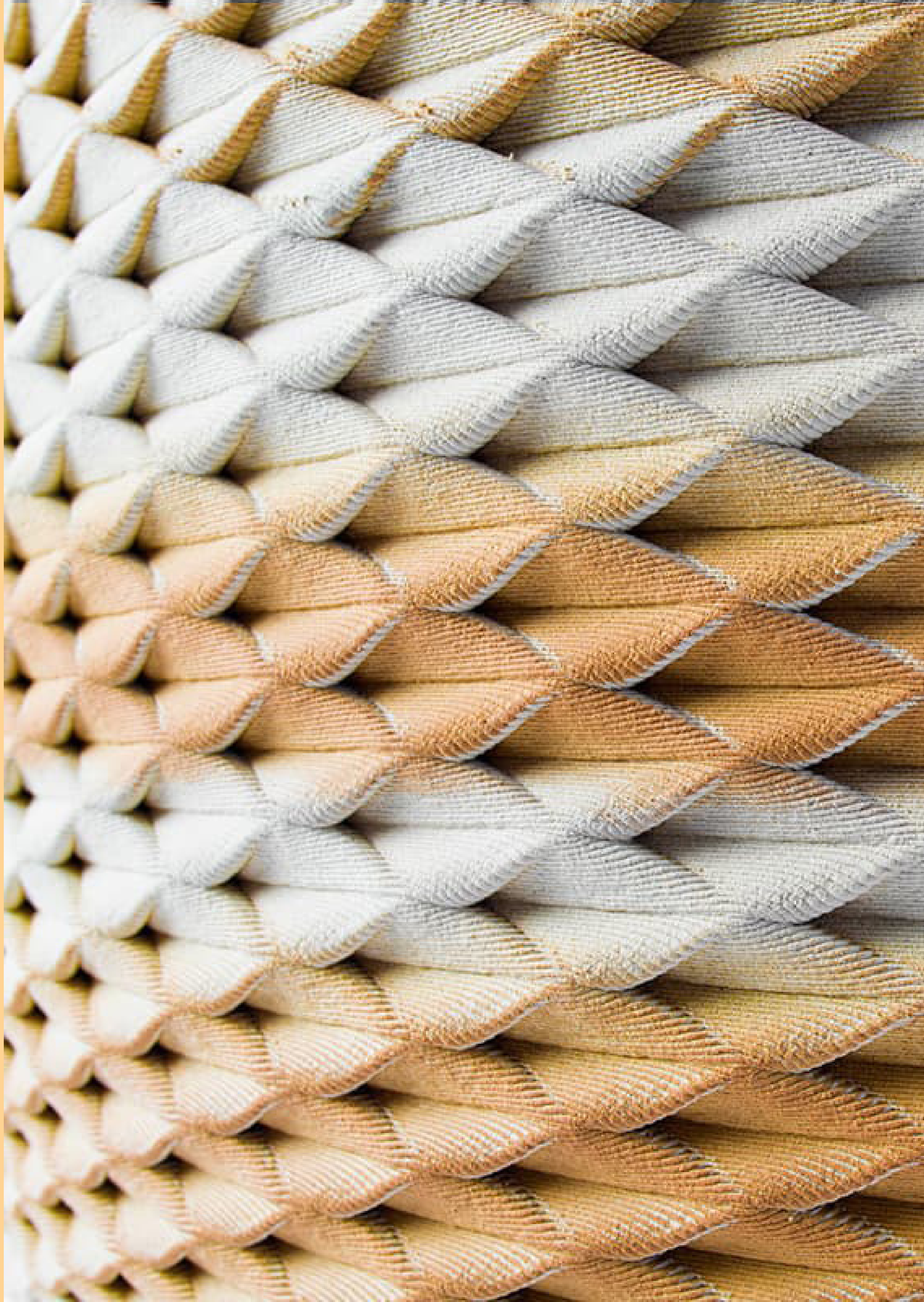
3D scanning can help to accurately document the warped ceiling and import it into a 3D modelling software. In a CAD environment, it is possible to accurately visualize, measure and understand the geometries of the warped ceiling and ornaments. Again, repairing the missing or damaged geometry by extrapolation can be done in this CAD environment. The big advantage with this method is that the repaired geometry will fit exactly into the warped ceiling, as the 3D scan has accurately documented the warped ceiling.

3.5. Additive Manufacturing for stucco ornament restoration

As discussed in the previous chapters stucco ornament restoration can be categorized into off-site and on-site approaches. It is evident that both off-site and on-site approach use their own set of tools and techniques. 3D scanning and Additive Manufacturing can help in both approaches and in off-site restoration this is already done to create moulds for pouring of prefab elements. However, it is the on-site manual work that is the most difficult, most labour intensive, most physically demanding and in certain cases is the only possible approach for proper restoration of stucco ornaments. Working above the head for long durations should be avoided for the physical well-being of restoration plasterers. Removing (parts) of a stucco ceiling to restore it off-site also has its clear disadvantages as the fragile removed elements can get damaged during transportation and installation. Developing an in-situ AM technique could prevent both such unfavourable situations for stucco ornament restoration.

04.

DIGITAL FABRICATION



4.1. Introduction

Today, in the Digital Age, designers, engineers and craftsman can harness the power and possibilities of new digital tools to create highly complex and customized shapes. “Digital fabrication” is a design and production process which combines 3D modelling, also known as Computer-Aided-Design (CAD), which additive and or subtractive manufacturing techniques (Rouse, 2014). CAD has been used in architecture and design for decades and today there are many different software tools available for digital design, such as AutoCAD, Revit, Rhinoceros and Sketchup. There are three main types of digital fabrication techniques commonly used:

Figure 17 Producing Chakli by means of "Additive Manufacturing". Adopted from: https://www.vegrecipesofindia.com/chakli-recipe-instant-chakli-recipe/

direct additive manufacturing (AM), indirect additive manufacturing (iAM) and subtractive manufacturing (SM). Additive and subtractive manufacturing techniques, in analogue forms, have been around for a very long time as well. In India, a savoury snack called “Chakli” is made by “extruding” a mixture made up of flours, rice and brown chickpea through a kitchen ram extruder for several decades (see figure X). The mixture is manually extruded out to create a desired shape for the snack.

For thousands of years, expert sculptures have been creating statues by carving and chiselling blocks of stone (see figure X). This is a basic form (manual) subtractive manufacturing and is done by removing the “negative” out of a block until the desired shape remains.

Figure 18 Stone sculpting, a form of subtractive manufacturing. Adopted from: http://ecs.com.np/features/stone-sculpting-in-nepal-the-art-of-making-gods

Additive manufacturing in the modern, digital context, is a layer-by-layer process in which material is added only where it is required to build up shapes, which makes AM a low waste production process. Direct additive manufacturing means the final geometry is directly fabricated by an AM process, so for example 3D printing an ornament in gypsum which will installed on a ceiling. Indirect additive manufacturing means that AM is used to create a mould which can then be used to create the final geometry of the object that needs to be produced. An example of this is, if a mould of an ornament is 3D printed in a material like silicon or PET by means of AM and this mould is then used to pour a gypsum mixture into to create the final ornament which will be installed on site. Subtractive manufacturing is when the final geometry is cut or milled out of a block of material. An example of subtractive manufacturing could be when an ornament is milled out of a block of gypsum with a milling machine. In traditional, analogue forms of Additive Manufacturing and Subtractive Manufacturing, it was human hand-craft which created (complex) shapes with such techniques. Today, in the Digital Age, machines can be programmed with the help of computers to follow precise paths to Additively or Subtractively Manufacture shapes.

4.2. General Digital Fabrication methodology for restoration

When dealing with restoration of damaged or missing parts, such as a damaged stucco ornament, a series of steps need to be taken for restoration by means of AM. Firstly, the damaged area is selected, reference markers are placed around it and the damaged area is scanned with the aid of a 3D scanning device. The 3D scan helps to generate a replica of the scanned area in the form of so called “point cloud” data. Next, this point cloud data is converted into a so called “mesh” 3D model with the help of special software tools. After this, the 3D model can be used to “digitally repair” the ornament by interpolating the missing or damaged geometry. Subsequently, a direct or indirect AM technique is chosen to produce the missing geometry. Once this is done, the 3D model of the ornament which is to be restored is prepared for the AM process with the use of a so called “slicer”. Finally, the element is produced with the chosen AM technique and is mounted on site. The next subchapters will give a brief overview of the various steps, techniques and tools involved in the entire process.

4.2.1. 3D scanning in restoration

There is a wide variety of 3D scanning methods commercially available. This subchapter will provide a brief overview of the principle behind some of the methods that are suitable for use in architecture and restoration. The principle behind these methods is using radiation or sound waves to determine the exact distance between the surface of the scanned object and a point of reference (Khan, 2016). The scanning methods can be divided into active methods and passive methods of scanning of which the principle is shown in Figure 19. Often in both active and passive scanning methods, markers are used as reference points. These reference points can help to match the exact location of a virtual model obtained from a 3D scan and the actual area. This will be further described in the chapter “robot calibration” at the end of this section.

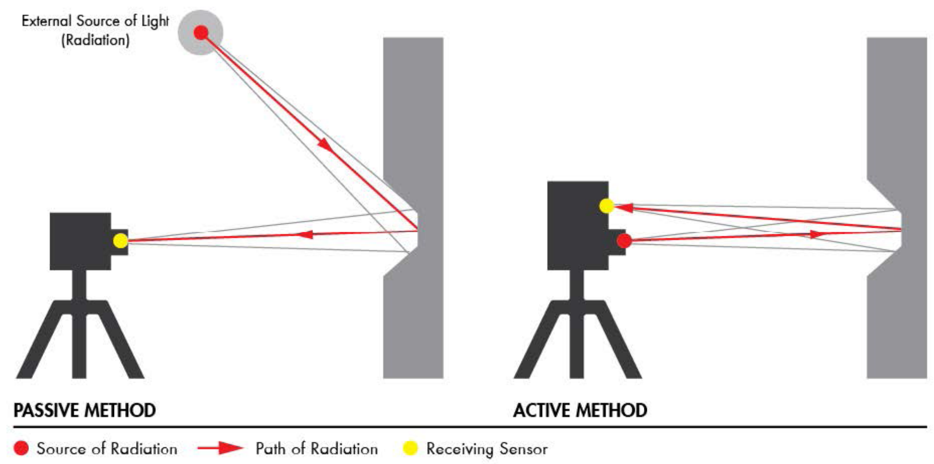


Figure 19 Principle behind the passive and active 3D scanning methods. Image source: (Khan, 2016)

Passive methods

Both active and passive methods require a source which emits light radiation and a sensor which can receive this radiation. The main difference between active and passive methods is that in active methods this source of the radiation is built into the scanner itself, while in passive methods only require a sensor to receive light radiation and algorithms are used to process this data into a 3D representation (Khan, 2016). This makes passive methods generally cheaper and the scanners more compact.

For example, a digital camera can act as a passive scanner in combination with software such as Autodesk 123D Catch or Recap. These software’s have algorithms that can predict the location of various points in the image to form a comprehensive 3D representation of that object by looking at multiple photos of the same object from different angles (Khan, 2016). This technique is known as Photogrammetry. There are more passive methods such as Photometric Stereo method or the Silhouette method, which also require only a photo camera in combination with specialized software to extract 3D information from 2D images. The latter techniques however are very light sensitive and form relatively crude images. Since geometrical accuracy is important when capturing intricate ornaments, such scanning techniques are unsuitable for Restoration and Digital Fabrication purposes.

Active methods
In active methods, the scanner itself emits radiation to the object that is being scanned. The radiation then bounces back from the object to a sensor built into the scanner (Khan, 2016). The radiation used in these methods can be in the form of visible light, x-rays or even ultrasound waves.

Laser scanning techniques are possibly the most commonly used 3D scanning techniques in Architecture and restoration. There are three types of laser scanning systems: Triangulation system, Pulse (or Time Of Flight) system and Phase system. Figure 20 shows an overview of various scanning systems along with their usage, typical accuracies and typical range. The different available techniques within these systems are suitable for different type of applications, from the documentation of small objects with accuracies of up to 0.0.5mm scanned from about a millimetre, up to 3D scanning of large areas of land with accuracies of up to 50 metres, taken from several kilometres height (Historic England, 2018). A scanning technique can be chosen depending on factors such as the size of the area which needs to be scanned, the required accuracy of the scan and the accessibility on site. These factors are highly dependent on the site, geometry of the elements that need to be restored as well as the budget.

Scanning System		Usage	Typical Accuracies (mm)	Typical Range (m)
Triangulation	Rotation stage	Small objects taken to scanner. Replica production	0.05	0.1 – 1
	Arm mounted	Small objects. Lab or field. Replica production	0.05	0.1 – 3
	Tripod mounted	Small objects in the field. Replica production	0.1 – 1	0.1 – 2.5
	Close range handheld	Small objects. Lab. Replica production	0.03 – 1	0.2 – 0.3
	Mobile (handheld, backpack)	Awkward locations eg building interiors, caves	0.03 – 30	0.3 – 20
Pulse (TOF)	Terrestrial	Building exteriors/interiors. Drawings, analysis, 3D models	1 – 6	0.5 – 1000
	Mobile (vehicle)	Streetscapes, highways, railways. Drawings, analysis, 3D models	10 – 50	10 – 200
	UAS	Building roofscapes, archaeological sites. Mapping and 3D models	20 – 200	10 - 125
	Aerial	Large site prospecting and mapping	50 – 300	100 – 3500
Phase	Terrestrial	Building exteriors/interiors. Drawing, analysis, 3D models	2 – 10	1 – 300

***Figure 20** Various laser scanning techniques and their use. Adopted from: (Historic England, 2018, p. 8)*

Wall- or ceiling-mounted stucco ornaments can consist of very intricate geometries and can cover areas as large as an entire room. This means that the chosen 3D scanning technique should ideally have an accuracy of up to a couple of millimetres at the most and should have a range of up to several meters so objects on tall ceilings can be scanned from the ground. From the techniques presented in Figure 20, five techniques seem to meet the previously mentioned criteria and are presented in Figure 21.

Pulse/ Time Of Flight method
The "Pulse" or "Time of flight" (TOF) method uses a scanning device with a laser source as well as a receiver. The scanning device emits radiation onto the target object, which then bounces the light back onto the sensor on the device. Since both the speed of the radiation and the medium in which the radiation travels (air) are known, fixed factors, the distance between each point on the target object and the scanner can be calculated (Khan, 2016). Such a scanning technique is also referred to as LIDAR (LIght Detection And Ranging) technique. By scanning a multitude of points on the surface of a target object in such a way, will give a cloud of points which all have a set of coordinates to determine their location in reference to a reference point. This cloud of points is called a "point cloud" and is used by special processing software to convert the point data into a 3D model. TOF scanners come in portable sizes and can be placed on a tripod or arm. The TOF method has a typical accuracy of 1-6mm and has a scanning range of 0.5 to 1000 meters, making it suitable for 3D scanning of interior spaces and stucco ornaments for digital fabrication.

Triangulation method
The Triangulation approach involves a laser (source) and a camera (receiver) which are at a fixed distance from the scanning area, called a 'baseline'. The laser emits radiation, which bounces from a target point within the scanning area onto the sensor at an angle. The distance between the camera and the laser source is known. The angle at which the radiation, that has bounced off a target point in the scanning area, is received at the camera can be measured. With this information, a triangle can be constructed between the laser source, the scanned target point and the camera, which helps to determine the exact location of a target point in the scanning area (Khan, 2016). By repeating this procedure for many points, the location of a cloud of points can be determined in the scanning area. Triangulation scanning devices can be mounted onto a tripod or arm for on-site use, making them easily deployable into a building. The triangulation method can achieve a high accuracy (up to 0.05mm) and has a range of up to several meters, sufficient for scanning large parts of ceilings and walls inside a room. However, this method is typically used to scan small objects at a close distance (generally up to a meter) in controlled environments, because ambient light and sunlight can affect the measurements (Historic England, 2018). Even so, in interior use, the lighting in a room can be controlled with the use of curtains, blinders etc. Given the range and accuracy of this method, it seems like a suitable scanning method for digital fabrication.

Phase method
The phase method is also referred to as Continuous Wave (CW) method and features a scanner that emits a continuous beam instead of pulses like in the previously mentioned methods (Khan, 2016). The beam emitted by the scanner consists of a so called "carrier wave", which includes a modulated sinusoidal signal to include measurement information within the beam. The beam bounces back from the scanning area and is detected by the scanner. Since the phase, or wavelength, of the outgoing sinusoidal wave is known, the difference in phase between in outgoing and incoming signals is used to determine the distance between the scanned point and the scanner. This done with the formula below, where R = the distance between the scanned point and the scanner, M = number of wavelengths (integers), λ = the known wavelength of the outgoing beam and Δλ) = the fractional part of the incoming wavelength (Khan, 2016):

$$R= ((M\lambda+\Delta\lambda))/2$$

Phase method systems capture a higher density of points than the previously mentioned methods, which means the point clouds generated with this method are usually more densely packed and thus can capture high level of detail of up to 2mm at a range of up to 100m, which makes this method suitable for restoration of stucco ornaments and Digital Fabrication.

Scanning system	Scanning platform	Usage	Typical accuracies (mm)	Typical range (m)
Triangulation	Arm mounted	Small objects. Lab or field. Replica production	0.05	0.1 – 3
Triangulation	Tripod mounted	Small objects in the field. Replica production	0.1 – 1	0.1 – 2.5
Triangulation	Mobile (handheld, backpack)	Awkward locations e.g: building interiors, caves	0.03 – 30	0.3 – 20
Pulse (TOF)	Terrestrial	Building exteriors/ interiors. Drawings, analysis, 3D models	1 – 6	0.5 – 1000
Phase	Terrestrial	Building exteriors/ interiors. Drawing, analysis, 3D models	2 – 10	1 – 300

Figure 21 3D scanning techniques suitable for stucco ornament restoration. Source: Author.

4.2.2. Point cloud to mesh transformation

The next step is to convert the point cloud data, generated by the 3D scan into a workable 3D model in the form of a so called “mesh” model. A mesh is the structural built of a 3D model consisting of polygon and is described in X, Y and Z dimensions (Rouse, 2016). There are two types of geometries that point cloud data is converted to: Polygonal Models or Rapid NURBS solids (Khan, 2016). In the first case, the point cloud is converted to a polygonal model by connecting points in the point cloud to form tessellated triangles or “polygons” (Direct-Dimensions, 2015). In the second case, Rapid NURBS solids are generated by wrapping NURBS surfaces over a polygonal frame (Direct-Dimensions, 2015). In this second method, first a polygonal model is created, similar to the first method, but is then wrapped to create smooth surfaces in an additional step.

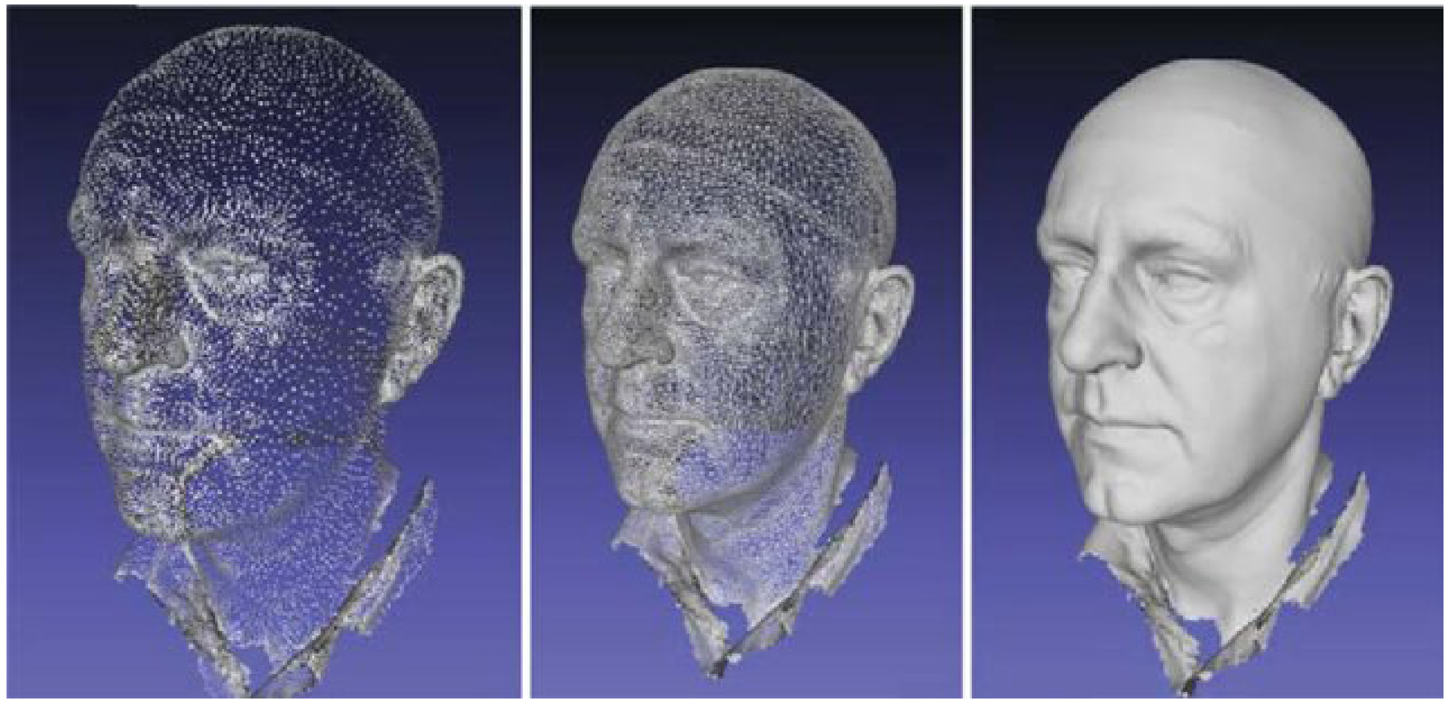


Figure 22 Example of point cloud (left), high dense point cloud (middle) and workable mesh (right). Adopted from: (Daanen & Psikuta, 2018)

The Polygonal models method allows to record all imperfections of a scanned object and is therefore suitable for restoration and digital fabrication. The rapid NURBS solids method allows the converted data to be parametrized, making it easier to manipulate them in software environments which offer parametric modelling. Generally, rapid NURBS solids method is used for reverse engineering and is less suitable for restoration as imperfections in the scanned geometry are lost due to the smoothening of the surface. Several software tools (both paid and free) are available to use for this purpose. Examples are GeoMagic, MeshLab, 3D Studio Max and Leica Cyclone.

4.2.3. Interpolation

After converting the point cloud data from the 3D scan into a workable 3D mesh model, the interpolation step can start. In mathematics, interpolation means the construction of new datapoints within a discrete set of known datapoints (Kress, 1998). This means, that when enough data points within the scan of known elements are available, it is possible to model the missing elements by interpolation. Interpolation can be done by copying repeating elements within the 3D scan to model the missing geometry or by modelling the missing geometry from scratch with the help of historic documentation.

In the case of stucco ornaments, if the missing or damaged elements are repeated somewhere else on the ceiling (where they are intact), then this area can also be scanned. The intact mesh can then be overlaid over the damaged mesh in a 3D modelling software such as Rhinoceros 3D, and a Boolean operation can be performed. This is an operation in which the two 3D models are split up by using each intersecting surface as a cutting surface. This operation results in creating parts that are exactly overlapping between the damaged and the intact geometry and parts that are only present in the intact geometry. The latter parts are the missing parts of the damaged ornament and are now precisely modelled, including any possibly complex fracture surfaces.

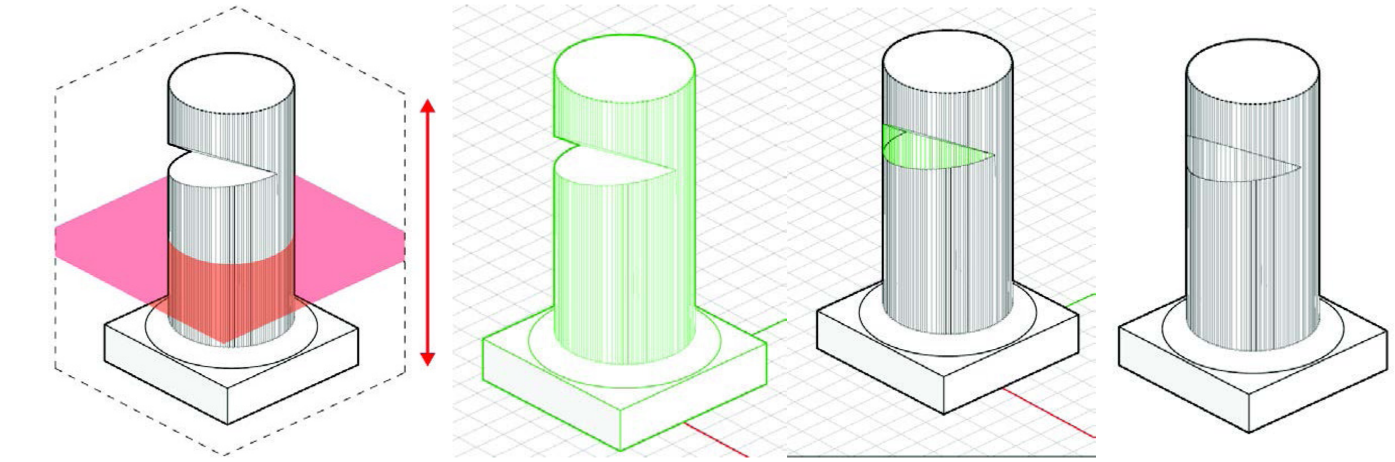


Figure 23 1) 3D scan damaged object, 2) convert point cloud to mesh, 3) repair digital geometry with Boolean operation, 4) Repaired element. Adopted from: (Khan, 2016, p. 33-35)

If there are no repeating elements that can be used for interpolation by means of Boolean operations, the missing geometry must be modelled from scratch. This can be done with the help of historic documentation (photographs or drawings) of the missing geometry. 3D modelling software such as Rhinoceros 3D are suitable for modelling such elements. The restoration craftsmen could add the computer mouse to their arsenal of tools to restore ornaments by means of digital fabrication.
This concludes the 3D scanning and digital repair methodology that can be used for (stucco ornament) restoration. An overview of the methodology is given in Figure 24.

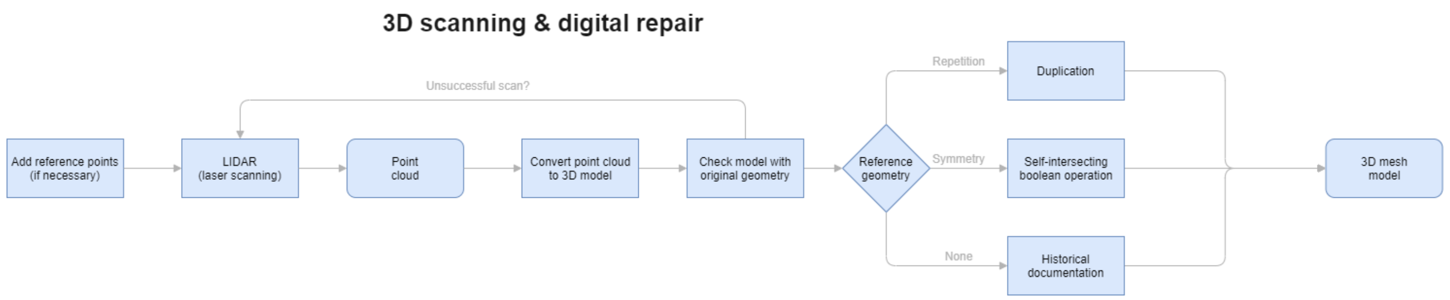


Figure 24 3D scanning & digital repair workflow. Source: Author

4.2.4. Choosing a manufacturing method

After the missing geometry has been successfully modelled with a 3D modelling software, the 3D model must be prepared for the chosen manufacturing process. As mentioned earlier, there are three main categories of manufacturing in digital fabrication: direct Additive Manufacturing indirect Additive Manufacturing and Subtractive Manufacturing (SM).

Subtractive manufacturing

Subtractive Manufacturing, such as “milling”, means that the geometry of the 3D model is cut out of a block of material. Milling essentially means, the negative of the material is removed by a fast-rotating router-bit from a block or plate, leaving behind the desired shape of the 3D model. This technique can be used for wood, stone or metal-based materials (Khan, 2016) and even gypsum. When dealing with geometries that have no overhangs or cavities, a 3-axis milling machine can be used. When dealing with overhangs and cavities, as can be the case with complex stucco ornaments, a multi axis machine, such as a 6-axis robot arm would be

required. For this technique to be used however, a block or plate of the desired material is required. For in-situ stucco ornament restoration, this could mean that the (rough) shape of the ornament is already applied on the ceiling after which the details of the ornament are milled out. High-end stationary CNC machines can achieve an accuracy of 0,02mm – 0,05mm (Owen-Hill, 2018), while Robot Machining is dependent on the repeatability and path accuracy of the robot used. For many industrial and collaborative robots this lies between 0,1 mm and 0,05 mm, which will result in milling accuracy’s of around 0,2 mm and 0,1 mm (Owen-Hill, 2018). This seems like a possible approach but would require double work as the rough shape must also be applied first, possibly by means of AM. Therefore, milling could be explored as a possible follow up step if AM proves to not be able provide the required resolution.

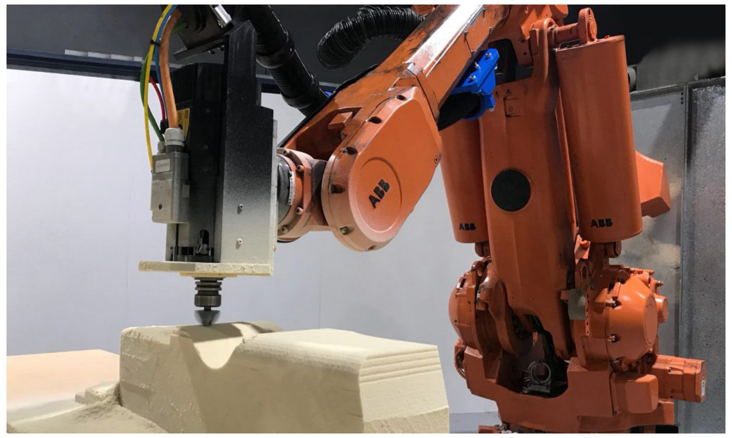


Figure 25 Milling with a 6-axis robot arm. Source: https://www.josephsworkshop.com.au/robotic-machining/

3D printing moulds

In indirect AM, the geometry is not directly fabricated by the AM process, but rather a mould is fabricated by AM. The mold is then used for casting the ornament. In some cases, the mold can be made from an existing 3D printing filament material, such as PLA or PET. In the case of stucco ornaments, the mold is required to be flexible and thus these molds are often made of silicon. To make such a mold, the ornament geometry can be made by means of AM (positive) with for example PLA. Then, this PLA geometry can be used to cast the negative shape around it in silicon. This will give a flexible mould (negative) made of silicon which can then be used to cast the ornament in with the desired materials.

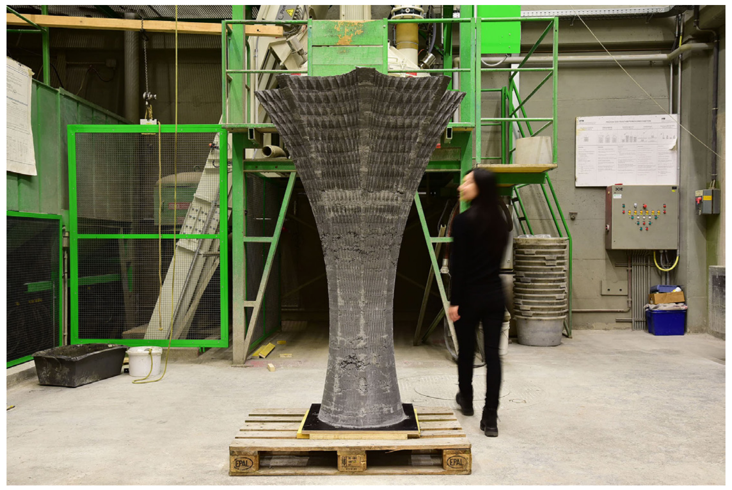


Figure 26 Eggshell: Self compacting concrete poured into a 3D printed plastic formwork. Image source: https://www.tudelft.nl/en/architecture-and-the-built-environment/study/student-projects/archiprix-preselection-2020/joris-burger/

Casting is widely used for a long time in stucco ornaments production and restoration. It allows to create a smooth surface and the mixture used for casting can be a simple mixture of water and gypsum powder (Kruyswijk, 2018). Casting is however unsuitable for in-situ restoration methods and for very large and thin ornaments, which have a risk to be damaged during transportation and installation.

Direct Additive Manufacturing

In direct AM the 3D model is used to print out the 3D model geometry itself. This is done in a layer-by-layer approach. For direct AM, the final material that is to be used for the restoration process must be used for printing. In case of stucco ornament restoration, this means that a gypsum-based mixture must be created which is printable on site.

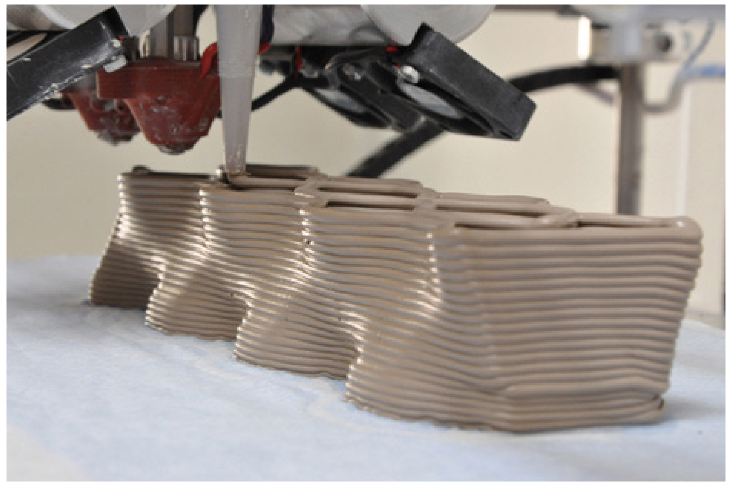


Figure 27 Direct AM of clay. Adopted from: https://projectsilkworm.com/clay-printing-first-steps/

4.2.5. 3D printing software

3D printing software, also referred to as "slicer" software is used to convert a 3D model into instructions for a 3D printer to fabricate the model. Slicer software slices the model vertically into thin slices, also known as "layers" which are cross-sections of the 3D model. The height of each layer determines the printing resolution of the object. As a general rule, the higher the printing resolution (so the smaller the layer height), the longer the printing time. By cutting the model horizontally into slices, the slicer software creates an outer shell and an infill. Only the outer shell will be visible in solid objects after they have been 3D printed. For most objects, including stucco ornaments, the geometry inside the model is not relevant, as long as it can support the weight of the model itself. The pattern and density of the inside of a model can be controlled with the slicer software and is referred to as "infill pattern" and "infill density". The layer height, infill pattern and infill density are three of many parameters which can be defined in a slicer software. Other parameters include the extrusion width, number of shell lines, printing speed and many more. After satisfactory settings have been chosen in the slicer software for a particular model, the slicer can "slice" the model, which means it will translate the geometry of the model, along with input data from the user as described above, into instructions for a 3D printer to fabricate the model. These instructions are referred to as "G-code". After the slicing, the slicer software can give an estimation of the printing time and amount of material needed for the print. For in-situ AM of stucco

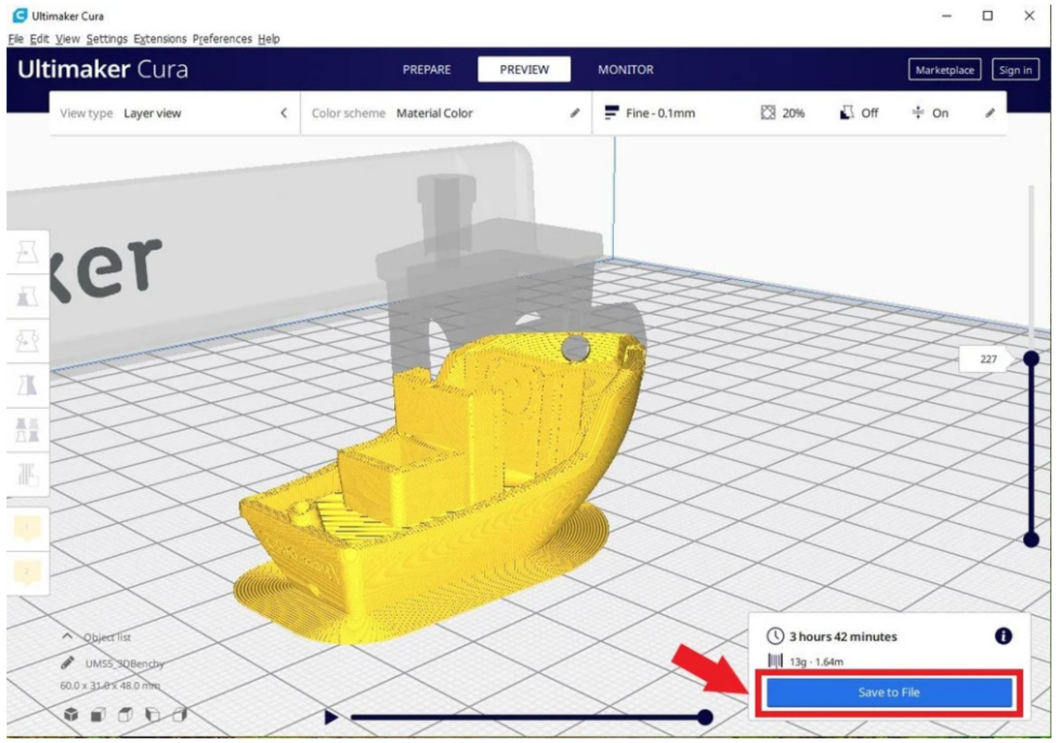


Figure 28 Example of interface of slicer software Cura. Adopted from: https://all3dp.com/1/cura-tutorial-software-slicer-cura-3d/

ornaments this information can be useful to determine if the print could be done on one go and how much material should be pre-mixed for the task. Examples of free to use open source slicer software are Cura, Slic3er, Repetier-Host and Simplify3D.

4.3. 3D printing in the manufacturing industry

3D printing has been widely adopted in the manufacturing industry today. Various different types of 3D printing techniques are used in combination with different types of materials and for different applications. This subchapter will give a very brief overview of some of the main techniques, their principle of working, the types of materials suitable for each technique and their application in practise. All 3D printing techniques have in common that they use a layer-by-layer method to form an object. This means that a 3D model of the object that is to be fabricated is first sliced into thin slices using 3D printing software. Each slice represents a cross section of the model. Then these slices are formed, layer upon layer by either extrusion, sintering, binding, polymerizing or other printing technologies (Ma, Wang, & Ju, 2018). By doing so, the layers accumulate into forming a solid model. Most common techniques used are Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), Stereo Lithographic Appearance (SLA).

Fused Deposition Modelling

FDM is an extrusion based 3D printing technique. It relies on extruding a melted and liquified filament material through a heated nozzle. The filament materials used for FDM include polymers such as PET, PLA, ABS, but can any material that can be turned into a filament and has a melting temperature of around 200 degrees Celsius could be used. The melted filament is deposited on a printing bed to the profile of the 3D models cross sections (Ma et al., 2018) (see Figure 29). After the material is extruded, it rapidly cools down and solidifies, after which it can support subsequent layers. Temporary supports, which can be removed later, can be printed to support large overhangs. FDM can reach printing resolutions of well under half a millimetre. The printing nozzle moves in X and Y direction to print one cross sectional layer and moves up in the Z direction after an entire layers is completed to print the next layer. FDM is one of the most commonly used techniques to produce physical prototypes of custom parts or mock-up models, as it is very accessible 3D printing technique which, over the years, has become more and more affordable. As of today, a variety of decent and affordable desktop 3D printers are available for under 200 euro (Hulette, 2019). This affordability has led to the rise of desk-top 3D printers reaching schools, universities, offices and hobby enthusiasts' homes. The advantage of FDM is in its ability to produce custom parts with complex shapes in a relatively short time with the compatible materials. This can be beneficial when a low number of customized parts are required for a specific application, which can save a lot of cost of producing such parts in more traditional methods such as injection moulding.

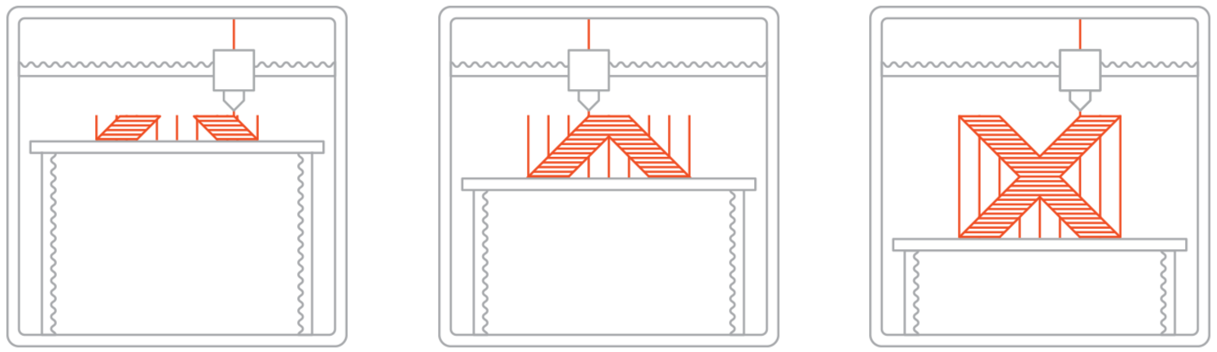


Figure 29 FDM 3D printing technique principle. Adopted from: https://www.3dhubs.com/knowledge-base/introduction-fdm-3d-printing/

Selective Laser Sintering

SLS is a powder bed based printing methods. It relies on spreading a thin layer of a powder over a printing bed with a roller. A printing head, which is equipped with a laser, solidifies specific areas of the powder layer to form one layer of the cross section of the model (see Figure 30) (Ma et al., 2018). After a layer of the 3D model is solidified in this way, the roller again rolls a thin layer of powder across the over the printing bed and the laser again solidifies specific areas according to the 3D model. The un-sintered powder, acts as support material for the solidified parts, so no supports need to be printed. After a print is done, the un sintered powder can be easily brushed off and re-used. SLS is used to create objects in metal alloys, gypsum, stone powders, ceramics and glass and has a very high resolution of up to 0,01mm (Ma et al., 2018).

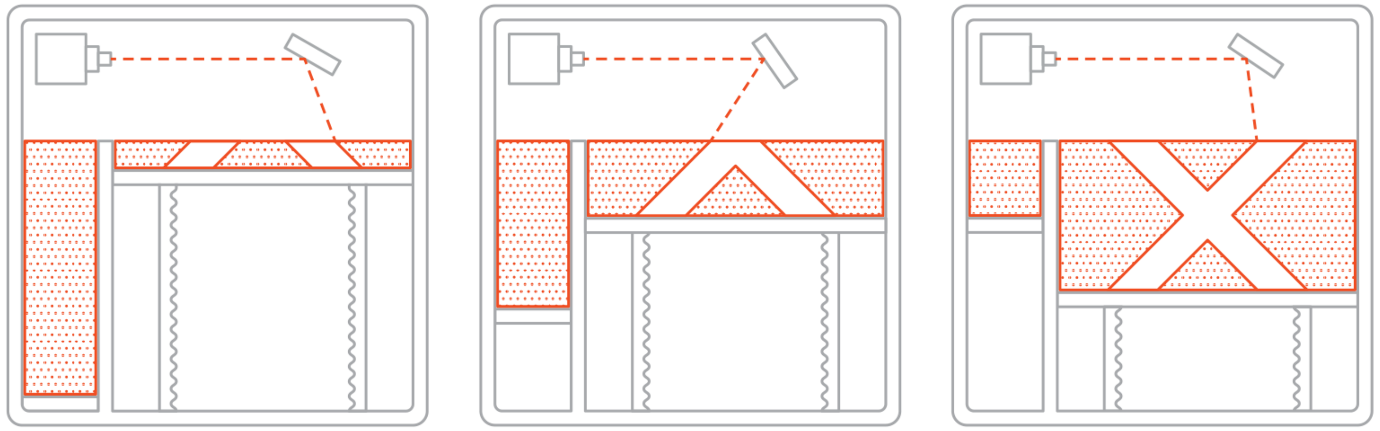


Figure 30 SLS 3D printing technique principle. Adopted from: https://www.3dhubs.com/knowledge-base/introduction-sls-3d-printing/

Stereo Lithographic Appearance

SLA is a 3D printing technique which relies on using UV light to solidify a liquid polymer to form objects. The building platform (printing bed) is initially placed inside a container containing a liquid photopolymer at a depth equal to the height of one layer of the 3D model. A UV laser is used in combination with a set of mirrors to cure and solidify (polymerize) parts of the liquid photopolymer selectively to form a cross sectional layer of the 3D model (see Figure 31) (Varotsis, n.d.). After a layer is done, the platform moves up and a sweeper blade sweeps across to re-coat the surface, after which the polymerizing of the next layer can occur (Varotsis, n.d.). SLA can be used for making objects at a resolution up to 0,016mm and works with liquid photopolymer materials (Ma et al., 2018) and may require further UV curing if high mechanical and or thermal performance is required for the printed part (Varotsis, n.d.).

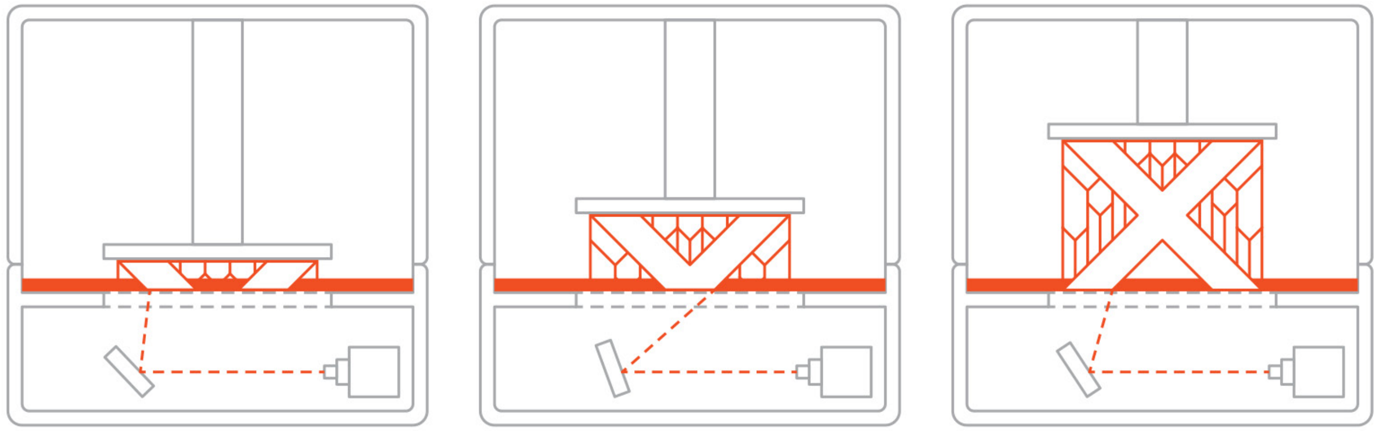


Figure 31 SLA 3D printing principle. Adopted from: https://www.3dhubs.com/knowledge-base/introduction-sla-3d-printing/

The 3D printing techniques described above are a small selection of the wide variety of 3D printing techniques used in the manufacturing industry. Most other commonly used techniques us similar principles are FDM, SLS and SLA 3D printing techniques and may be used with other materials. An overview of the type of techniques, technology behind the technique and materials used in each technique are presented in figure X, adopted from Ma et al. 2018.

Type	Technologies	Materials
Extrusion	Fused deposition modeling (FDM)	Thermoplastics, eutectic metals, edible materials, rubbers, modeling clay, plasticine, metal clay
	Robocasting or Direct Ink Writing (DIW)	Ceramic materials, metal alloy, cermet, metal matrix composite, ceramic matrix composite
	Composite Filament Fabrication (CFF)	Nylon, nylon with short carbon fiber reinforcement in the form Carbon, Kevlar, Glass
Light polymerized	Stereolithography (SLA)	Photopolymer, resin
	Digital Light Processing (DLP)	Photopolymer, resin
Powder bed	Powder bed and inkjet head 3D printing (3DP)	metal alloy, powdered polymers, plaster
	Electron-beam melting (EBM)	Almost any metal alloy
	Selective laser melting (SLM)	Titanium alloys, cobalt chrome alloys, stainless steel, aluminum
	Selective heat sintering (SHS)	Thermoplastic powder
	Selective laser sintering (SLS)	Thermoplastics, metal powders, ceramic powders, glass
	Direct metal laser sintering (DMLS)	Almost any metal alloy
Laminated	Laminated object manufacturing (LOM)	Paper, metal foil, plastic film
Powder fed	Directed Energy Deposition	Almost any metal alloy
Wire	Electron beam freeform fabrication (EBF^3)	Almost any metal alloy

Figure 32 Overview of various AM techniques in manufacturing industry. Source: (Ma, Wang, & Ju, 2018)

4.4. 3D printing in the construction industry

In recent years 3D printing has gained more attention in the construction industry. While the 3D printing techniques discussed earlier for the manufacturing industry are highly suitable for creating small-scale high-resolution objects with various types of materials, the construction industry has very different demands in terms of scale, strength, function and material. The high geometrical freedom, low waste production and possibility to customize construction materials have led to the development of three main AM techniques for the construction industry: D-shape, Contour crafting and Concrete printing (Ma et al., 2018). The following subchapters give a brief description of each technique and mention the advantages and disadvantages of each technique to be used for in-situ restoration of gypsum-based materials. Finally, the three techniques will be compared, and one technique will be selected based on criteria defined for in-situ stucco ornament restoration.

4.4.1. D-shape

D-shape is a printing process for large scale 3D printing and has been used successfully in construction projects. A large 3D printer uses a magnesium-based binder to bind powder particles (usually sand) to form stone-like geometries (Ma et al., 2018). A D-shape printer typically consists of a frame made from four legs in four corners of a printing bed. Horizontal beams run between these legs to create a square or rectangular base above the printing bed. A collection of many printer nozzles is mounted on a gantry system that can drive over the beams of the square/rectangular base in X and Y direction, while the entire square/rectangular base can move in the Z direction along the four legs (see Figure 33) (Ma et al., 2018).

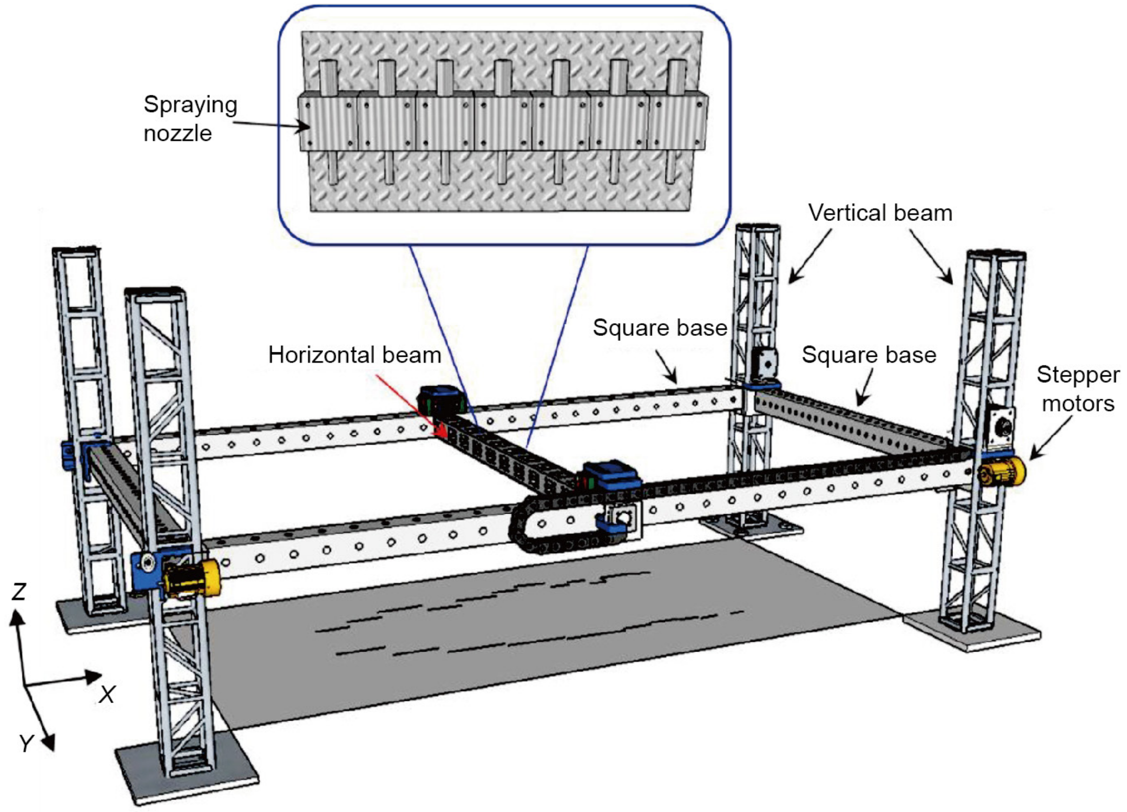


Figure 33 Schematic illustration of D-shape 3D printer. Adopted from: (Ma et al., 2018).

The first layer of powder is spread out in the desired thickness over the printing bed, after which the gantry moves over this layer. The gantry system can have hundreds of nozzles which selectively spray the binder onto the desired spots of the powder layer when the gantry moves overhead. After a layer has been sprayed, a new layer of powder is deposited over the previous layer and the process is repeated until the desired geometry is fabricated. The powder, which is not sprayed with the binder, acts as a temporary support for the built geometry, which means no extra supports need to be printed with this 3D printing system. It also means D-shape offers a very high level of form freedom and all the leftover powder can be removed and re-used as well. This technique relies on a large gantry system with hundreds of nozzles on a long beam to deposit and inject the powder. Additionally, this method relies on gravity to keep the new layer of particles in place before the binder liquid sticks them in place, therefore this method cannot be used to print in any print orientation other than vertically down and thus seems unfeasible for in-situ AM.

Advantages:
- High level of form freedom
- No printed support geometry required
- Support powder can be re-used

Disadvantages:
- Relies on gravity to keep powder layers in place: not possible to print on an inclined printing bed.
- Mobile platform for inside buildings seems unfeasible.

4.4.2. Contour crafting

Contour crafting is a large-scale extrusion-based AM technique used in the construction industry. It involves extruding cementitious or clay-based materials out of a nozzle which has two trowels mounted onto the sides to create planar geometries with a smooth finish (Ma et al., 2018). A contour crafting printer typically consists of such a special nozzle, mounted on the end of a multi-axis robot arm. This arm allows the nozzle to move in the X and Z direction, while two sliding support structures allow the nozzle to be guided in the Y direction (see Figure 34) (Ma et al., 2018). When creating walls, such as the ones shown in the in-situ construction project in Figure 34, the external edges are created first, after which the middle of these walls is filled by pouring in another material (Ma et al., 2018). If only the multi-axis robot arm is used without the entire gantry system, this technique could potentially be made into a mobile platform which can be moved into a building.

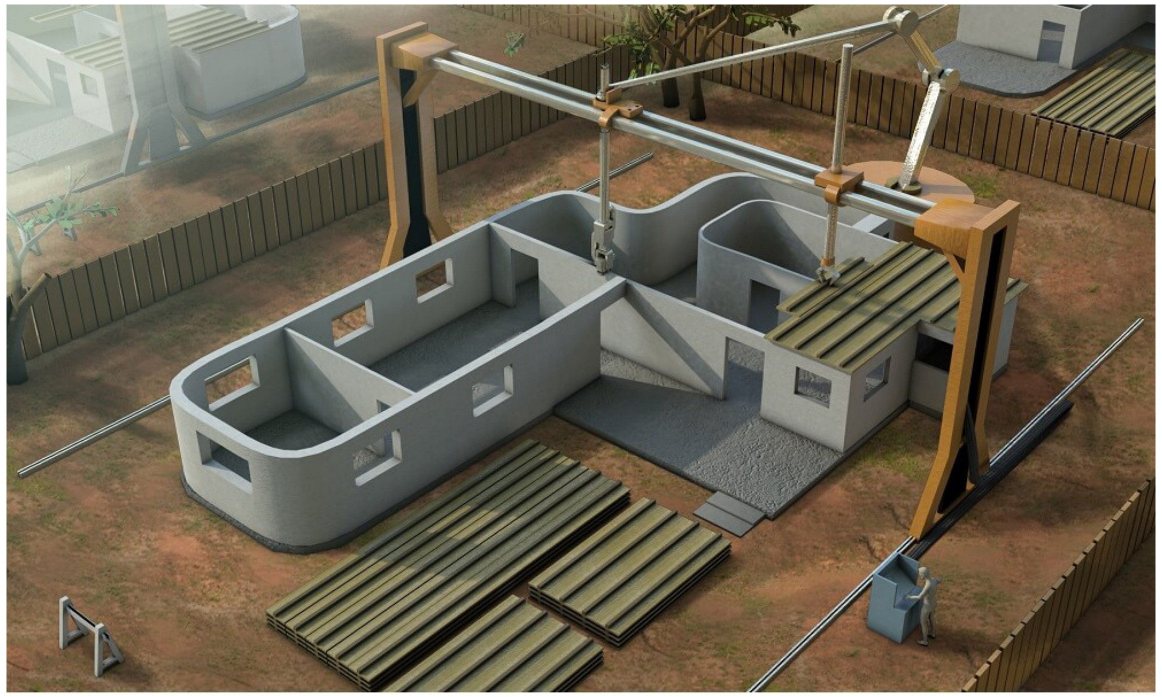


Figure 34 Illustration of contour crafting. Adopted from: https://www.sculpteo.com/blog/2018/06/27/3d-printing-for-construction-what-is-contour-crafting/

Advantages:
- Smooth surfaces achievable
- Possible to operate on-site
- Mobile platform for inside buildings seems feasible.

Disadvantages:
- Limited to planar geometry surfaces, which makes complex double curved surfaces difficult to produce.
- Large overhangs not possible without temporary supports.

4.4.3. Extrusion-based (concrete) printing

Extrusion based printing is a very similar technique to contour crafting and is widely explored with concrete mixtures as well as clay mixtures. A mixture is extruded out of a nozzle, which can be mounted on a gantry system similar to that of a contour crafting printing system or on a multi-axis robot arm as shown in Figure 35. The printing nozzle of a concrete printer, unlike the nozzle of a contour crafting printer, does not have trowels mounted on its sides (Ma et al., 2018). Other than this difference, the two techniques are similar. By using a nozzle with a smaller diameter and using a small layer-height, the resolution of a concrete printer can be increased, giving this technique the ability to produce detailed with a high degree of form freedom geometries (Ma et al., 2018). Given a 6-axis robot is equipped with a concrete printing extruder, it seems potentially feasible a mobile platform could be made for this technique.

***Figure 35** Concrete 3D printing with a 6-axis robot arm. Adopted from: https://www.bam.com/nl/pers/persberichten/2019/1/primeur-weber-beamix-en-bam-infra-openen-3d-betonprintfaciliteit*

Advantages:
- High level of detail possible with small nozzles
- Possible to print on inclined and uneven printing beds when using a 6-axis robot arm.
- Possible to operate on site.
- Mobile platform for inside buildings seems feasible.

Disadvantages
- High level of detail and small nozzles mean long printing times
- Large overhangs not possible without temporary supports.

4.5 Additive Manufacturing techniques selection

Figure X gives a summery and overview of the three discussed 3D printing techniques used in the construction industry. The figure can be used to compare various characteristics of these techniques to help deciding which type of technique is most suitable for the in-situ AM application.

Table 2 Similarities and differences of largescale AM process in construction

	Contour crafting	D-shape	Concrete printing
Process	Extrusion based	Selective binding	Extrusion based
Support	Vertical: no Horizontal: lintel	Unused powder	A second material
Material	Cementitious material	Sand	High performance concrete
Printing resolution	Low (15 mm)	High (0.15 mm)	Low (9–20 mm)
Layer thickness	13 mm	4–6 mm	5–25 mm
Print head	1 nozzle	Hundreds of nozzles	1 nozzle
Nozzle diameter	15 mm	0.15 mm	9–20 mm
Printing speed	Fast	Slow	Slow
Printing dimension	Mega-scale	Limited by frame (6 m×6 m×6 m)	Limited by frame

***Figure 36** Summery of 3D printing in construction. Adopted from: (Ma et al., 2018)*

To choose a suitable AM technique for in-situ restoration of stucco ornaments, several criteria must be considered, which can be used to assess the presented 3D printing techniques:

- Printing material: Can gypsum be used as printing material with this manufacturing technique?
- Printing on inclined printing bed: Can this technique accommodate printing directly onto a wall or ceiling?
- Resolution: Can this technique achieve a high printing resolution?
- Double curved shapes: Can this technique be used to create double curved/non-planar shapes?
- Mobility potential: Is this technique suitable to made into a mobile platform?

	Contour crafting	D-shape	Extrusion based
Printing material	YES	YES	YES
Inclined plane	YES	NO	YES
Resolution	NO	YES	NO
Double curved shapes	NO	YES	YES
Mobility potential	YES	NO	YES

Figure 37 compares the three presented AM techniques in the construction industry with respect to the

Figure 37 *AM techniques vs. criteria for restoration by means of in-situ AM. Source: Author*

criteria for in-situ stucco ornament restoration. It is evident that Extrusion based 3D printing has the potential to meets most of the criteria. In concrete printing, the layer height is limited to 5-25mm and the printing resolution is limited to 9-25mm, which is not high enough of a resolution for creating highly detailed ornaments. However, extrusion based printing with gypsum-based mixtures could possibly achieve higher resolutions due to the fact that such mixtures have a lower viscosity and can be made by using finer aggregates than concrete mixtures. Even though D-shape is a technique that can achieve a very high resolution (0,15mm) the main issue with this technique is that it cannot be used to print on inclined planes as the powder layer would slide off if the printing bed is tilted. Contour crafting is suitable to create planar geometries with smooth edges due to the trowels mounted on the nozzle. However, this makes it unsuitable for creating double curved geometries as the trowels would scrape along geometries unwantedly. Theoretically it may be possible to have movable trowels that adjust their angle according to the toolpath and shape of the printed object. This could be explored in a future study but goes beyond the scope of this research.

4.6. Multi-axis robots

To bring AM to the restoration site, a versatile, movable and robust machine is required. Multi-axis robots offer much of the required versatility, movability and robustness and are the choice of preference for developing the on site AM methodology. The following chapters will explore these machines' hardware, software, operation and application possibilities for in-situ AM.

4.6.1. Hardware

There are two main types of multi-axis robots: Industrial robots and Collaborative robots. Industrial robots are typically large, strong, heavy, bulky and robust. They are made to have long cycle times before needing maintenance, so they are built to be very tough. Being built to be tough comes at the price of being heavy and being heavy comes at the price of needing strong motors and a lot of power to be operated. Industrial robots are often used in fully automated manufacturing lines in factories and perform tasks such as welding, ironing, painting, pick and place etc, which they can do in high speed and with high precision (Robotics Online, 2020). The car manufacturing industry is a good example of an industry where industrial robots have replaced human workers almost completely in the production line.

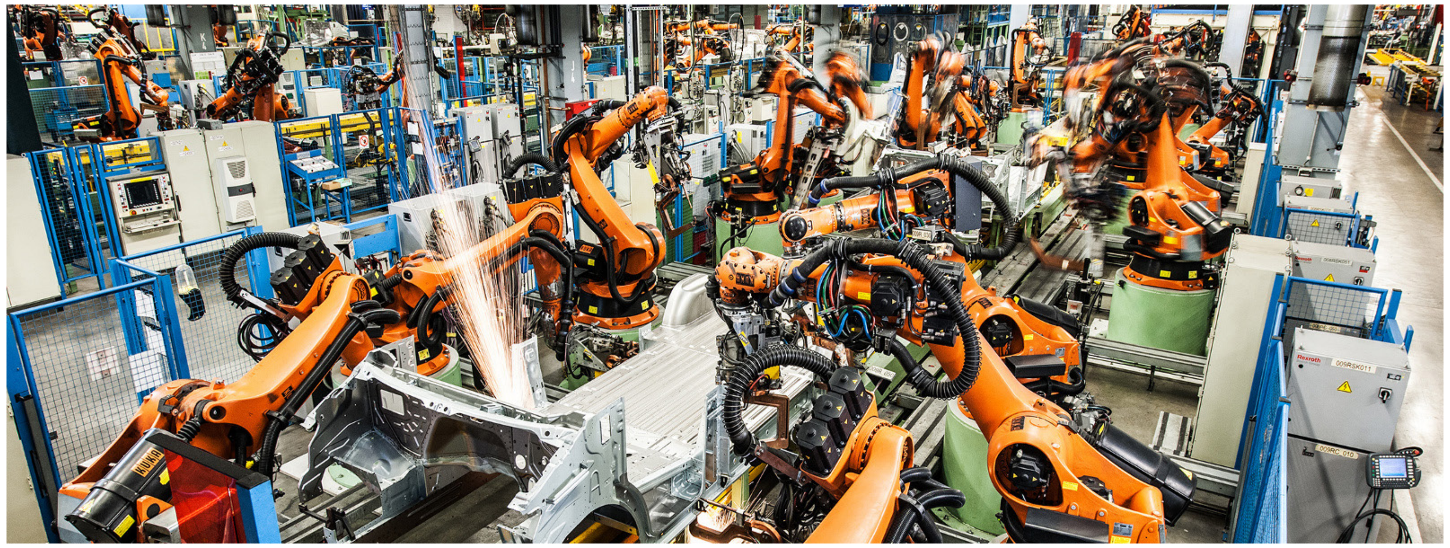


Figure 38 *Industrial Robots from KUKA building cars in a Mercedes Benz factory. Notice the human-less work floor and the many fences placed around the robots for safety of humans.*

Collaborative robots, also referred to as “Cobots”, are usually smaller, lighter, weaker and less bulky as compared to their industrial counterparts. But the main difference is that collaborative robots are designed to work in collaboration with humans. They can work in a factory or laboratory with human co-workers and can perform tasks which may be too dangerous, tedious or strenuous for humans (Roehl, 2017). Cobots have built in safety-rated sensors, which activate the robots brakes in case the robot would collide with anything or anyone (Thaler, 2017), which make them safe to work in close proximity to humans. The fact that they tend to be smaller, lighter and therefore weaker also contributes to this safety factor. Cobots are applied for applications such as packaging, palletizing, pick and place and inspection.

Figure 39 Industrial Robots from KUKA building cars in a Mercedes Benz factory. Notice the human-less work floor and the many fences placed around the robots for safety of humans.

Both industrial and collaborative robots consist of several joints which are connected by linear elements. The joints are typically made up of servo motors and are connected to each other by linear steel or aluminium parts. A six-axis robot has six individual joints which can rotate. The UR5 collaborative robot from Universal Robots for example can rotate each of its six joints 720 degrees. Robot joints cannot rotate indefinitely even though most servomotors can rotate indefinitely, which sets limitations to the type of movements a robot is capable of. The base joint of a robot can be referred to as the robot's shoulder, while the second, third and next joints can be referred to as the elbow and wrists of the robot. A tool can be attached to the last wrist of the robot to do a certain task. By attaching different tools to the wrist of the robot, the same robot can be used for different type of applications, making robots versatile machines for a wide range of applications. In the last decades, industrial and collaborative robots have been discovered by designers and architects and applications for the built environment are being explored. Though there are examples already of such robots being used for architectural applications, it is important to note that these robots are not originally intended for construction applications. To use robots to their full potential for architecture and construction may require the development of customized robots, specifically suitable for such on site applications.

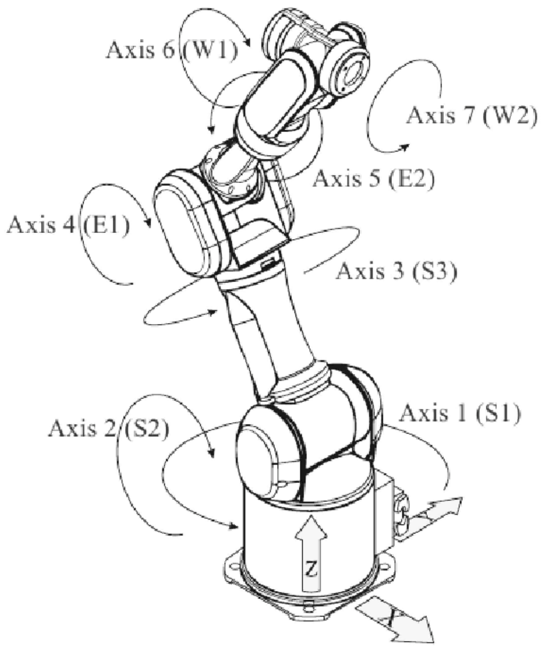


Figure 40 Scheme of 7-axis robot. Adopted from: https://www.researchgate.net/publication/233529256_Decentralized_Neural_Block_Control_for_an_Industrial_PA10-7CE_Robot_Arm

4.6.2.Robot controller & pendant pad

Any industrial or collaborative robot comes paired with a so called "robot controller" or "control box". This robot controller contains various inputs and outputs (I/O) which can be used to couple the robot to a wide range of external equipment such as pneumatic relays or PLC's or emergency stop buttons (UniversalRobots, 2014). The robot is plugged into the robot controller for power and the robot controller is plugged into a power outlet. Depending upon the robot used, this power outlet can be a standard 220V wall socket outlet, which would be beneficial if a robot is to be used inside homes or other type of non-industrial buildings. To control and interact with the robot manually, a tablet, known as a "pendant" is part of the robot controller. With the use of such a tablet, the user can interact with the robot by teaching the robot to do certain tasks by moving it around and allowing it to remember certain waypoints. The next chapters will go more in depth about how this programming works.

Figure 41 UR5 collaborative robot with robot controller and pendant. Adopted from: https://www.robots.com/robots/universal-robot-ur5

4.6.3. Robot movement fundamentals

Consider the UR5 robot, which is a 6-axis collaborative robot from Universal Robotics. A 6-axis machine means that the robot has three movement axes (moving in X, Y and Z) and three rotational axes (rotation around X, Y and Z-axis). This means that theoretically, a six axis robot can reach any point within its working range from any angle. In the case of the UR5, this means that it can roughly reach any point inside a sphere with radius of 850mm around the middle of its base joint, from any angle. To reach a point, the six motors which control the six joints of the UR5 have to work together to move the robot from one point to another.

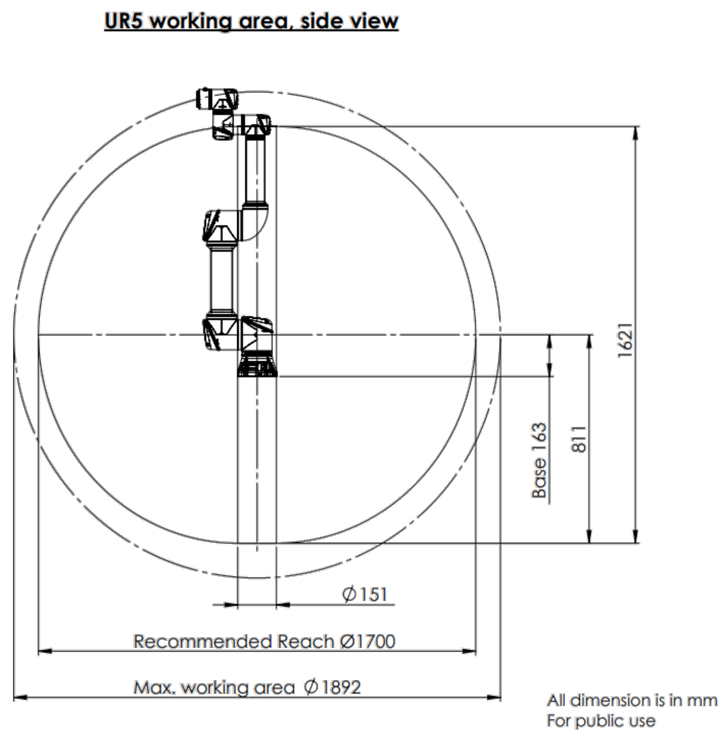


Figure 42 UR5 working range. Source: https://www.universal-robots.com/articles/ur-articles/what-is-a-singularity/

Fundamentally, there are three ways of calculating the movement of a robot between two waypoints. Waypoints are predefined points in space which the robot can visit by programming instructions. The first movement type is called “MoveL” and describes a linear movement between two given points (Skovsgaard, 2018). So, MoveL is a movement type which tells the robot to move in a straight line between the two waypoints. This means, that the Tool Centre Point (TCP) will move in a straight line between the two waypoints. In case of 3D printing, the TCP is the tip of the nozzle, in case of milling, the TCP would be the tip of the milling bit. Essentially the TCP is the point which is directly interacting with the workpiece. In order to move the TCP in a straight line between two waypoints, all motors on the robot must move in coordination with each other in order to keep the TCP in a straight line, which is achieved through advanced mathematical calculations that generate the instructions for the motors to turn.

A robot such as the UR5, moves by rotating its motors, which means the nature of its movements are curved and round (Skovsgaard, 2016). You can imagine a viper of a car to visualize this, the viper tip moves from one end of the windshield to the other in a curved motion, because the viper arm rotates around one point. The aluminium “arms” connected between the motors of the UR5 allow the robot to move in cartesian space through the rotation of the motors. This is important to keep in mind to understand the second type of movement, which is MoveJ, a is non-linear movement. Typically, MoveJ is the standard movement setting for robots (Skovsgaard, 2018), as it is usually the fastest and easiest way to move for a robot given the curved nature of the robot’s movements. The MoveL moves the TCP in cartesian space (so in x, y, z), while MoveJ moves the TCP in join-space (so by determining motor joint rotations). MoveJ is the standard movement setting because most robots are made for assembly line work and for tasks such as “pick and place”, where it is important to pick and place the object from-and at the right location, but the movement in between does not have to specified. MoveL can have limitations when two waypoints are programmed such that the robot would have to go through itself to reach the second point in a straight line. MoveJ can avoid such collisions, however you do not have control over how the robot will move exactly between the two points. Therefore, for applications like AM, where the robot will be following a set path for continuous printing to generate the ornament geometry accurately, MoveJ is not suitable.

The third type of movement is MoveP, which is a circular motion within a movement from one point to another. Such a movement type could be used for applications like robotic weaving, where the robot makes circles around protruding pins with a thread. For AM applications MoveP is unsuitable.

It is important to realize that robots follow either MoveJ or MoveL from waypoint to waypoint. So, if you want to 3D-print a curved line, the robot will move from point to point on the curve with MoveL or MoveJ. Since with MoveJ the path is not predictable, MoveL is preferred for the AM application. However, MoveL is a linear movement, so to create a curved path, the curve must be divided into many individual waypoints so the robot can move through those waypoints to create a smooth looking curve. By adding more waypoints, the robot program contains more instructions for the robot and thus becomes heavier. My personal experience in working with the UR5 robot, has shown that the robot cannot handle instructions which contain tens of thousands of waypoints, so a balance must be found between geometrical accuracy and the length of the robot program. This must be experimentally determined.

4.7. Programming & Simulation

A variety of different software programs are available to interact and program industrial and collaborative robots. Some examples are Xamla, Visual Components and RoboDK. Some of these software programs are tailored to specific applications. Visual Components is tailored towards programming and visualizing factory manufacturing applications for example. For this research, RoboDK is used for programming the robot for AM applications. RoboDK has a simple interface, does not require any prior programming knowledge to use it and works seamlessly with other CAD and parametric design software like Rhinoceros and Grasshopper.

Simple manual teaching

When using a robot for simple pick and place type of applications in a factory or lab setting, the programming of the robot can be done in a very simple way, without the need of any prior programming knowledge or external software tools. The robot can be manipulated using the pendant touchpad in the “Move” menu (see Figure 43). It is possible to assign waypoints by pressing the “Teach” button. With the various move controls, it is possible to move the robot to another position and by again pressing the “Teach” button, the robot learns the new waypoint. It is also possible to move the robot arm manually into a desired position and then press the “Teach” button for the robot to learn new waypoints. This approach is suitable for teaching a robot simple pick and place type of tasks. The path that the tool (which in the case of pick and place applications could be a gripper) mounted on the robot, has to follow is known as the “toolpath”. The toolpath of a robot picking up an object from one table and placing the object on another table is simple and can be manually taught (see Figure 44). However, teaching a robot to 3D print complex shapes of ornament, this approach is unsuitable. To teach a robot to follow complex, precise and long toolpaths, the robot must be programmed with a robot programming software.

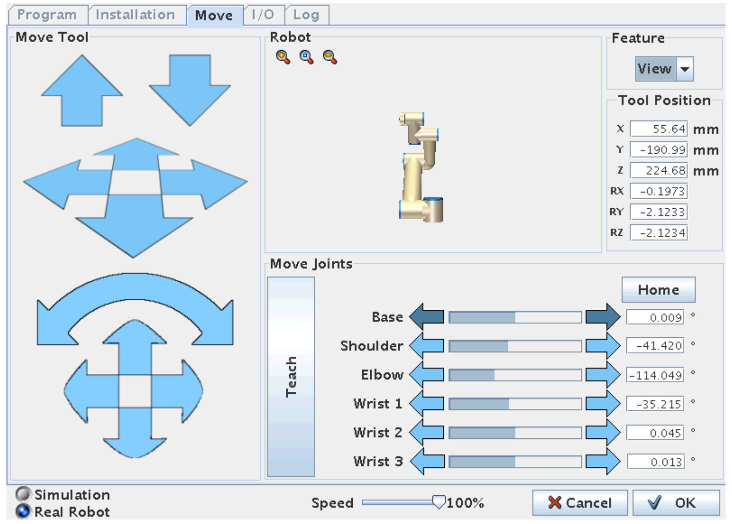


__Figure 43__ Move menu for UR5. Notice the various moving options. Source: https://www.zacobria.com/universal-robots-knowledge-base-tech-support-forum-hints-tips/knowledge-base/basic-ur-teach-waypoints/

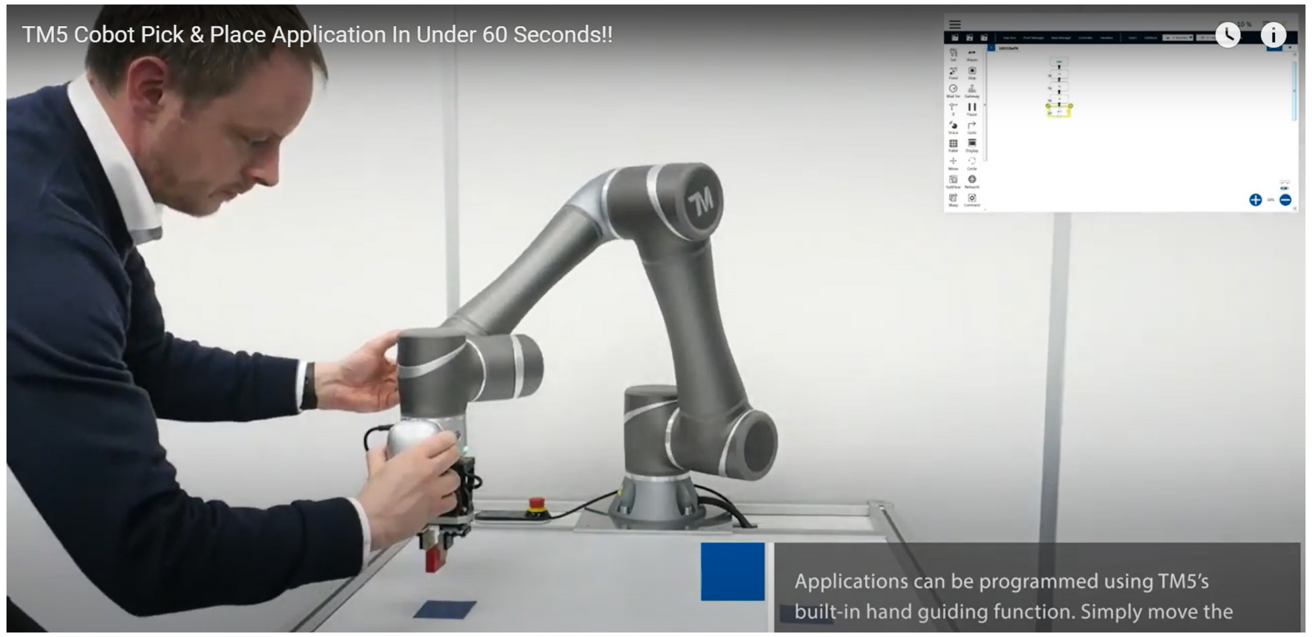


__Figure 44__ Manual teaching for pick & place application. Source: https://www.youtube.com/watch?v=qM-OHMFFKVU

4.6.5. RoboDK workflow

This subchapter will briefly describe the general workflow when programming a robot with RoboDK. A RoboDK file, is called a “station”. When creating a new station, the first thing you can do is select the robot you are using by opening the online robot library. You can also search for a robot you want by using several filters such as brand, weight, payload, repeatability, number of axis etc. In this example, we are choosing the UR5 robot.

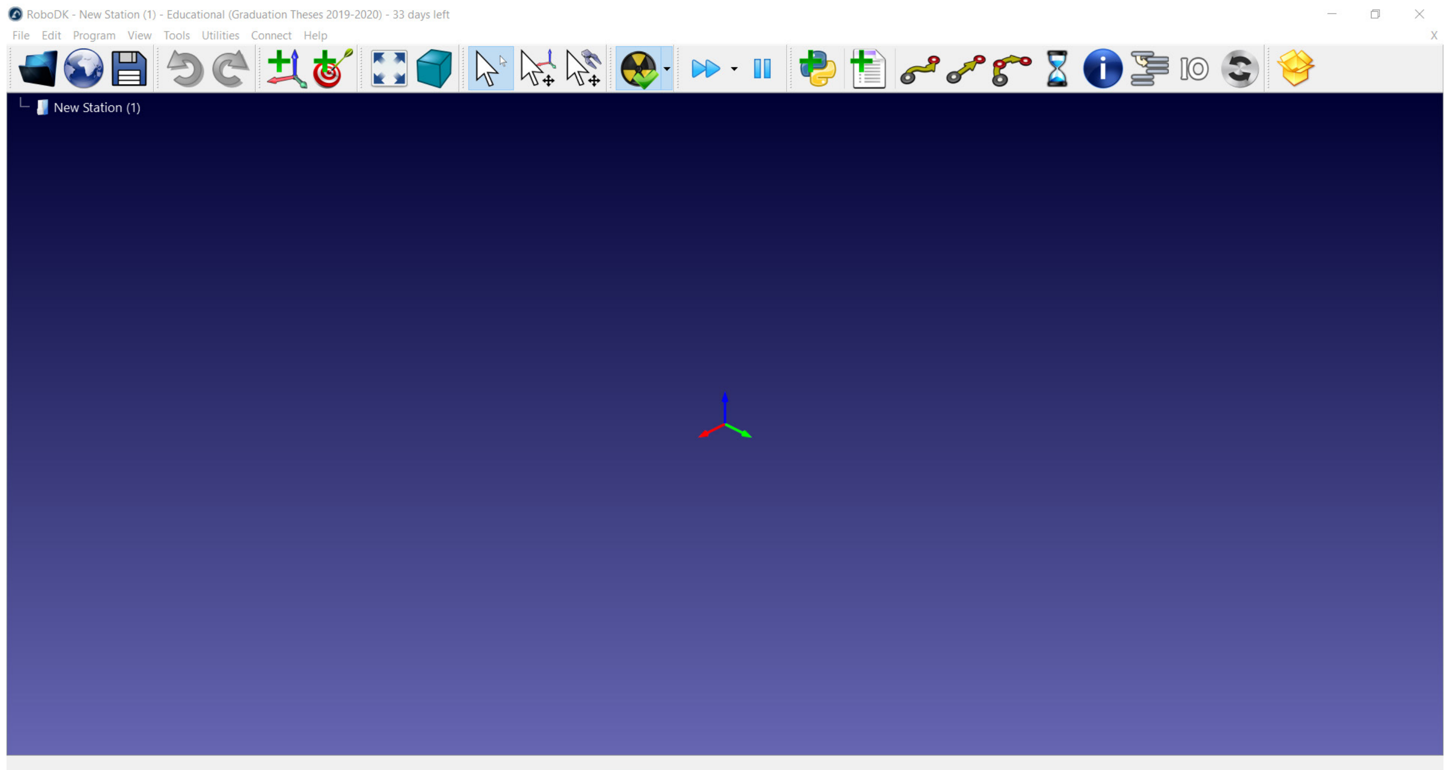


Figure 45 Home screen of RoboDK. Source: author.

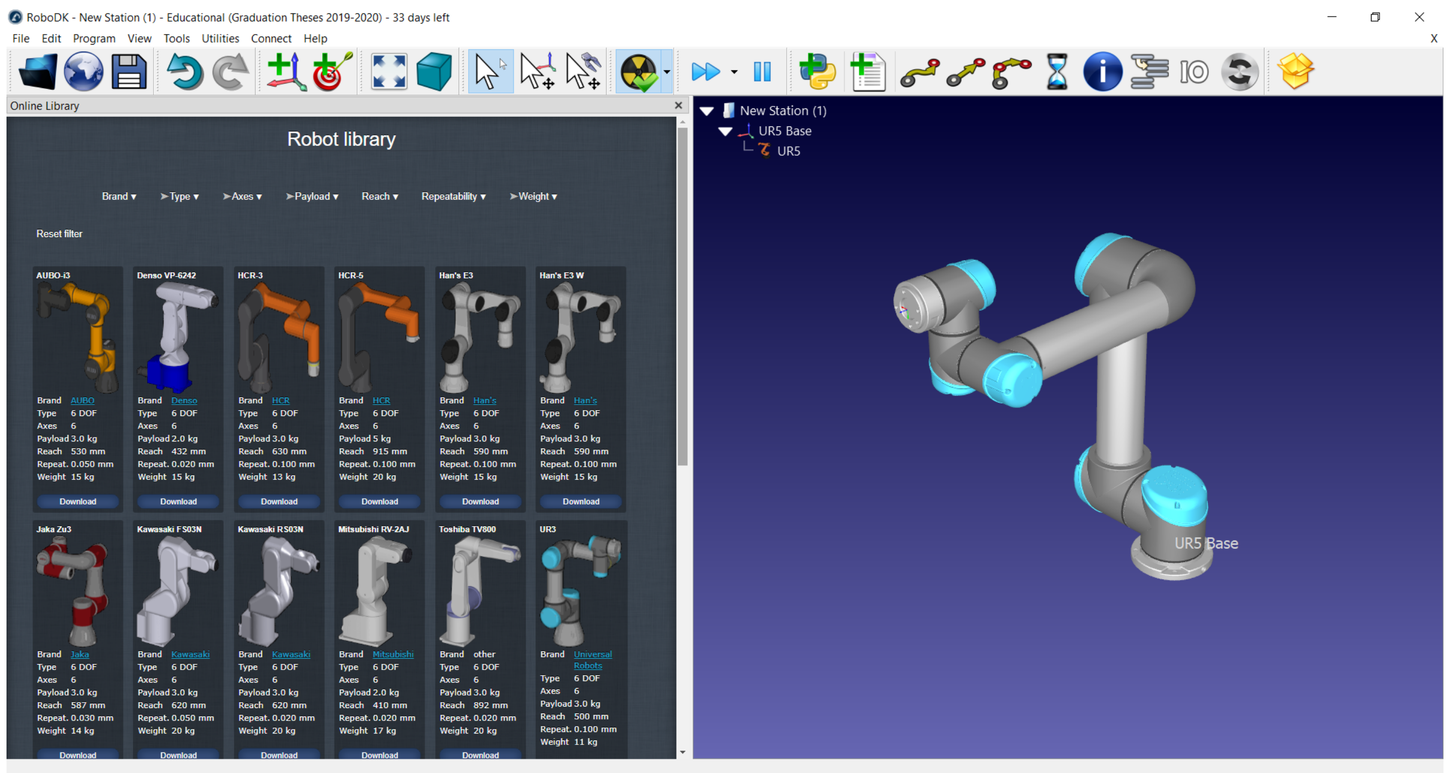


Figure 46 Online Robot Library. Notice the UR5 base frame and UR5 robot in the program tab middle left top. Source: Author

Once the robot has been selected, it will appear in the main viewport as well as in the program tab (see Figure 46) on the top left. Along with the robot, the UR5 base reference frame will also be created. This reference frame is basically creating a coordinate system within which the robot can be programmed. This reference frame is taking the centre of the base of the UR5 as its origin and the red, green and blue arrows indicate the X, Y and Z axis respectively. Another reference frame is created at the end of the last wrist of the robot, which without a tool connected to the robot, acts as the robot TCP. This reference frame creates a local coordinate system for the TCP of the robot and if the TCP point is moved anywhere, the robot’s motors will rotate to accommodate the movement of the TCP, while the base of the robot remains fixed.

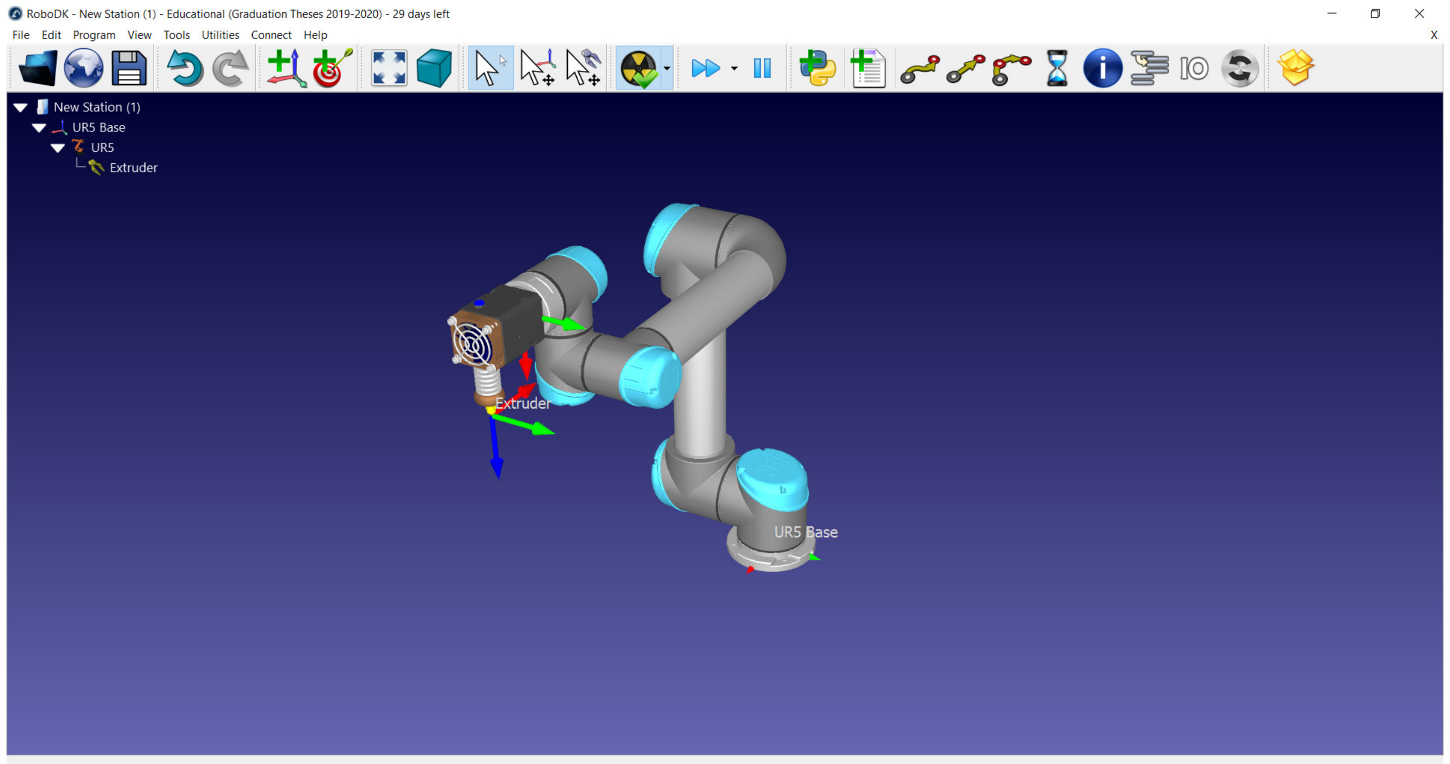


Figure 47 UR5 with extruder tool attached. Source: author.

A tool, such as an extruder, can be attached to the robot by importing the CAD file of the tool as an .OBJ file. After doing this, the tool must be fixed to the wrist of the robot. This can be done by aligning the origin of the reference frame of the tool with the origin of the reference frame of the robot TCP. Once this is done, the new tool TCP must be defined. This can be done by simply moving the TCP reference frame relative to the robot wrist until the origin of the TCP reference frame is at the tip of the extruder tip. In this example, the tool TCP is located by moving the TCP first in the blue axis and the in the red axis. Notice that axes of the TCP are rotated, compared to the axis of the robot. It is recommended that the blue axis (which is the Z-axis) should always be pointing away from the tool to make moving and programming easier. Now that the robot and extruder are ready, the 3D print geometry can be imported into RoboDK. In the example, we will use a simple curve generated in Rhinoceros design software. By installing the free “RoboDK” plugin for Rhino, it is easy to export geometry to RoboDK by simply clicking “export curve to RoboDK” and selecting the station you are using in RoboDK (see Figure 48).

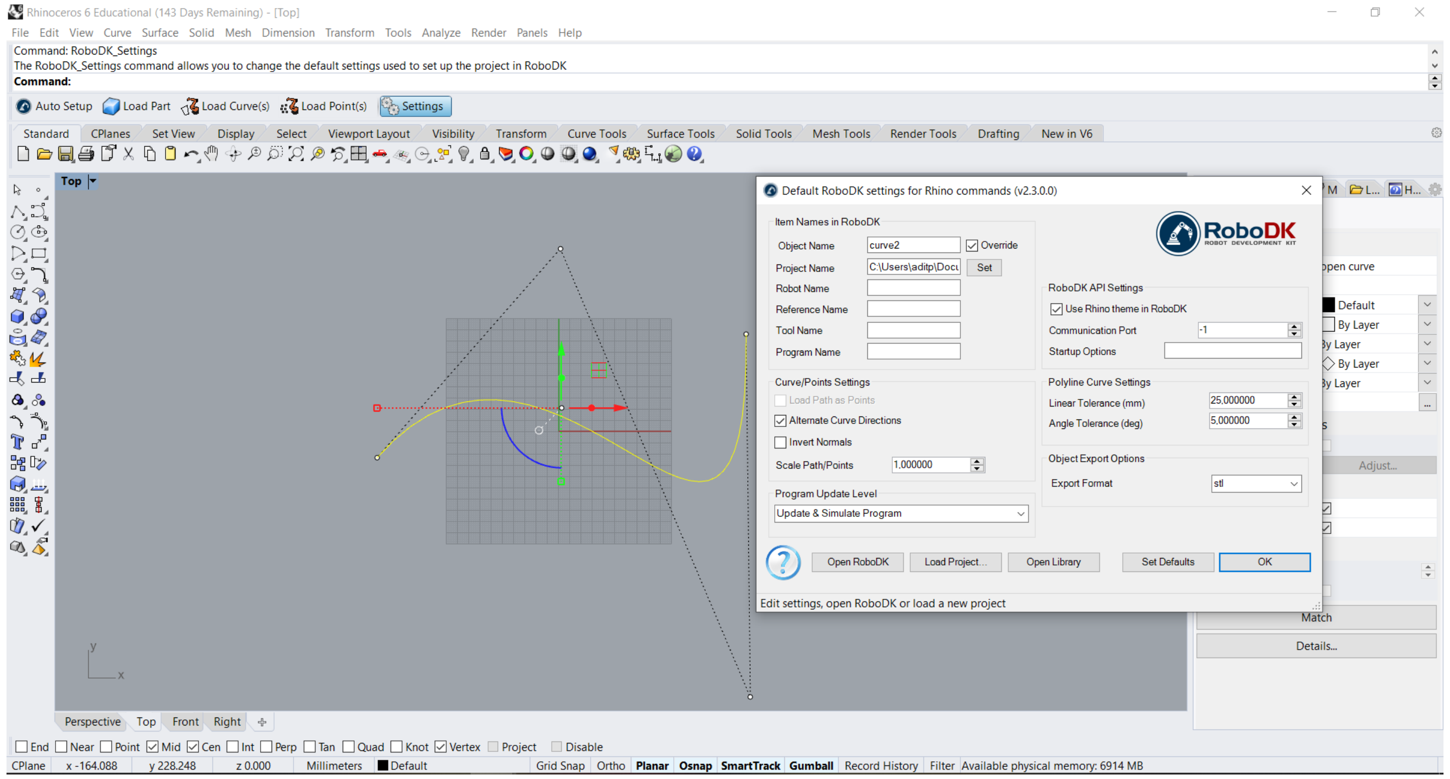


Figure 48 Rhinoceros with RoboDK plugin for easy geometry export. Source: author

In RoboDK you will notice the geometry, which has been named “curve2” appears in the main viewport and also in the program viewport on the top left (see Figure 49). It is automatically placed under the UR5 base reference frame. Notice an additional reference frame called “Reference Rhino” is imported as well. This is the reference frame from Rhinoceros design software itself. You can move the robot closer to the Curve2 geometry if necessary.

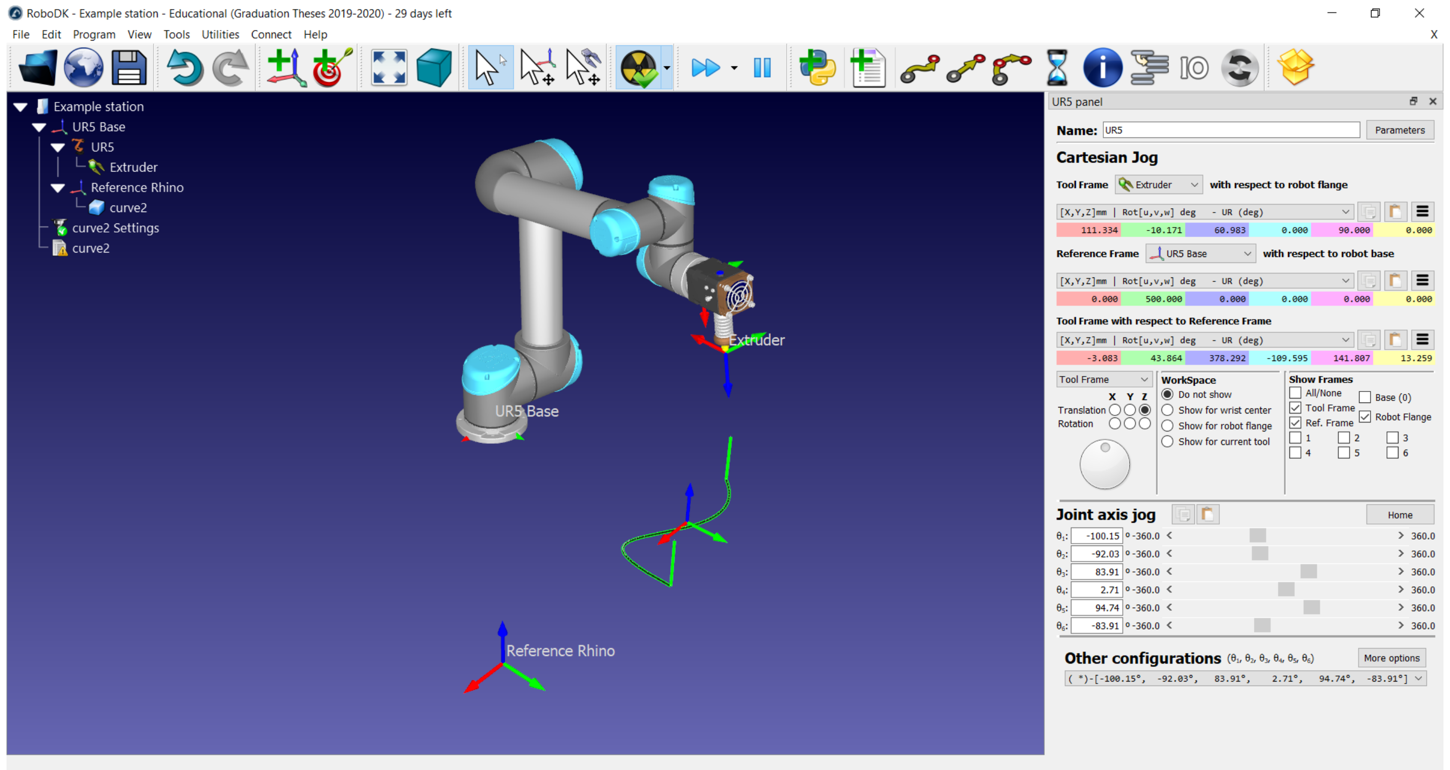


Figure 49 Print geometry imported into RoboDK. Source: Author.

You can also notice a “curve2 Settings” tab on the top left. This is the robot programming tab with which you can control the toolpath of the robot (see Figure 50). A toolpath is the path that the robot will follow to complete an automation task, which in this case will be to follow the curve with the tip of the extruder tool to simulate 3D printing. After opening the curve2 settings tab, a window with several options appears.

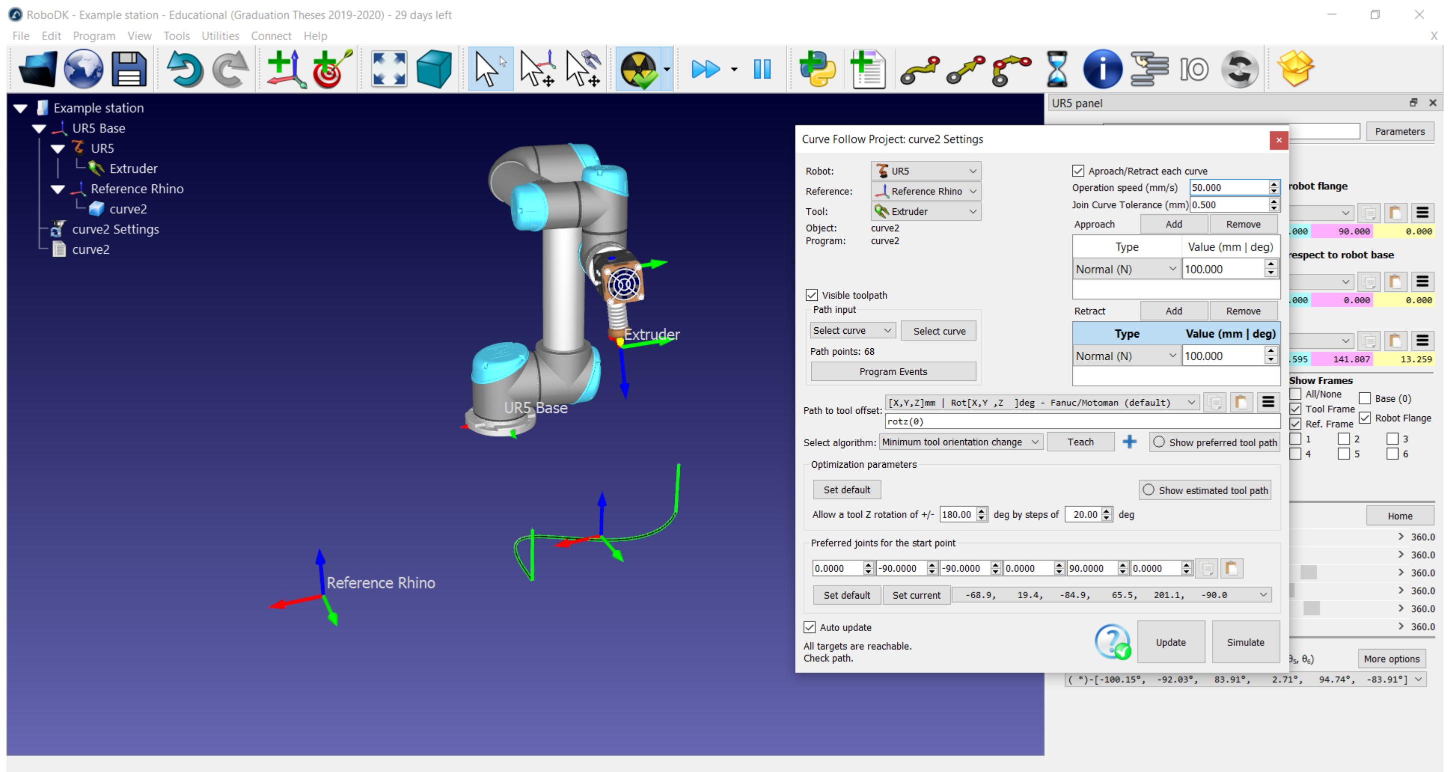


Figure 50 Toolpath settings tab for curve2. Source: Author.

You will notice that the curve2 geometry has two additional lines added in vertical direction at the start point and endpoint. These are the approach and retract paths for the robot to approach and retract away from the curve. From this tab, various path settings can be controlled such as the length of these approach and retract paths and the speed at which the robot should move along these paths (see Figure 50). The approach and retract is an important path parameter when in restoration, because when 3D printing on a partially damaged ceiling, often the printing substrate will not be flat and smooth. The robot must therefore avoid colliding with any protruding parts of the ceiling. Imagine there would be two of such curves that the robot would print, but there is a part of another in-tact ornament protruding 100mm from the printing substrate (ceiling) in between these two curves. The robot must avoid colliding with this protruding part and so the approach and retract distances can be set such that they are always larger than maximum protruding distance of objects in the workspace. RoboDK also has a collision check feature, which will be briefly explained later.

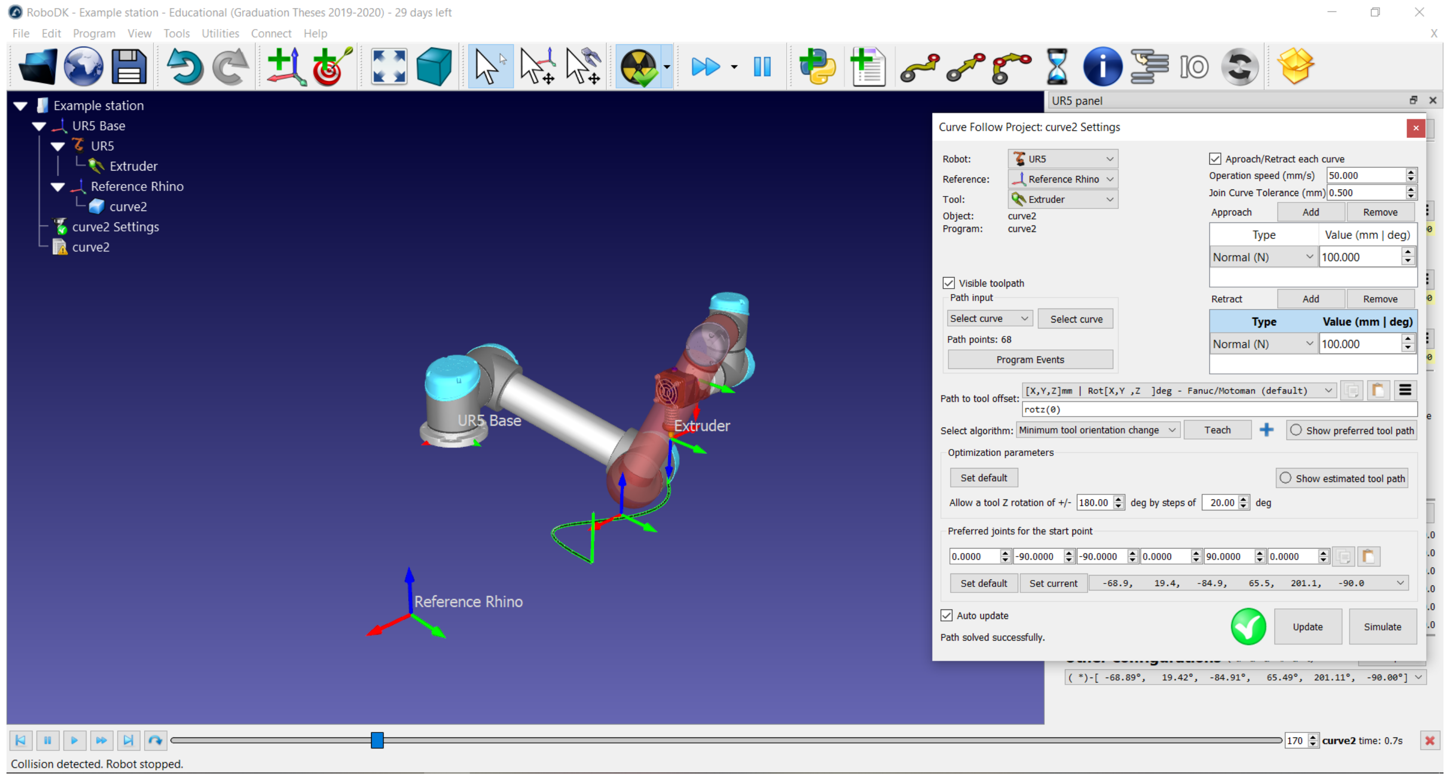


Figure 51 Robot colliding with itself during simulation. Source: Author.

The curve2 Settings tab allows to control more such settings for the path creation, which can be explored in more detail on the website of RoboDK. For in-situ AM the approach and retraction paths may be the most relevant to mention. After these settings are finalized, the program can be updated with the update bottom and the toolpath can be simulated with the simulate button. If there are any problems in the robot path, it will be shown after simulating the created path. In the example shown in Figure 51 there is a problem: the robot is colliding with itself. A simple method to avoid this, is to select a different start joint position for the start point. This can be selected in the “Preferred joints for the starting point” tab (see Figure 52). You can cycle through various options for joint positions provided by RoboDK for the given starting point, or you can manually set preferred joint positions yourself. You can check if the new program has any collision issues by updating the program with the newly selected preferred joint positions and simulating the program.

It is also possible to important other objects into RoboDK, such as the room in which the robot is operating or a scan of the ceiling. RoboDK has a collision checker function. By assigning the ceiling geometry and room geometry as collision objects, RoboDK can check if anywhere in the robot path, the robot will collide with an object that has been assigned as a collision object.

As an example, a small black box, called “box 1” has been imported into the station. The box has been placed close to the robot and curve2. In the collision map menu, visible in Figure 53, the settings have been turned onto check for collisions between box 1 and all the joints on the robot as well as the extruder. Now if a path is created and the robot or extruder is colliding with box 1, the program will show this error. Again, by changing the preferred start joint positions a different path can be generated, avoiding collisions between the robot and box 1. There are also more advanced methods to create collision free paths, by assigning target points to where the robot can move in between printing individual parts etc. However, the above mentioned method can provide a good initial approach to collision avoidance.

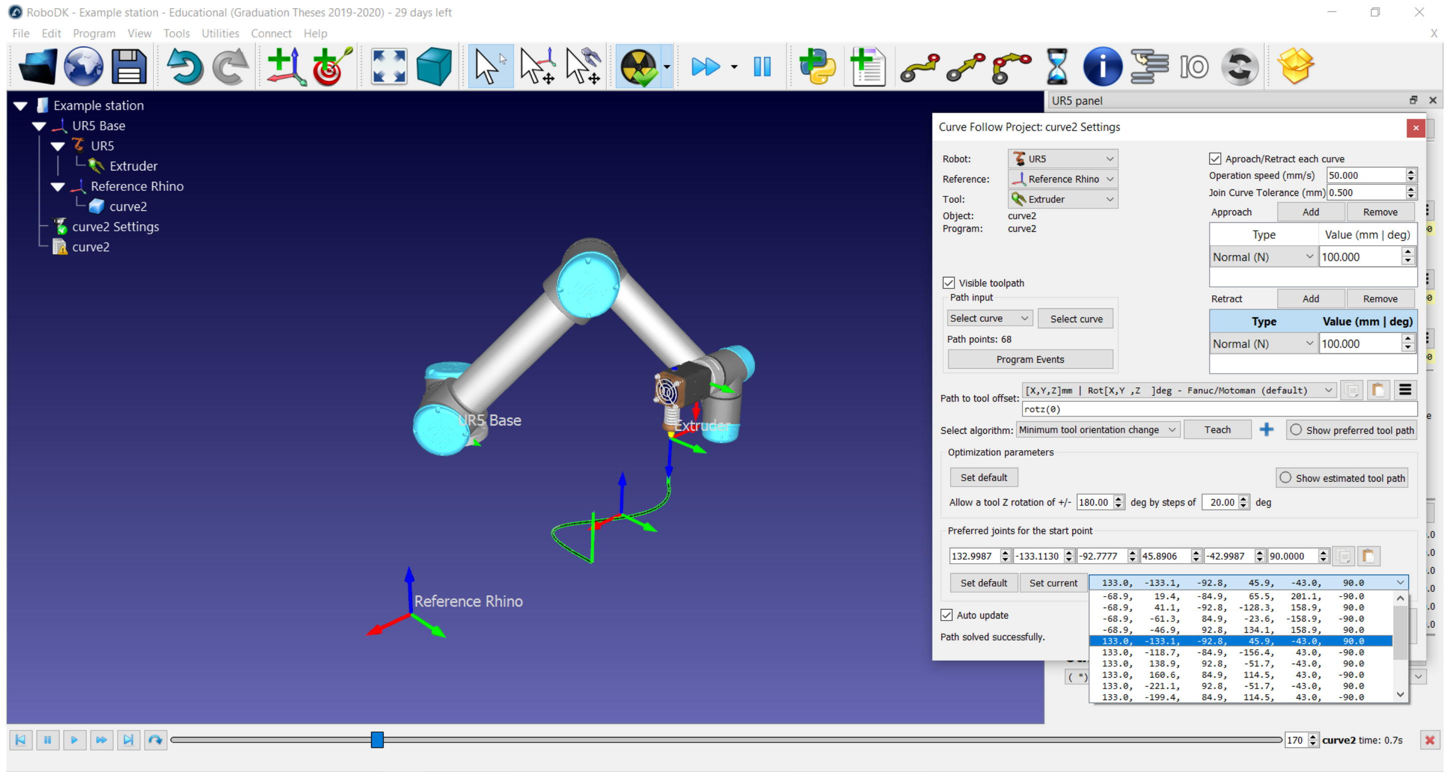


Figure 52 Select different preferred joints for start point to avoid self-collision of the robot. Source: Author.

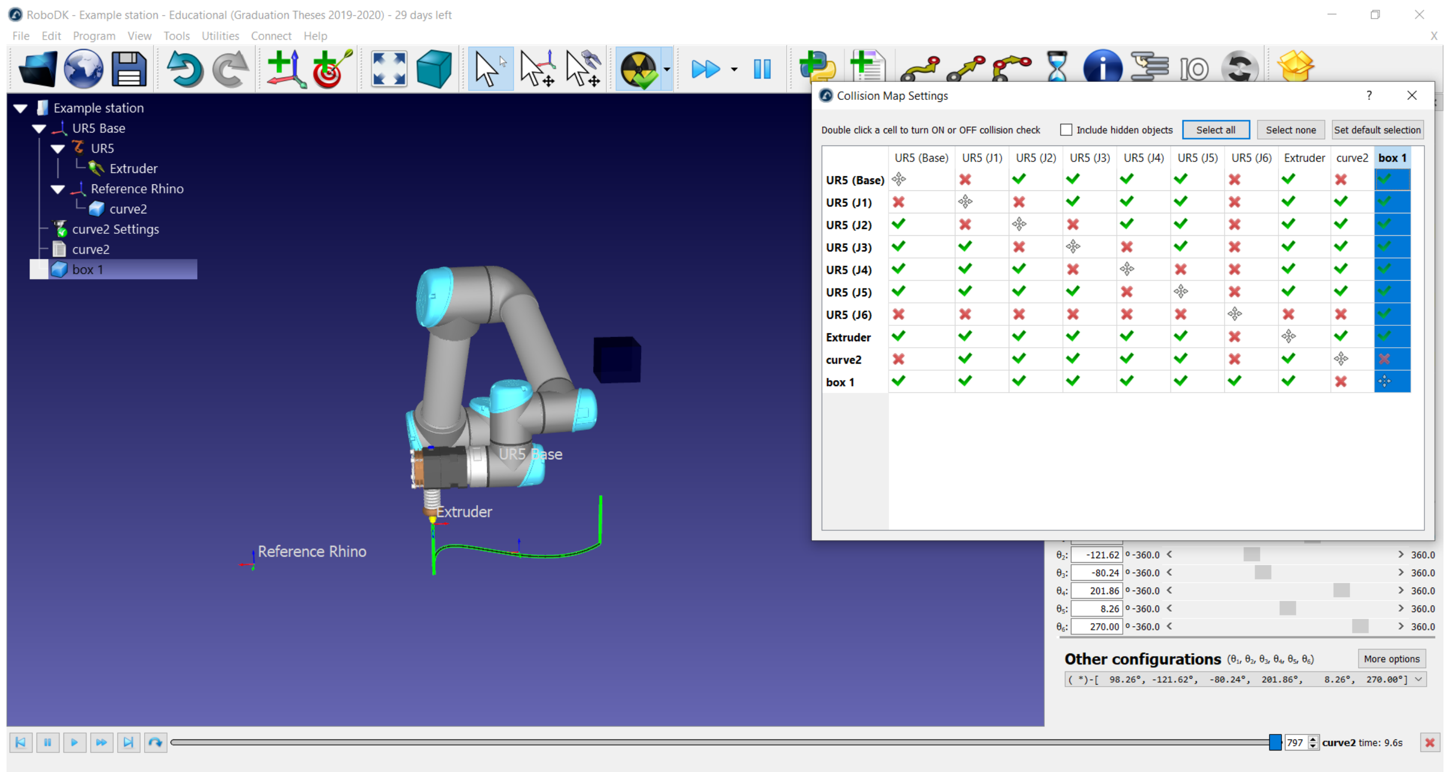


Figure 53 Collision check assignment menu with detection of collisions between box 1 and robot & extruder are turned on. Source: Author.

A final note on this matter is that the 3D scan data of the ornaments and surrounding objects can help to create a collision free map. By determining the length in Z-direction of the furthest downward protruding element on the ceiling, the approach and retract paths can be assigned, but the position of the robot during the printing process can also be determined. If through simulations it is evident that the robot is colliding with protruding elements on the ceiling, then perhaps the robot can be moved down a little bit, which will decrease the chance of collisions between the robot and any protruding elements on the ceiling.

4.8 Robot calibration

Calibration and alignment of the robot for any task is an important step, especially when working in new environments. Calibration means "the documented comparison of a measurement device against a traceable reference device" (Beamex, n.d.). In the context of robot calibration, it is the alignment of the virtual coordinate system with the physical coordinate system. Put in more simple words, the robot must be told where it is positioned on site and where exactly it should 3D print the ornament on the ceiling. The geometry of the ornament which it is supposed to 3D print, initially only exists virtually. This virtual model must be given an exact location in the physical world, so the robot will know where it should 3D print this geometry. If this information is not precisely told to the robot, then it cannot restore the ornament properly.

Robot calibration involves many steps and is a procedure which starts at the very beginning, before creating the 3D scan and finished all the way the end, right before the robot can start 3D printing on site. Therefore, the calibration procedure is part of the overall Digital Fabrication for restoration methodology.

Before the 3D scanning of the damaged are of an ornamented ceiling is done, 3 physical reference points or "markers" must be placed on the ceiling in the vicinity of the damaged area. These physical markers could be as simple as needles which can be easily pushed into the ceiling and also easily be removed from the ceiling. It is important that the markers chosen will not leave any mark behind after they are removed to prevent any damage to the original ceiling. This must be kept in mind when choosing a type of marker. The purpose of placing the three markers is to create a physical coordinate system which can be used to align a virtual coordinate system to. By placing the markers in such a way that a right angled triangle can be formed in between them, it is possible to draw virtual lines between them. The line between two points form an X-axis and the line perpendicular to this line forms the Y-axis. The Z-axis can then be virtually constructed by creating a virtual line perpendicular to the XY plane. In this way, a virtual XYZ-coordinate system can be created, which is connected to the three physical markers on site.

After the markers are placed, the 3D scan can be done. The 3D scan should include the three markers as well, to create a so called "virtual twin" of them. Next the point cloud acquired from the 3D scan is converted into a mesh and later is "digitally repaired" by interpolation as described in chapters 1.2. and 1.3. After this, the repaired geometry, which is to be 3D printed on site, can be brought into the RoboDK environment along with the virtual markers. Next the printing geometry is prepared for 3D printing with the help of a slicer software and the robot path is calculated in RoboDK.

Once the robot is brought on site the actual robot calibration process can be performed. To do this, there is a variety of different calibration methods, such as manual calibration, Bulls-eye calibration, Calibration by Force Control, Laser LAB and more (Bergström, 2011). These different calibration methods all have their advantages and disadvantages, some being highly accurate but at the cost of requiring additional equipment and or being expensive and time consuming, while others are relatively fast or inexpensive and don't require additional equipment but are less accurate. For the in situ AM application, the manual calibration method is considered, since an accuracy of 1mm should be enough and this accuracy should be obtainable with manual calibration method.

The manual calibration method involves moving the robot to reference points which define the work object (Bergström, 2011). In the case of in-situ AM, this means once the robot is positioned underneath the damaged area of the ceiling on site, the TCP must be moved to each marker individually until the TCP touches the end of each marker with as much accuracy as possible.
To do this, it is advised to mount a tapered tool on the wrist of the robot, such as a pen (see Figure 54). Each time the robot is moved to a point where the TCP touches the tip of a marker, this point is saved in the robot's memory as a "reference point". The robot then saves this point's X, Y and Z coordinates, relative to its current position. Next, by overlaying the virtual markers from the CAD file with the newly determined reference points, the virtual world and physical world are aligned with each other for the robot. The robot now knows exactly where it must 3D print the ornament geometry on the ceiling and can now start the AM process. The markers must only be removed at the very end, after the 3D printed ornament geometry has dried and the results are satisfactory.

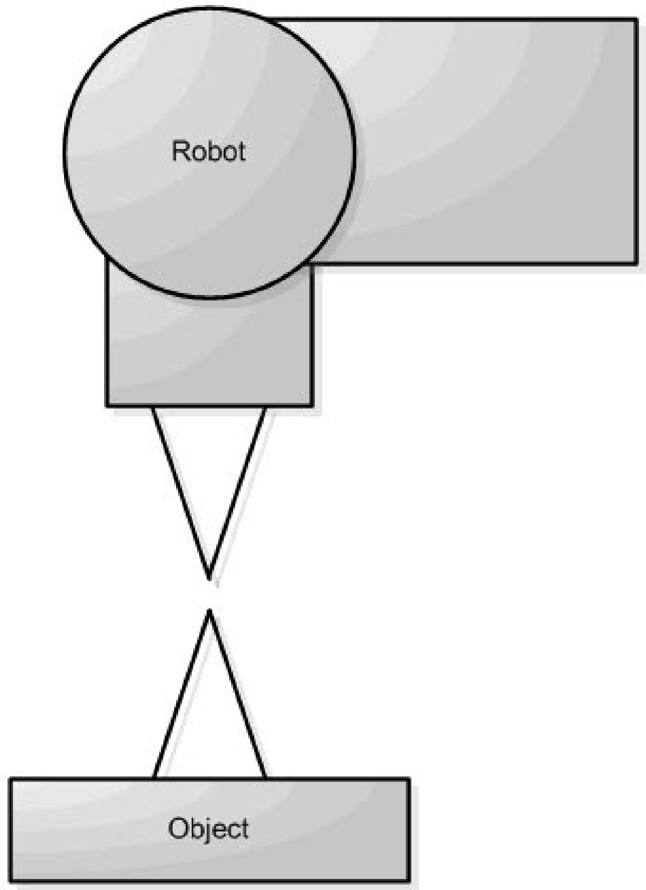


Figure 54 *Manual calibration. Adopted from: (Bergström, 2011)*

4.9. Prospects of Additive Manufacturing

From the previous chapters it is evident what type of existing scanning and AM techniques, hardware and software could be used for restoration of stucco ornaments by means of in-situ AM. Extrusion based printing technique with a multi-axis robot is suitable for this application, while a Pulse 3D scanning system could be used to scan the damaged geometry. RoboDK could be used to generate a safe, collision-free toolpath for the robot. The main gap in knowledge and research exists in creating a gypsum-based printing material and the 3D printing process with such a printing material on an inclined printing substrate. Developing a compatible and printable gypsum-based mixture is one of the main goals of this research. 3D printing on inclined substrates is rarely done, because 3D printing is currently not much explored as a method of in-situ restoration. However, there is one research project which has explored the topic of printing on inclined substrates, or as the researchers call it: Anti-gravity printing.

Mataerial: Anti-gravity printing

Research has been done on so called 'anti-gravity additive manufacturing' at the Institute of Advanced Architecture of Catalonia in cooperation with Joris Laarman Lab design studio. The research aims at developing a method of printing on any given working surface, independently of the surface inclination and smoothness, and without need of additional support structures (Laarman et al., 2014). This is achieved by implementing extremely fast hardening thermo-set resins combined with innovative extrusion technology (Laarman et al., 2014). The project focusses on 3D-printing double curved lines of varying diameter on both horizontal and vertical planes without the need of additional support structures.

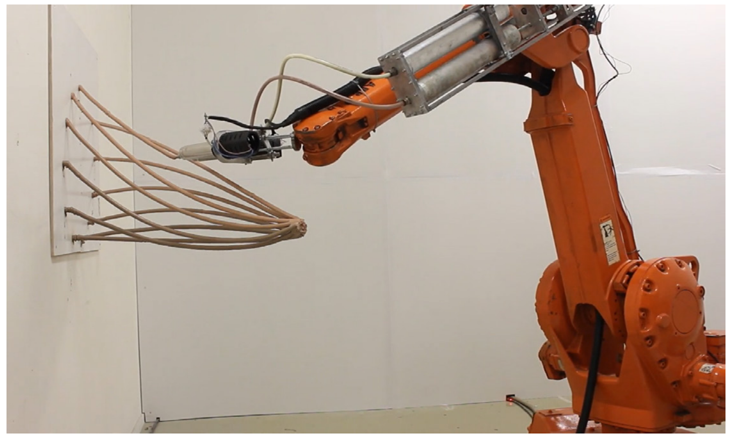


Figure 55 Fabrication on vertical plane. Adopted from http://www.mataerial.com/#3rdPage on 06-12-2019

Figure 56 Material container with two thermo-resins. Adopted from http://www.mataerial.com/#3rdPage on 09-12-2019

This project innovates on three different topics. Firstly, extensive research and testing is done in finding a material combination which can harden extremely fast and gain enough strength to bear its self-weight. Secondly, an extrusion mechanism is designed and built to allow the material to flow out at the right speed and in communication with the robot movement. This is because the speed of the robot and the extrusion speed must have a certain fixed relationship to make sure the material is extruded slow enough, so it doesn't tear and fast enough to avoid it from bundling up at the end of the extruder. This speed of extrusion and thus the speed of the robot are determined by the chemical properties of the thermo-set resins (Laarman et al., 2014). Finally, the project team had to create a custom end effector since a simple extruder would not suffice. To speed up the hardening process of the material, two heat guns were mounted on the sides of the extruder (see figure 8). In the final set-up, the material would harden 1 mm away from the extruder end. The final printing speed achieved was five minutes per meter of printing (Laarman et al., 2014).

For the experiment, the team used an ABB 2400L robot with the custom-made extruding system, material and end effector. In order to allow the extrusion speed and the robot movement speed to be in synch, a customized plug-in was created by the team for Rhinoceros and was scripted in Python programming language. Additionally, the plug-in allowed control over the extrusion thickness by changing the extrusion speed. By extruding the material twice as slow, the extrusion diameter becomes twice as thin (Laarman et al., 2014). The geometries printed could vary between 5 and 15mm in diameter and the printed curves would have a flexural strength of 160 mPa, which is evidently enough to sustain the self-weight.

Figure 57 Extruder with heat guns for rapid curing. Adopted from http://www.mataerial.com/#3rdPage on 09-12-2019

According to the research team this technology brings on-site additive manufacturing closer and, among other things, enables the development of restoration robots (Laarman et al., 2014). It is evident that the material properties are the first base factor of influence in the printing process. The research team did extensive testing to find material combinations which would harden extremely fast. The project shows that chemical properties of the materials and geometry thickness are influencing the material hardening speed and extrusion speed.

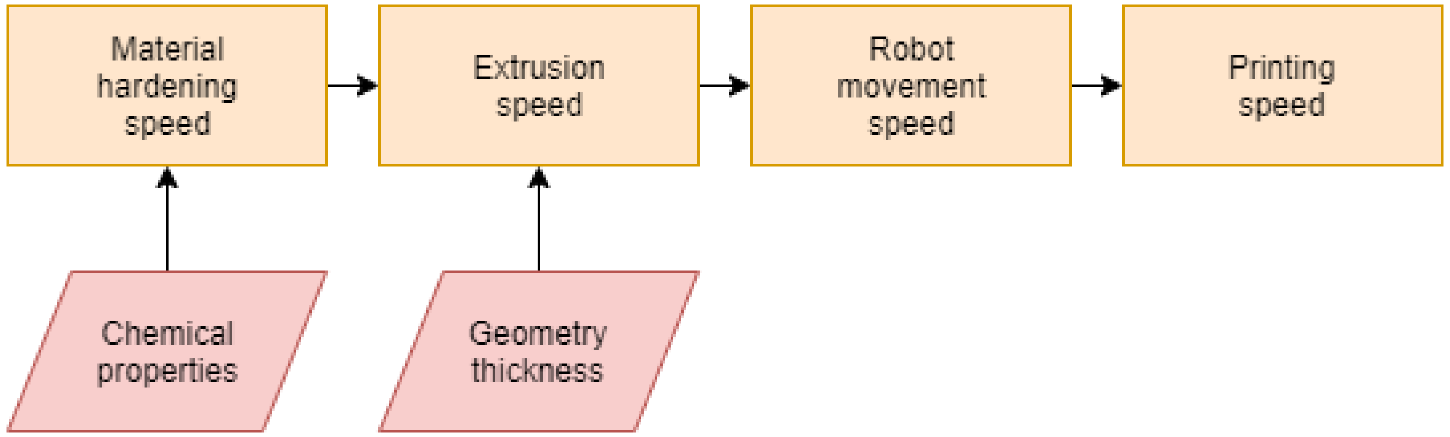


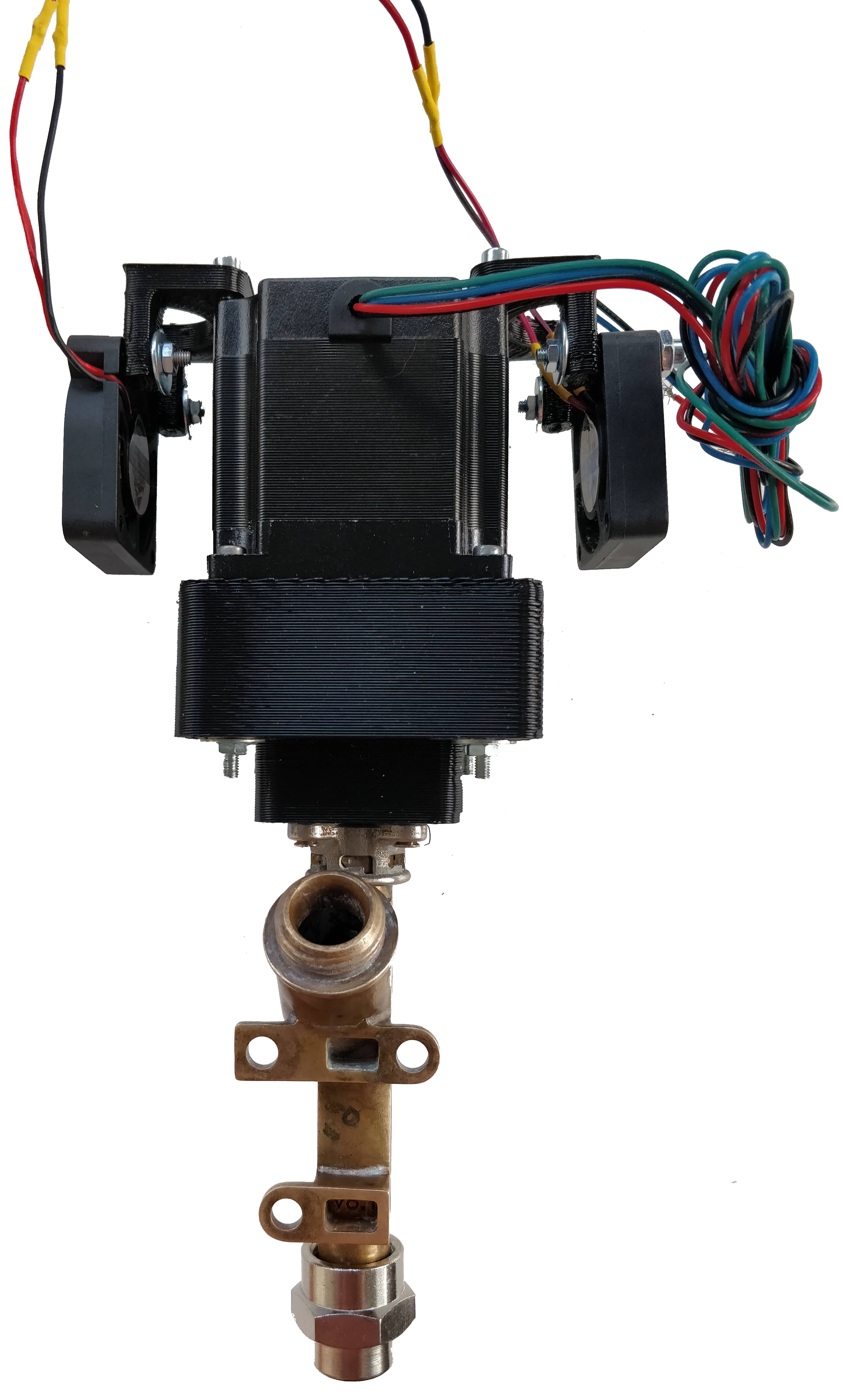
Figure 58 Relationship and order of influence in printing process. Source: Author.

Even though the materials used in this project are very different from materials that would be required for stucco ornament restauration, the project gives some insights into important aspects to keep in mind when trying to print on inclined substrates. Firstly, the material properties form the base constraints. The printing process can only be developed in accordance to the printing material's hardening properties. It is evident that the faster the material cures after it has been extruded, the stronger it gets and the more weight it can support. Heat guns are added onto the end-effector, which accelerate the curing process of this particular material. The principle of the extruded material needing to rapidly gain strength to support its own weight is important to realize for the in-situ restoration application as well.

In order to conduct experiments with various material mixtures designed for 3D printing, various tools must be designed and built, including a material delivery system and extruder. In the next section, the design and assembly of these tools will be discussed.

05.

TOOL DESIGN



5.1. Introduction
Two material delivery systems are explored for the purpose of 3D printing with gypsum-based mixtures: a compressed air-powered system and a mechanical ram system. The first was developed to work with a multi-axis robot and the latter was designed to work with a standard cartesian 3D printer. Even though the two material delivery system rely on a different mechanism, they are similar in that they both push a paste material, in this case a gypsum-based mixture, out of a nozzle. In the following chapters of this section the design, mechanisms and assembly of various components of the material delivery systems are described.

5.2. Mechanical robot extruder
The UR5 robot from LAMA was intended to be used for the 3D printing experiments, therefore the mechanical extruder was designed to work with this robot. The extruder has to be made lightweight (under 5kg) to comply with the maximum payload of the UR5 robot. The UR5 is a lightweight collaborative robot which has 6-axis of rotation and thus can reach any point within its 850mm reach from any orientation (see Figure 60). The different components of the robot extruder and their function will be described in this chapter.

Aspect	Value
Max payload	5 kg
Working radius	850 mm
Weight	20.6 kg
Repeatability	0.01 mm
Protection rating	IP54

Figure 60 *UR5 specifications. Source: Universal Robots*

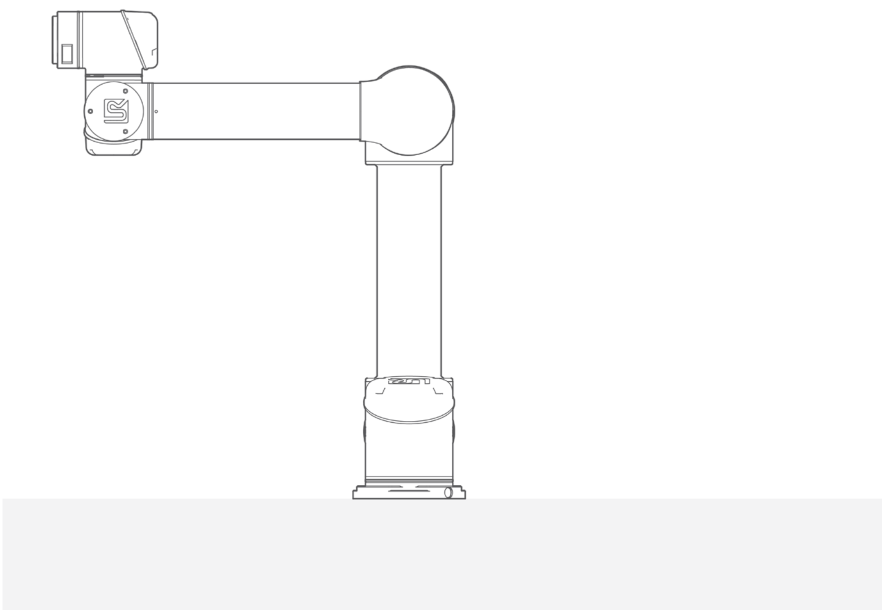


Figure 59 *UR5 robot from LAMA. Source: Author.*

Steel funnel
A steel inlet funnel with three openings. One acts a printing material inlet, the second acts as the inlet for the auger and the third is the end where the printing material is extruded out from.

Stepper motor
To push the material through the steel funnel, a NEMA 23 stepper motor is used (see Figure 62). It has a strength of 12.85kg*cm at an accuracy of 1,8 degrees per step. A stepper motor does not rotate smoothly, but rather moves in steps. The advantage of this is that the amount of rotation and speed can be very accurately controlled, which is essential when very precise amount of material is to be moved through a system as is the case here. This is why stepper motors are commonly used for 3D printers as well, as they provide great accuracy and control.

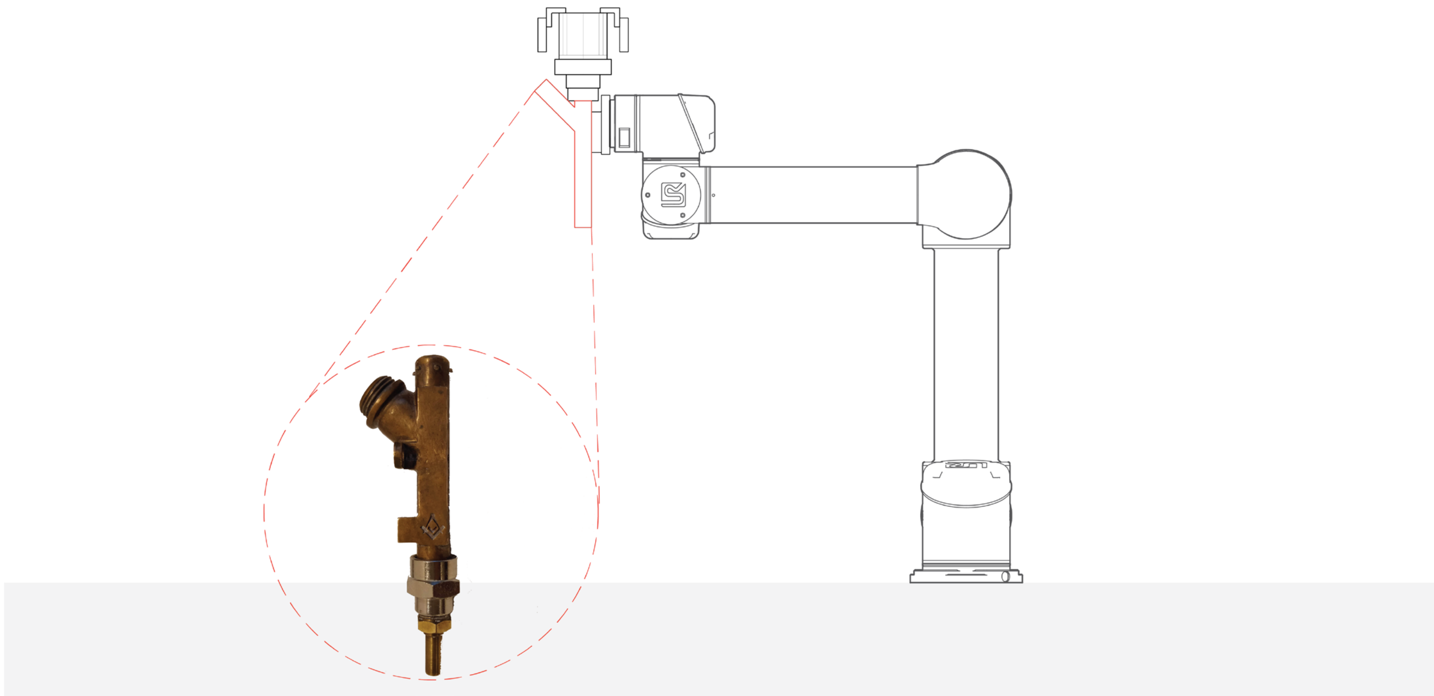


Figure 61 *Steel funnel with openings for material inlet, material outlet and augur inlet. Source: Author.*

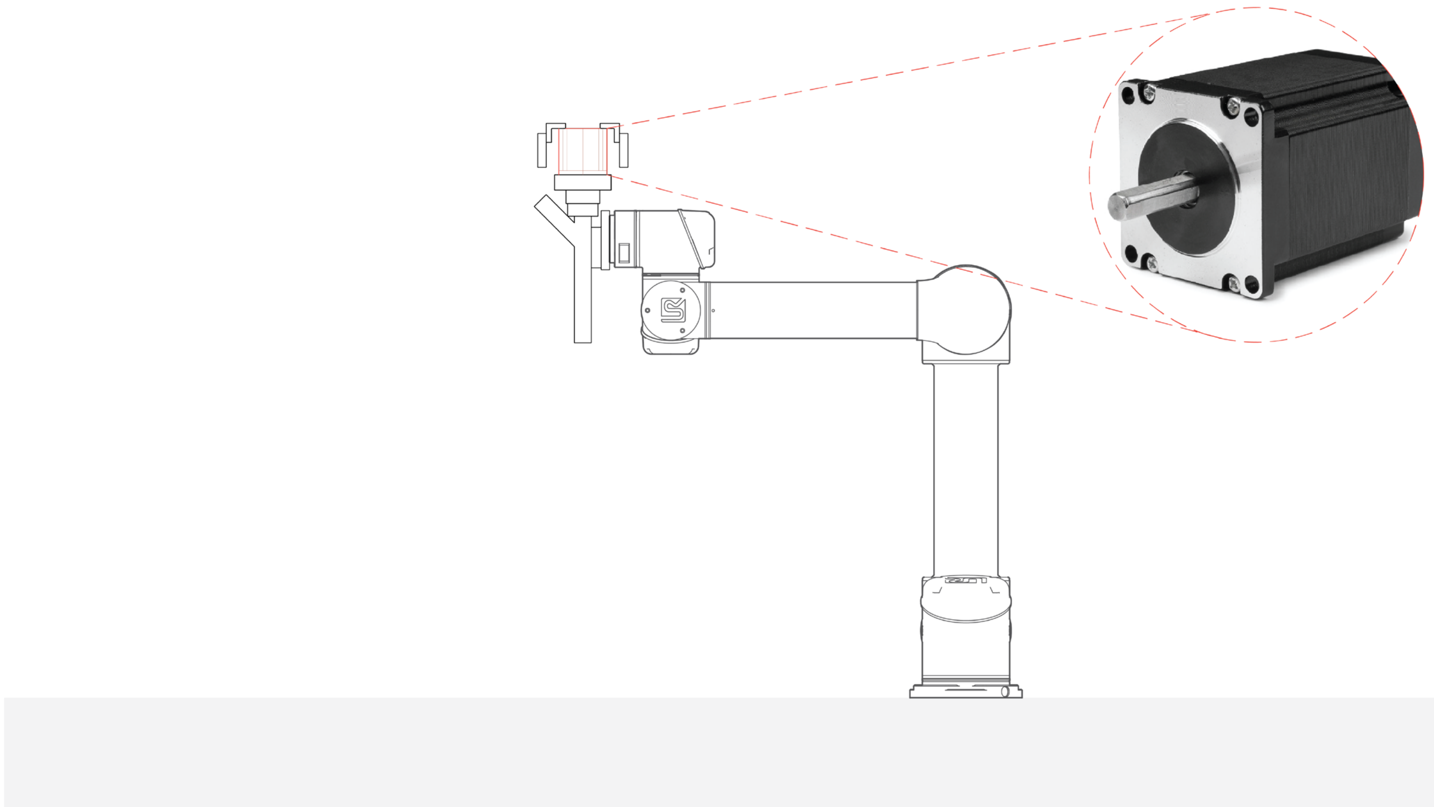


Figure 62 *NEMA23 stepper motor, 12.85kg*cm, 1.8 DEG. Source: Author.*

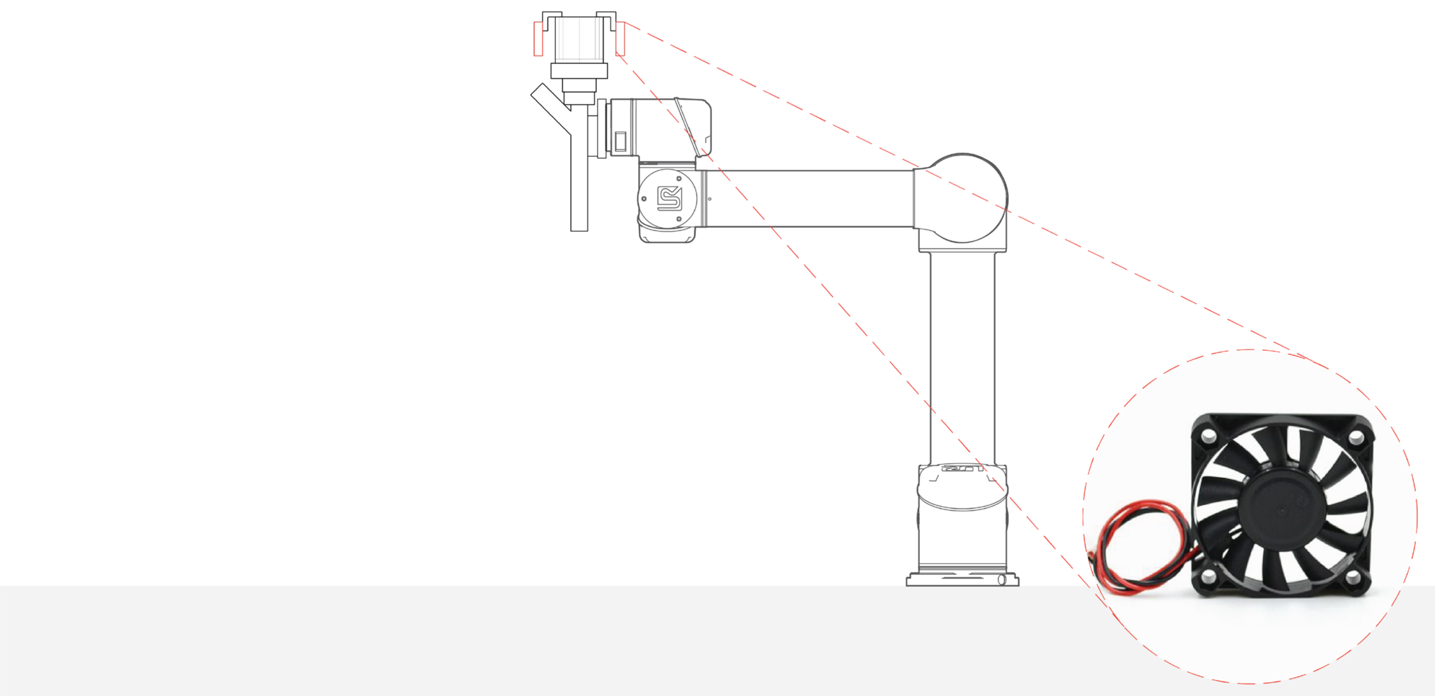


Figure 63 Two 3D printer cooling fans to cool the stepper motor. Source: Author.

Cooling fans

Since the motor gets hot when in use, two 12V 3D printer cooling fans are mounted on the flanks of the stepper motor to cool it (see Figure 63).

Figure 64 Stepper motor to steel funner connector parts, 3D printed in black PLA. Source: Author.

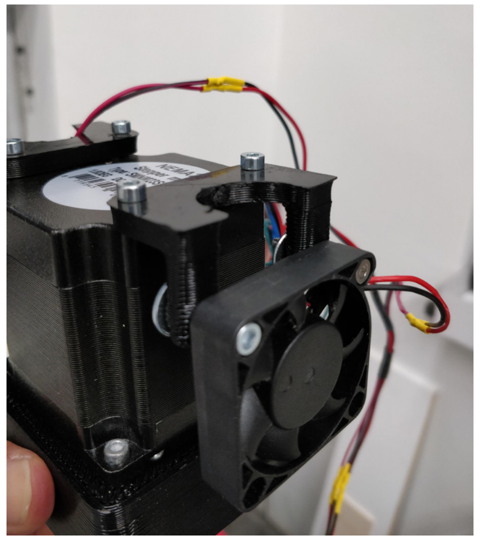


Figure 65 Cooling fan to stepper motor connector part, 3D printed in black PLA. Source: Author.

Augur

An augur with 6mm diameter is connected to the stepper motor with a steel coupling (see Figure 67). By turning the augur clockwise with the stepper motor, any material entering the steel funnel will be moved out from the extrusion end. By turning the augur counter clockwise, the material can be retracted if the extrusion has to be temporarily stopped during the printing process.

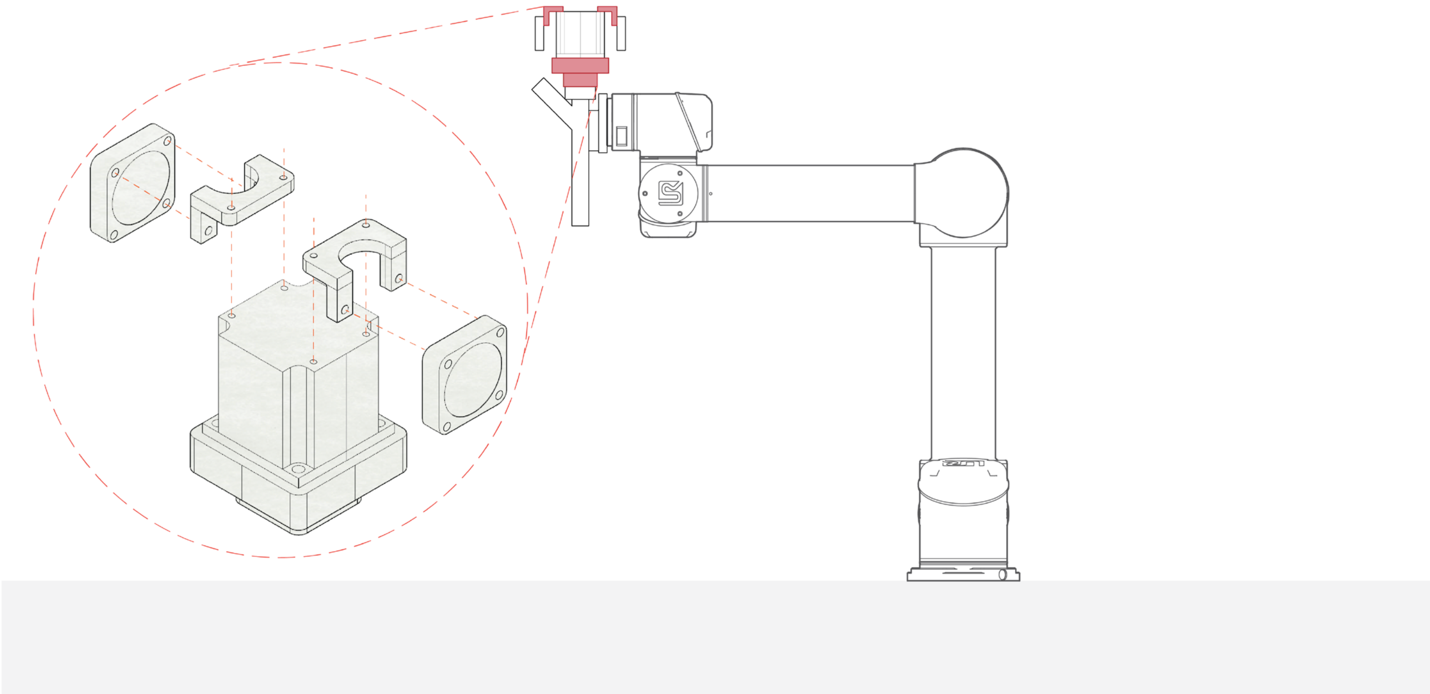


Figure 66 Connector parts connect stepper motor, cooling fans and steel funnel together with bolts. Source: Author.

Connector parts

To connect the steel funnel, stepper motor and cooling fans, three connector parts are designed in Rhinoceros and 3D printed in black PLA (see Figure 66). The largest part connects the stepper motor with the steel funnel with four long bolts. The inside geometry of this part is designed to allow a coupling and augur which connect to the stepper motor to turn freely (see Figure 64). Two small fan connector parts are mounted on the top of the stepper motor with small bolts (see Figure 65). All parts are connected with same sized bolts and nuts for easy assembly and disassembly with one sized Allen key. This makes the extruder easier to clean and maintain.

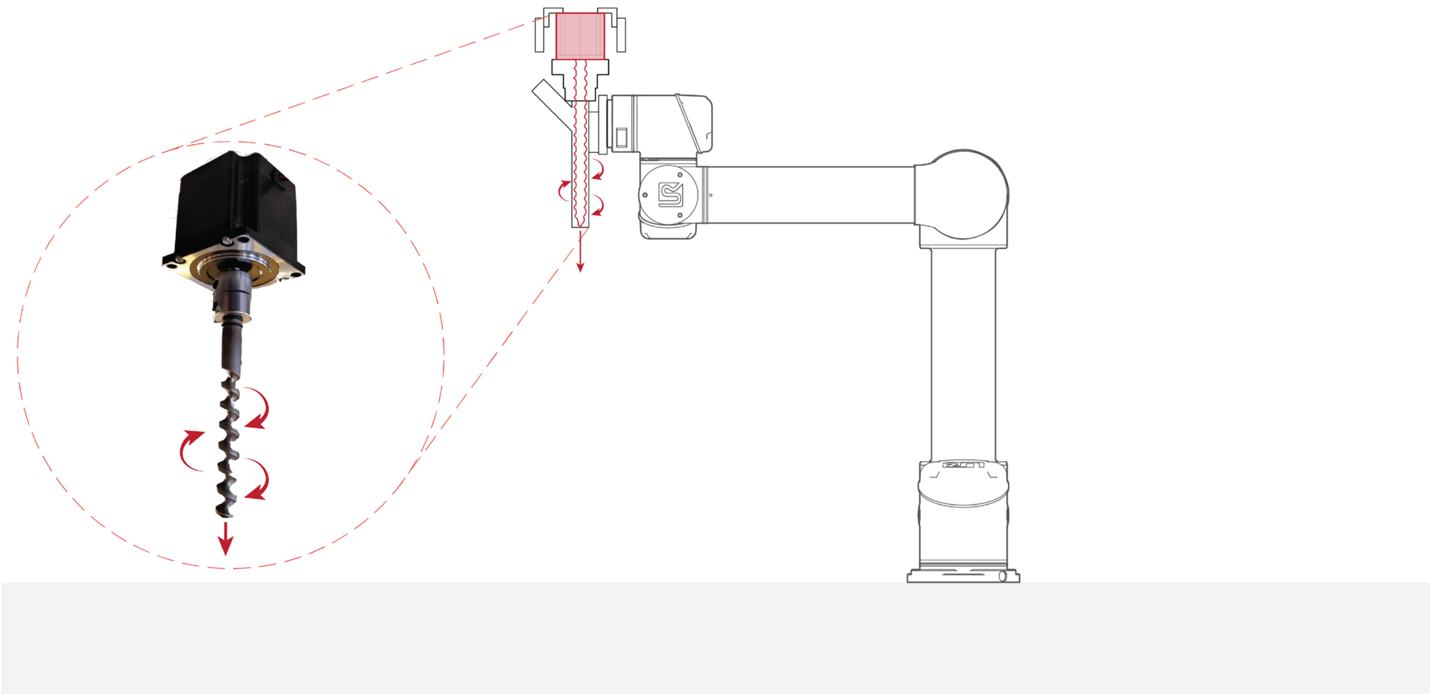


Figure 67 Connector parts connect stepper motor, cooling fans and steel funnel together with bolts. Source: Author.

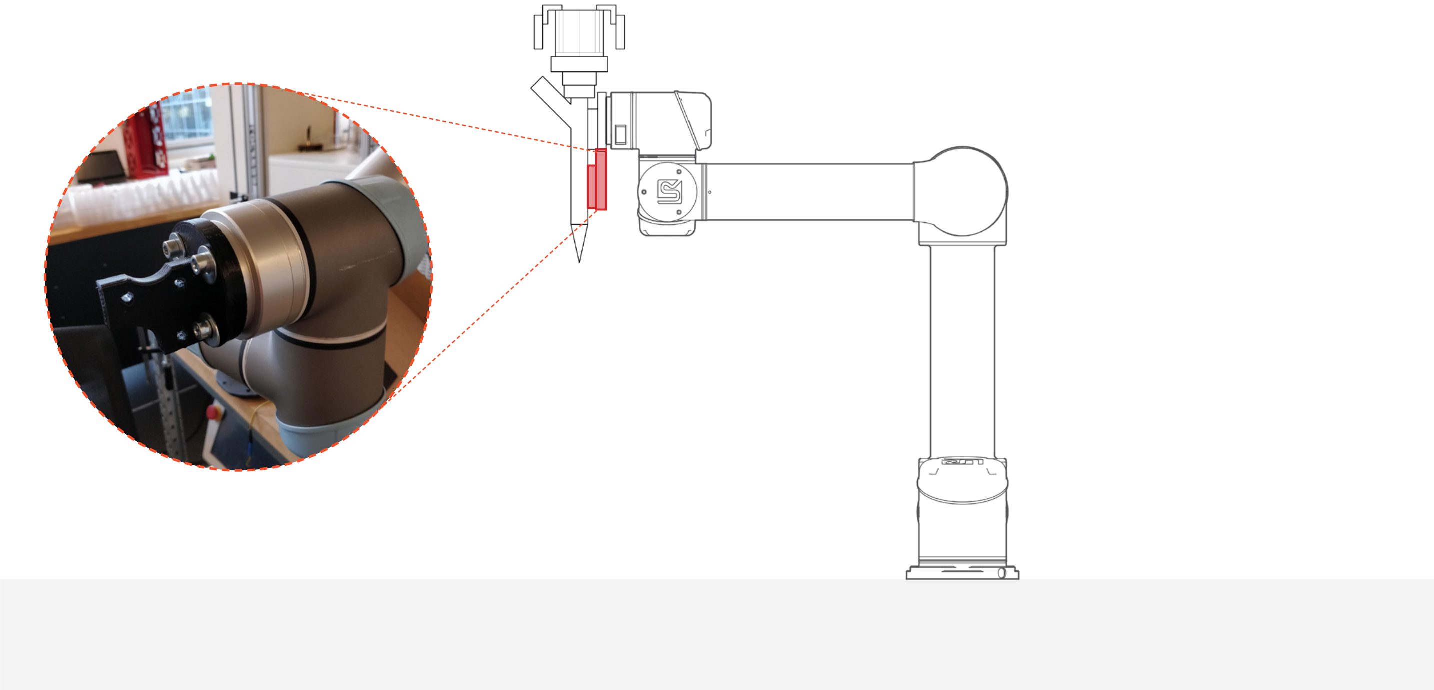


Figure 68 Part to connect extruder to the robot wrist. Source: Author.

Robot connector part

A part is designed to connect the extruder to the wrist of the UR5 robot (see Figure 68). This part too is designed with Rhinoceros design software and 3D printed in black PLA. Cut-outs are made in the part for bolts and to leave space for the material delivery tube to attach to the steel coupling. Four M6 bolts connect the part to the robot, while three M4 bolts connect to the steel coupling part.

Figure 69 Robot connector part close-up 1. Source: Author.

Figure 70 Robot connector part close-up 2. Source: Author.

5.2.1. Extruder & robot control

Robot controller & pendent pad

Communication and control of the UR5 robot is done through the robot controller and pendant pad, which are shipped with the robot. Instruction for the robot can be uploaded via USB stick to the robot through plugging the USB stick into the pendent pad and running the program.

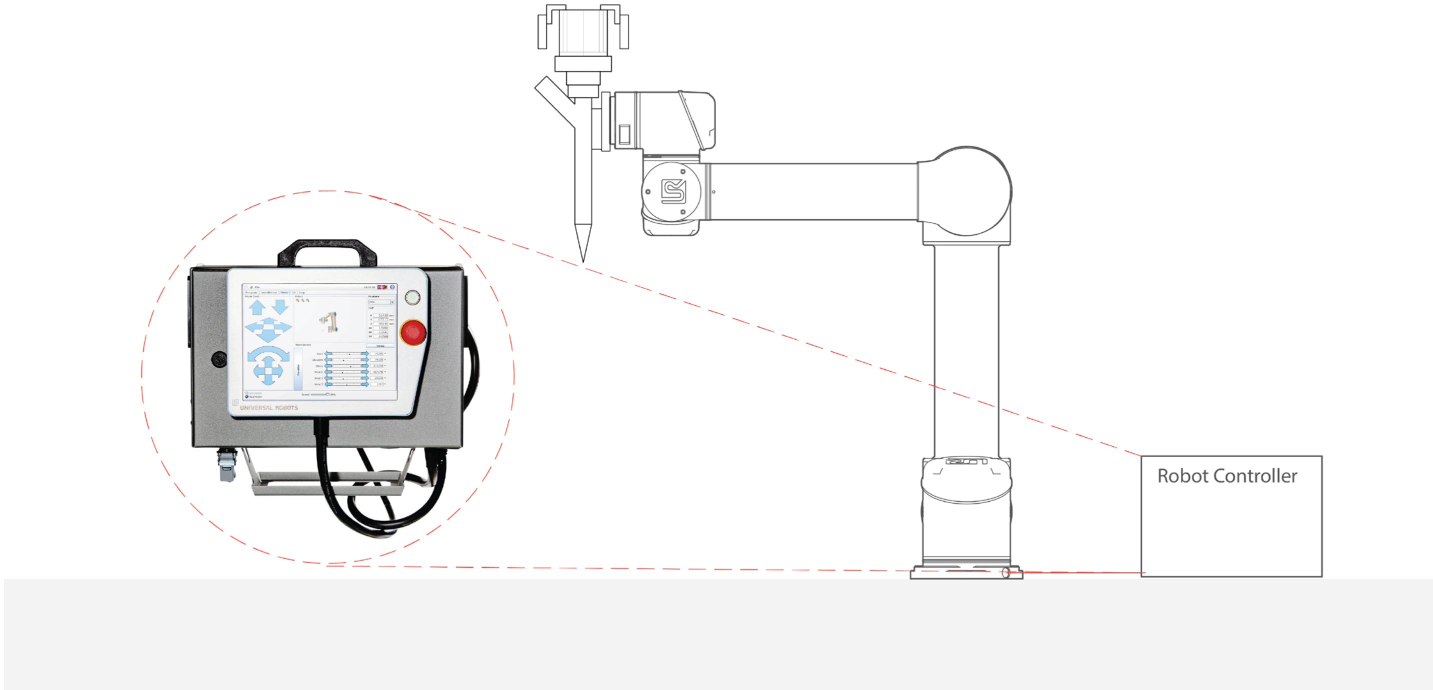


Figure 71 Robot controller box & pendent pad to control the UR5 robot. Source: Author.

Robot control

The robot toolpath is created with RoboDK robot programming & simulation software as described in the chapter “RoboDK workflow”. After successfully creating and simulating such a program, it can be saved as G-code to a flash-drive and plugged directly into the pendent pad to upload it to the robot.

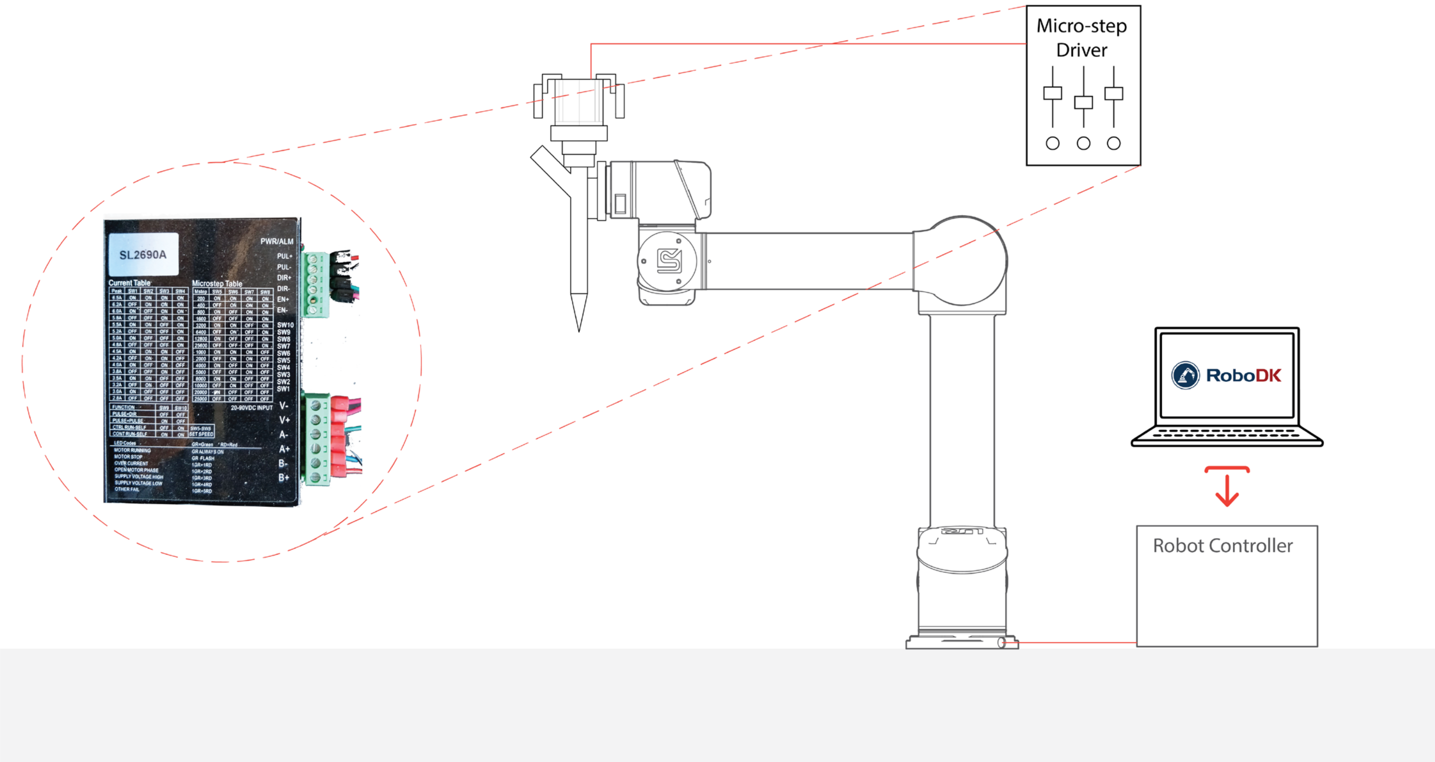


Figure 72 Micro step driver to control the NEMA23 stepper motor of the extruder. Source: Author.

Micro step driver

The stepper motor of the extruder is controlled with a micro-step driver compatible with the NEMA23 stepper motor (see Figure 72). The NEMA23 connects directly into the micro-step driver's "pulse-" and "pulse+" inputs. The micro step driver's power ports plug into a 24 volt power supply which supply power to the stepper motor. The various switches on the micro step driver can be flipped to control the number of steps per revolution of the stepper motor.

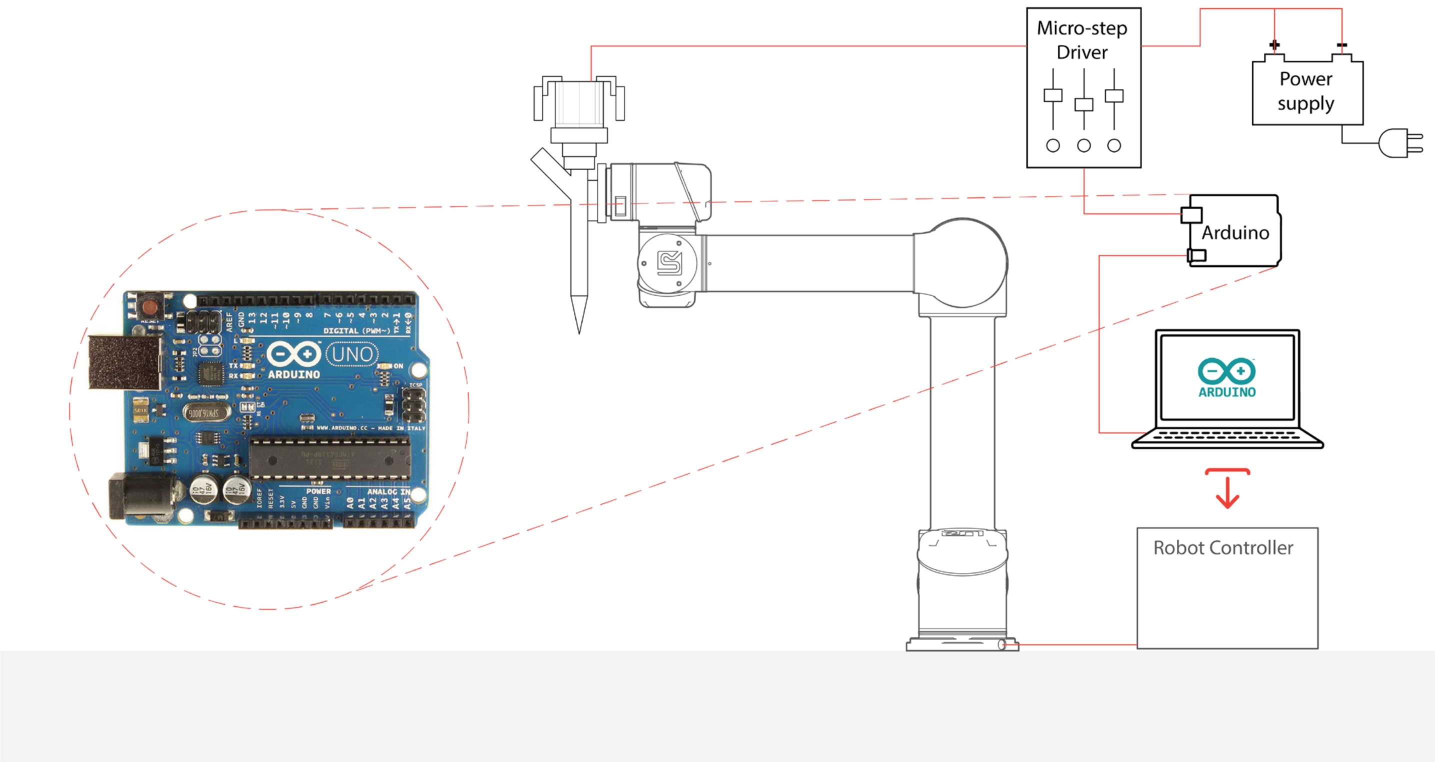


Figure 73 Arduino Uno used to interact with the stepper motor with Arduino programming software. Source: Author.

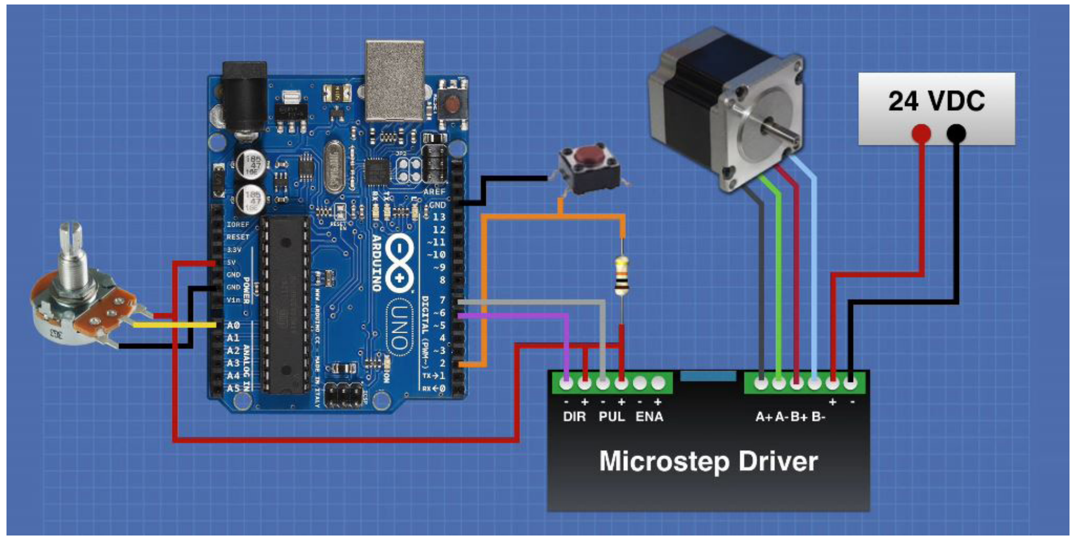


Figure 74 Scheme for Arduino, Micro-step Driver, Stepper motor and power source. Source: https://dronebotworkshop.com/big-stepper-motors/

Arduino Uno control board

An Arduino Uno is used to control the stepper motor via the Arduino programming software (see Figure 73). A physical button is used as on/off switch for the motor. A potentiometer is used to manually control the speed of the motor. A scheme showing the wiring can be found in Figure 74. The Arduino sketch, which controls the motor, written by fellow graduate student Athanasios Rodiftsis can be found in appendix Y.

5.2.2. Summery

Figure 75 shows an overview of the complete setup of the extruder control via the micro step driver, 24V power source, Arduino Uno board, Arduino programming software, potentiometer and on/off button; and of the robot control via the robot controller, pendent pad, flash drive and RoboDK software.

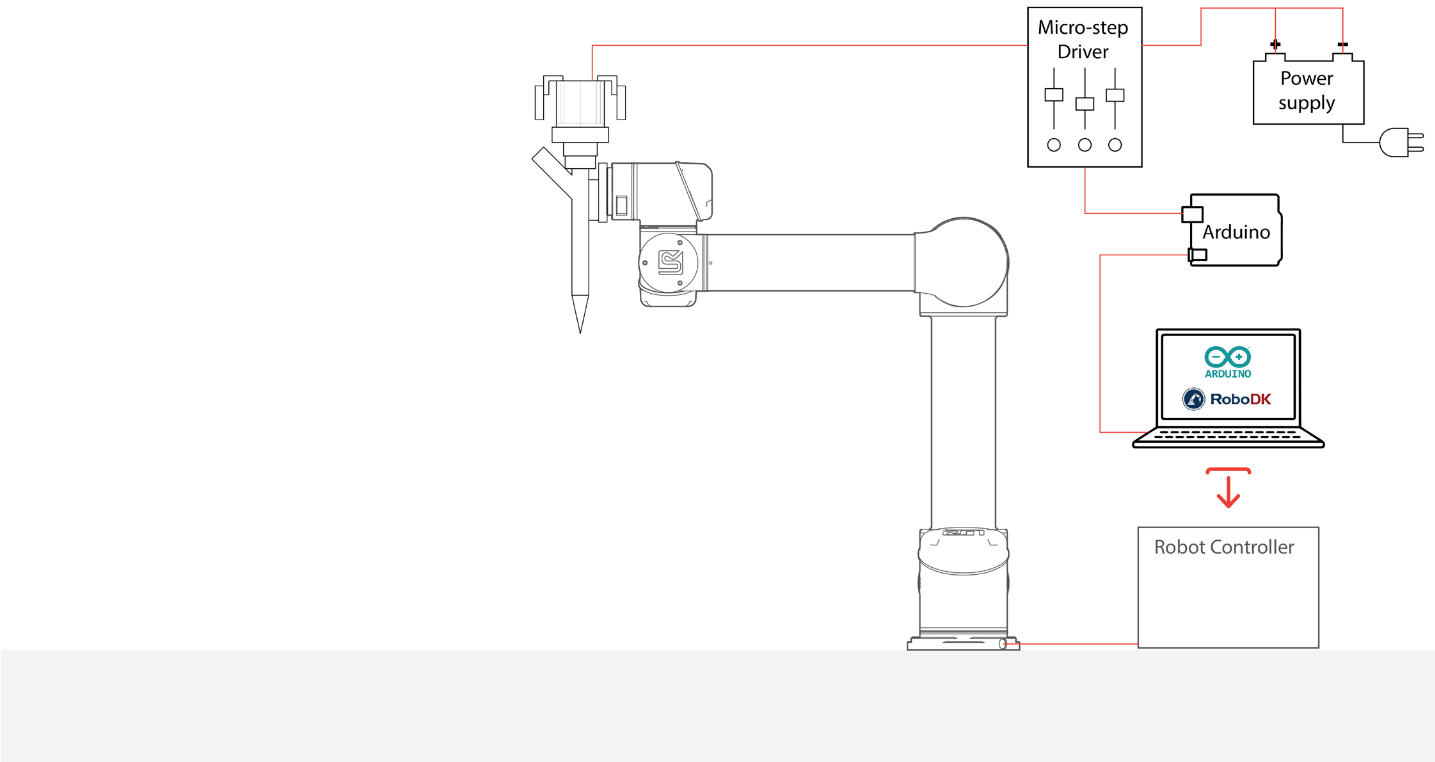


Figure 75 Complete scheme showing control of extruder and robot. Source: Author.

Nozzles

Finally, a nozzle can be attached to the outlet end of the steel coupling. A variety of different nozzles are available to use with this setup. The nozzles have different opening diameters, which allows for creating different sized extrusions (see Figure 76).

Figure 76 Five different nozzles. Source: Author

Final design

With all the before mentioned components together, the final design of the extruder is ready for use with the UR5 robot. It can extrude any paste-like material, including gypsum and clay, so it could be used for research into ceramic 3D printing as well.

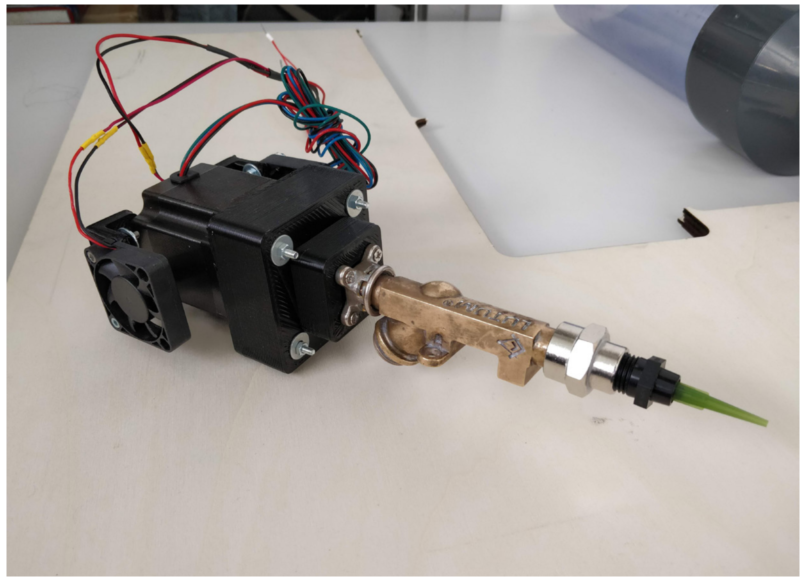


Figure 77 Final mechanical extruder design. Source: Author

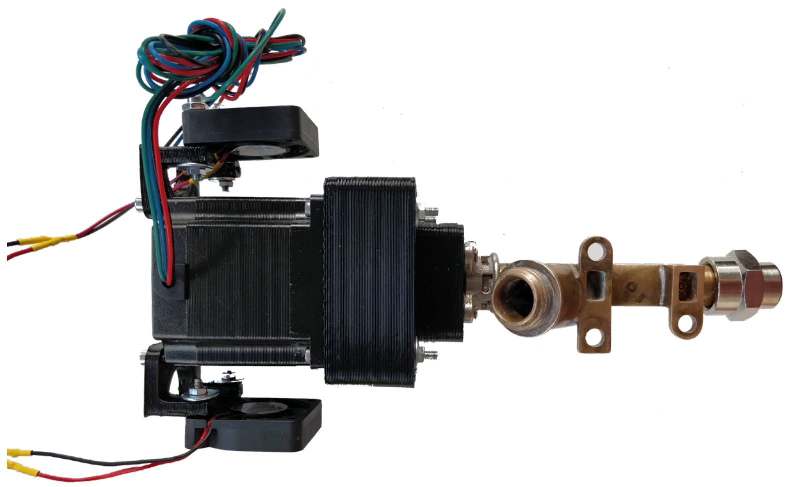


Figure 78 Final mechanical extruder design. Source: Author

5.3 Air powered material delivery system

The air powered material delivery system consists of three main components:

- Material reservoir
- Material delivery tube
- Compressor

Material reservoir

The cylindrically shaped material reservoir, made by Vorm Vrij, can hold about 1000 ml of material and is made from plastic. The cap on the top has a small hole into which a tube can be inserted. This is where the compressor is attached to via a thin rubber tube. The reservoir can be pressurized up to 8 bar.

Material delivery tube

The material delivery tube is 1.5 meter long and is made of transparent flexible plastic. It is connected to the steel coupling of the extruder on one end and to the material reservoir on the other end. In the end, for the experimenting phase the material delivery tube is not included due to unforeseen circumstances. Instead, the material reservoir was directly connected to the steel coupling cover of the extruder.

Compressor

A compressor is used to deliver the printing material from the material reservoir to the extruder. The compressor pushes the printing material from the material reservoir through the material delivery tube to the extruder with an adjustable pressure. By using a compressor, the material can even be pushed upwards if the extruder would be printing on a ceiling, while the material reservoir would be placed at a lower height. Figure 81 shows the final setup for the air powered material delivery system. The specifications of the compressor are mentioned in the table below.

Air out-put	Power	Max. pressure	Voltage	Capacity	Weight
45L/min	0.75PK	8 Bar	230	20L	23kg

Figure 79 Material reservoir made by Vorm Vrij. Source: Author.

Figure 80 HBM air compressor. Source: Author.

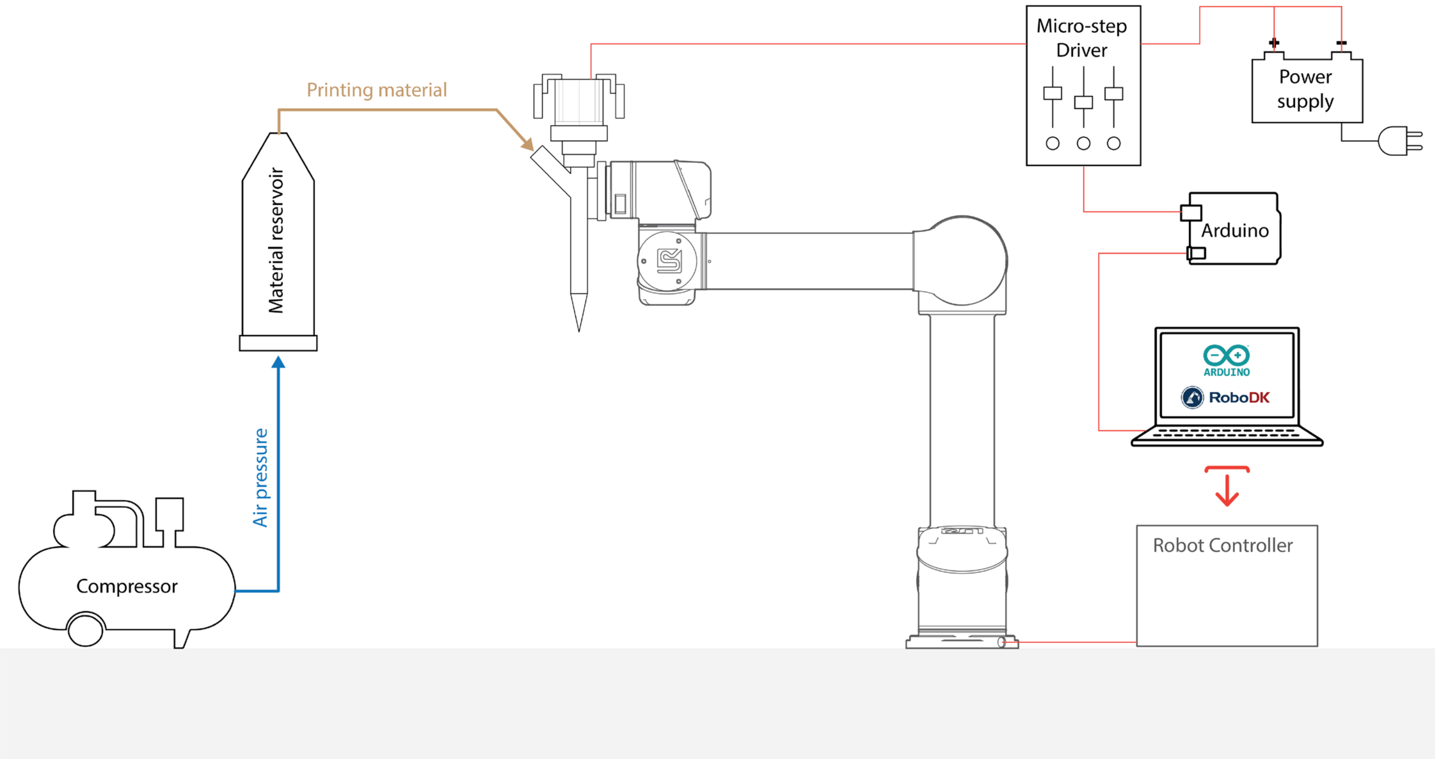


Figure 81 *Final setup for air powered material delivery system and mechanical extruder. Source: Author*

5.4. Other extruder tools

Syringe

A simple syringe, made for extruding icing on baking products, is used for the initial extrusion tests. The syringe can hold about 200 ML of material and has a nozzle diameter of about 4.5mm. The material is pushed out by pressing a spring loaded plunger on the back.

Figure 82 *Syring extruder. Source: Author*

HBM electric caulking gun

The HBM electric caulking gun was used as an alternative for the robot extruder. This caulking gun is easy to use by one person, as the speed of the flow is controlled on the machine itself and can be used with a standard 300 ML empty glue cartridge. The caulking gun has an electromotor which pushes the printing material out of the cartridge with an adjustable speed between 0 and 9,6mm/s. The standard nozzles of the empty glue cartridges were adapted to be able to mount various sized nozzles.

Figure 83 *HBM electric caulking gun. Source: HMB-machines.com*

5.5. Printing bed & Adjustable printing bed frame

The printing bed consists of a 350*400*20 mm gypsum plate (see Figure 84). This plate is made by casting the Molda 3 Normal gypsum with water (1.55/1 ratio) into a Polystyrene foam mould.

Since the angle of the printing bed must be changed consecutively in later stages of the robotic experimenting phase, a wooden frame is designed and built to accommodate this. The frame consists of an inner frame, on which the gypsum printing bed can be placed. The inner frame is connected to an outer frame with an aluminium tube. The two frames can rotate with respect to each other around the aluminium tube. The outer frame has legs mounted underneath so it can be placed stable on a table, while the inner frame can be moved up at different angels. Steel L-profiles are drilled into the outer frame at four different distances from the aluminium tube. These marking indicate the area where a timber bar (section dimensions of 40mm x 25mm) can be placed to rotate the printing bed to an angel of respectively 25, 45, 60 and 90 degrees. This frame allows for 3D printing experimenting onto inclined printing beds (see Figure 85).

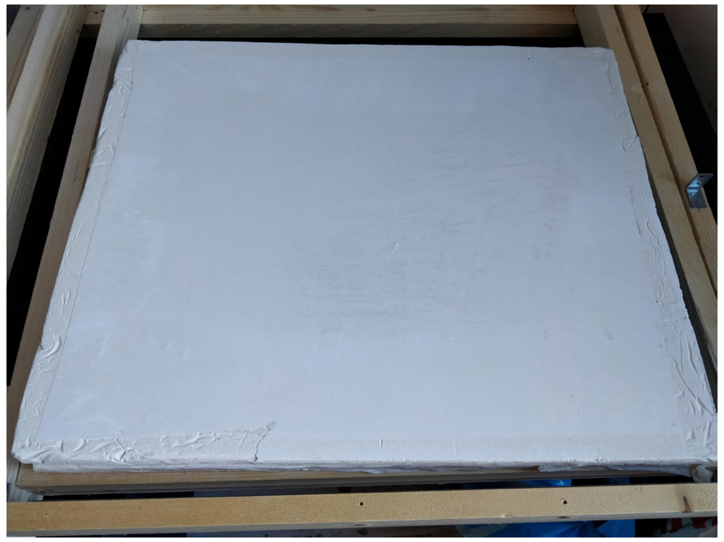


Figure 84 *Gypsum printing bed. Source: Author.*

Figure 85 *Frame for printing bed. Source: Author.*

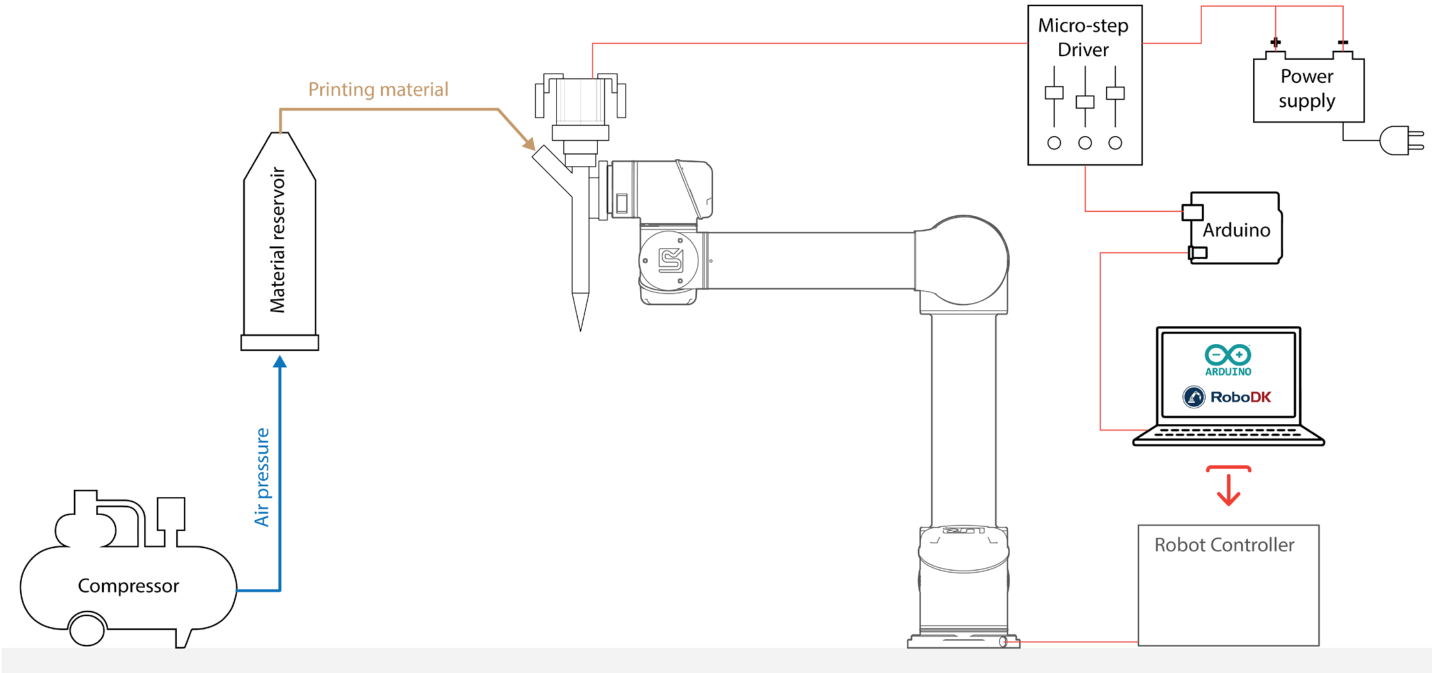


Figure 86 *Sketch of complete proposed setup. Source: Author.*

5.6. Final setup

After testing if all components work, the power supply, micro-step driver and Arduino board are mounted into a PC frame. The potentiometer and button are mounted on the outside of the PC frame for easy access and by removing the top cover of the PC frame, the switches on the micro-step driver can be accessed easily from above (see Figure 87). All wires leading from the extruder to the PC frame are wrapped in a protective plastic cover.

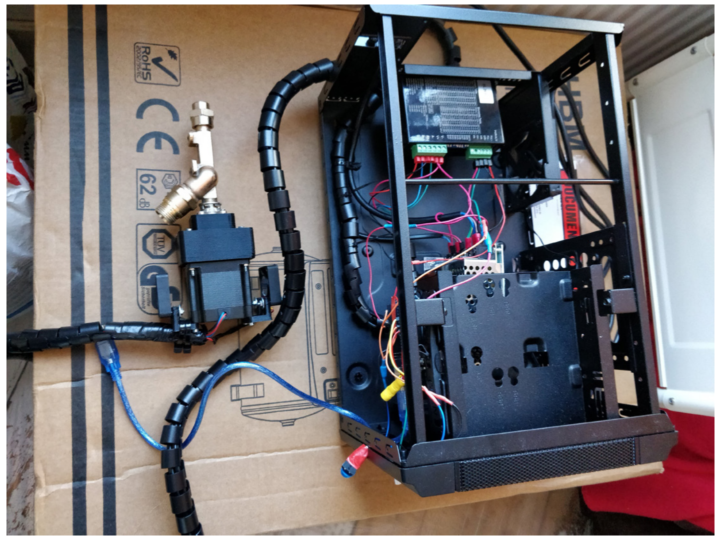


Figure 87 Power supply, Microstep driver and Arduino board into a PC frame. Credits: Ir. Paul de Ruiter. Image source: Author

Figure 88 Home 3D-printing lab setup. Source: Author.

Eventually, due to the world-wide Covid-19 outbreak, access to LAMA and the UR5 robot were lost. Therefore, the experiments were all conducted in a makeshift small home lab, Mini-LAMA. The robot and robot controller were removed from the equation for the experiments, but the other components remained the same as can be seen in the sketch in Figure 89.

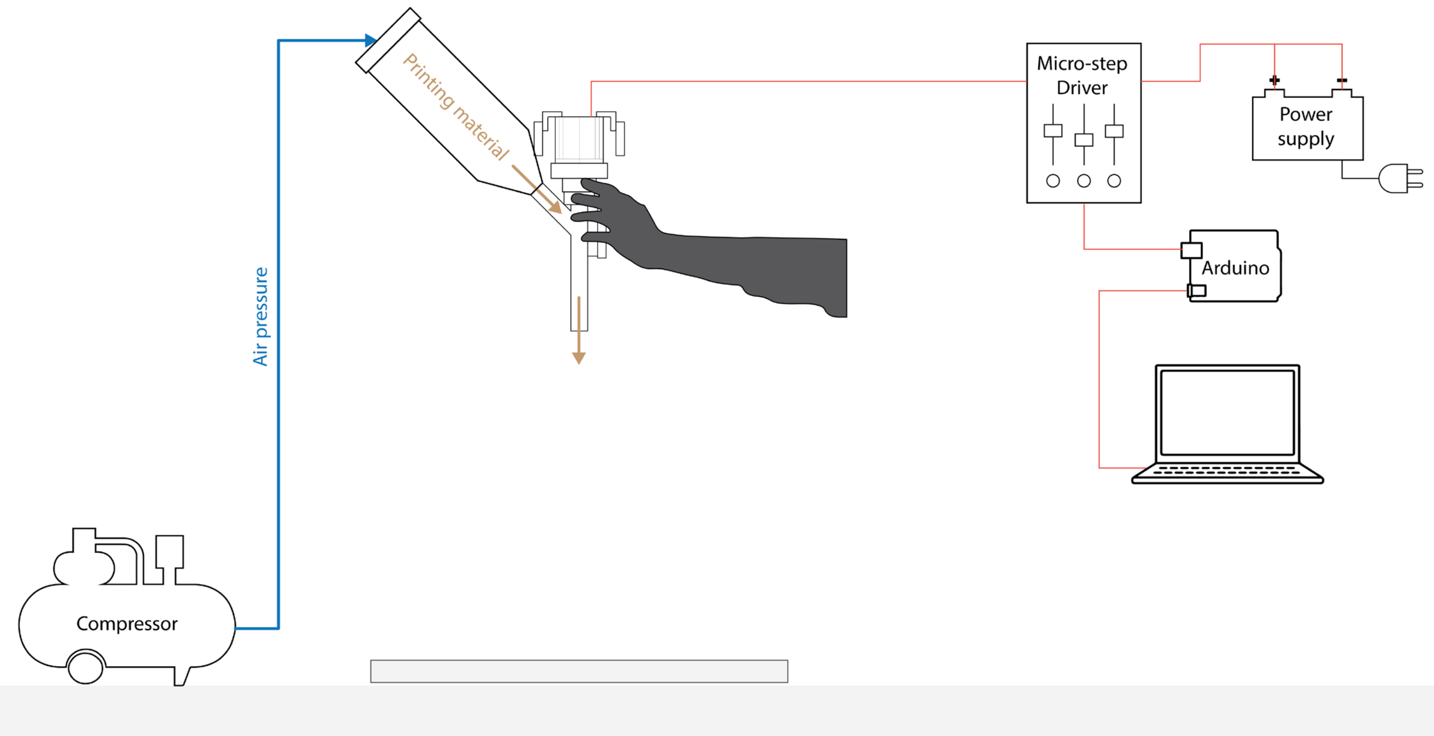


Figure 89 Sketch of final experiments setup used for the experiments. Source: Author.

5.7. Alternative tools

In the last few weeks of the thesis, a 3D printer was available for conducting some 3D printing tests. The 3D printer was Anycubic Chiron, a cartesian style 3D printer with a build volume of 400x400x450mm. A variety of different 3D printing tools were designed to create test prints with the Chiron printer.

The air-powered material delivery system was modified by the addition of several different pipe fittings (see Figure 90). The filament extruder of the 3D printer was replaced by a simple paste extruder, also made with various pipe fittings (see Figure 92).

Due to the heavy weight of the material reservoir on the moving 3D printer gantry, a material delivery tube was added to the air-powered material delivery system after initial tests (see Figure 91). Eventually, the compressed air alone did not provide enough control over the extrusion rate of the gypsum mixture and the threads on the inside of the pipe fittings caused the gypsum mixtures to get clogged, making tests conducted with this system unsuccessful. Avoiding exposed threads on the inside of the material delivery system is advised for the design of an improved version of such a material delivery system.

An alternative design was made of a mechanical ram which would be able to deliver the material from a glue cartridge to the nozzle of the 3D printer with mechanical force. A stepper motor, mounted on the back of the system, moves a nut on an 8mm threaded rod slowly forward, which in turn pushes a plunger into the back of the cartridge holding the gypsum mixture. The system consisted of a NEMA23 stepper motor, connected to the 8mm threaded rod and nut. These elements are connected together with hollow aluminium and 6mm threaded rods and nuts, which in turn are held in place with specially designed 3D printed parts (see Figure 93). Eventually, the pressure required by the stepper motor to push the mixture through the cartridge caused so much torque on the whole assembly, that the aluminium rods and 3D printed PLA parts turned and deformed, making tests conducted with this system unsuccessful as well. A more rigid assembly is recommended for the next version of such a mechanical ram, made out of an aluminium cylinder and aluminium connector parts would be preferred for high strength, low weight and easy cleaning. Due to time limitations, it was not possible to complete the tests conducted with the 3D printer.

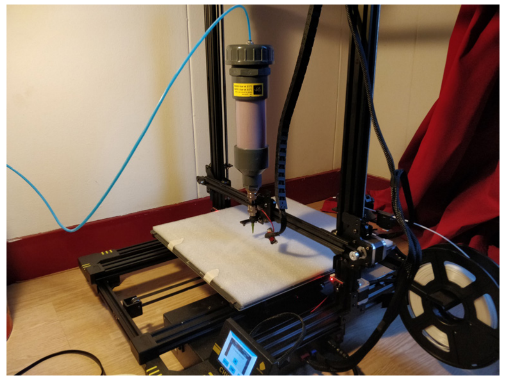


Figure 90 Air powered material delivery system, adapted to for the 3D printer. Source: Author.

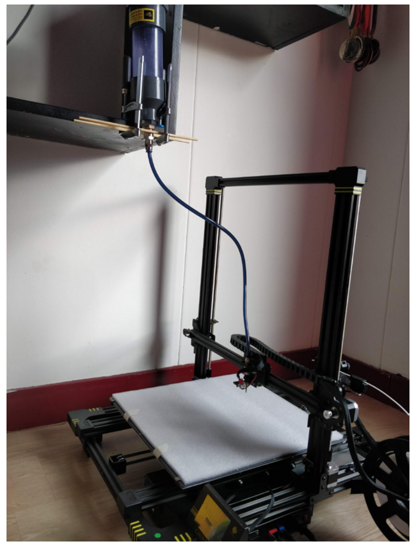


Figure 91 Air powered material delivery system with material delivery tube. Source: Author.

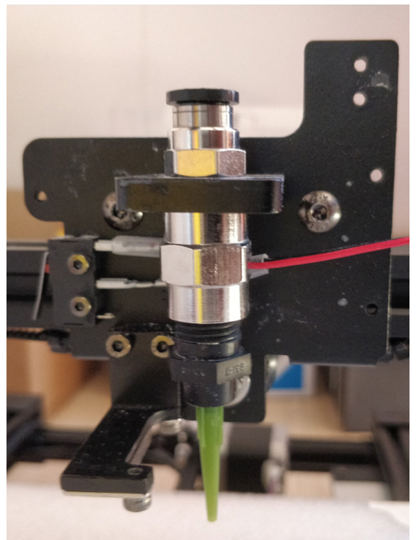


Figure 92 Modified paste extruder mounted onto 3D printer gantry. Source: Author.

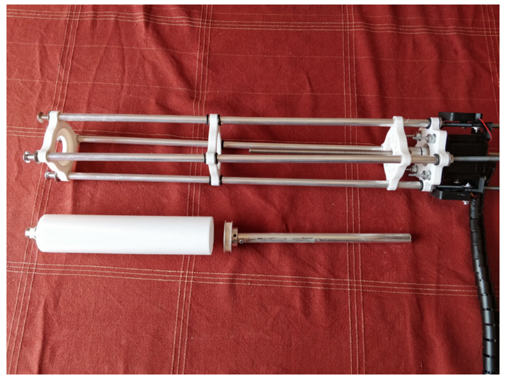


Figure 93 Ram extruder material delivery system made of 3D printed parts and aluminium rods. Source: Author.

06.

MATERIAL DESIGN RESEARCH

6.1. Introduction

One of the key goals of this research is to develop a printable material mixture which can be used for in-situ AM and at the same time is compatible to the original substrate. A restoration or conservation material and/or intervention can be defined as compatible, if it does not lead to technical (material) or aesthetic damage to the historical materials. Additionally, the material and/or intervention should be as durable as possible. In this research, the focus will be on compatibility and printability. Assessing durability of the intervention is, because of time reasons, not within the scope of this research.

This section will first explore gypsum and its properties; after this; its compatibility will be explored in this context and, finally, the aspect of printability will be investigated. At the end of this section various material design strategies and assessment methods to assess compatibility and printability will be presented in the form of a decision making model, which can be used for the next phase of the research, which is the printing material design.

6.2. Gypsum

Traditionally, stucco ceilings can be made up of a variety of different ingredients, as briefly described in the introduction chapter of this thesis. In this research, pure gypsum will be considered as the substrate material of the ceiling. Gypsum is widely used in stucco ceilings, especially in the Netherlands during the late 19th and early 20th century (Prins, 2013). To aid in achieving compatibility between the printing material and the substrate, gypsum will also be used as the main ingredient for the printing mixtures.

Gypsum is a sulfate mineral composed of calcium sulfate dihydrate ($CaSO4·2H2O$) and is found and mined widely in different parts of the world (Saggar, 2011). Due to its abundance and near-global availability, it is widely used for different applications including plaster, and as a sculpting and a building material. In construction gypsum is used to make products such as gypsum plasterboards, which are wall components. Gypsum has also been used by craftsman and artists to make sculptures and ornaments for centuries.

Figure 94 Gypsum powder. Adopted from: https://www.eurekalert.org/pub_releases/2019-02/asoa-gaa020519.php

The gypsum, which is obtained from the quarry in the form of $Ca2SO4\ 2H2O$, is burned in a process known as calcination. By burning the gypsum, it is turned into calcium sulfate hemihydrate ($Ca2SO4$ ½ $H2O$) or calcium sulfate Anhydrite. By mixing calcium sulfate hemihydrate with water, a paste-like mixture is created, which hardens by hydration of the hemihydrate back to back to $Ca2SO4\ 2H2O$) and evaporation of water.

By mixing the gypsum with water in specific ratio's, a wet and thick mixture is created which can be poured into a mould or applied directly onto a surface by hand or with a tool. Because the mixture is wet and thick, it can be sculpted into any desired shape. However, this can only be done for a limited time, as the gypsum-water mixture (from here on referred to as gypsum mixture) starts a "setting process". Mixtures made for pouring may have a setting time as short as 3 minutes (Trehan, 2018). The gypsum mixture starts to harden out as more and more of the water molecules react with the gypsum and excess water slowly evaporates out, leaving behind a solid material (Trehan, 2018).

The details of this process are not relevant for this research; however, it is important to understand what factors influence the setting process and how these factors can be controlled. Additionally, it is important to understand that the viscosity of the gypsum mixtures depends on its use. Mixtures for casted ornaments will need to be fluid enough to be poured into a mould; mixtures to be shaped into objects by hand and scraping tools & brushes will need to be less fluid but still plastic enough. This gives an indication of the workability of the mixtures and an idea about what the setting timeframe of the traditionally used mixtures may be. While 3 minutes of setting time would be enough for mixtures created for pouring into a mould, this would be much too short for AM applications. Therefore, methods of modifying and controlling the properties of gypsum mixtures must be explored for the AM application. In commercial gypsum products in the construction industry, various additives are used in to improve certain qualities of the mixture. "Rotband", a gypsum product manufactured by Knauf, is a product intended for plastering walls, which is a task that cannot be done within a timeframe of around 3 minutes. By adding certain additives in this product, Knauf claims Rotband has a setting time of 90 minutes. This shows that gypsum mixtures can be highly customized for certain applications, which will be required for creating a gypsum-based printing material for AM application as well. This will be further explored in later chapters in this section.

6.3. Compatibility

Compatibility between the newly added printing material and the original (gypsum) substrate is essential for successful restoration. In the case of stucco ornament restoration, generally no extreme contrast is desired between the restoration and the original work. The restoration should be technically and aesthetically compatible to the original substrate (Lubelli, Hees, Hunen, Nijland, & Quist, 2018). Technical compatibility means that the restoration intervention should not lead to an accelerated degradation of the original materials used and that the intervention itself is as durable as possible (Lubelli et al., 2018). Aesthetical compatibility means the colour and texture of the new elements should be similar to the original materials (Lubelli et al., 2018). Considering these definitions, the following criteria have been setup for compatibility between restoration material and original substrate by Lubelli et al. (2018):

- Colour and texture of restoration material and substrate should be similar.
- Moisture transport and capillary absorption of restoration material and substrate should be similar.
- Thermal and hygric dilatations of restoration material and substrate should be similar.
- Porosity and pore size distribution of restoration material and substrate should be similar.
- Compressive and flexural strength of restoration material should be less than of the substrate.
- Shrinkage and cracking should be avoided. (Will be discussed in the subchapter 8 "Shrinkage & cracking"of this section.
- Adhesion strength between restoration material and substrate should be sufficiently high, but the bond at the interface between the restoration material and original substrate should also be weaker than the material strength of the substrate.

6.3.1. Aesthetic compatibility

Aesthetic compatibility has to do with what the restored element looks like in comparison to the original elements and substrate. According to article 12 from the Charter of Venice, "the restored elements must be harmoniously integrated with the whole, but at the same time must also be distinguishable from the original so that restoration does not falsify the artistic or historic evidence (Icomos, 1964). The statement made in this article seems to be a little in conflict with itself. It may be up to the restoration experts of a particular restoration task to decide whether the restoration must be distinguishable from the original or should be completely harmoniously integrated. Or perhaps there might be a midway. This dilemma is not unique to restoration by means of AM or for stucco ornaments. However, AM can provide suitable solutions for any position chosen by creating mixtures with any desirable colour or texture.

Gypsum ornaments are generally white (see Figure 95), so the printing mixture must match this colour. Since gypsum is the main ingredient of the printing mixture, this should not be a problem. However, the aggregates chosen must also be white, which means regular sand cannot be used. But marble powder or chalk could be used, as they are both white.

Figure 95 White colour and smooth texture of stucco ornaments in Huize Nolet, Schiedam. Adopted from: https://www.tbafbouw.nl/Mebest/publicatie/Huis-Nolet%2C-een-vroeg-19e-eeuws-fenomenaal-interieur-in-restauratie

Gypsum ornaments usually have smooth surface textures. This is effect is easily achievable when creating an ornament with a mould. When creating ornaments by hand, the stucco artists and restoration plasterers can use their hands or a wet brush to smoothen a surface. AM is a layer-based building system, which means to avoid a visible contouring effect, the ornaments must be printed with a fine printing resolution. The layer height of each layer and extrusion width of each extruded line are the key printing parameters which affect the printing resolution. The smaller the layer height and extrusion width; the smoother the finish of the printed sample (see Figure 96). In general, the closer the ornament is to the observer, the higher the printing resolution must be in order to achieve a "close to smooth" texture. The opposite is also true: the further away the ornament is from the observer, the courser the resolution can be to still give the appearance of a close to smooth surface texture. But what would be the required resolution to give the impression of a close to smooth surface texture?

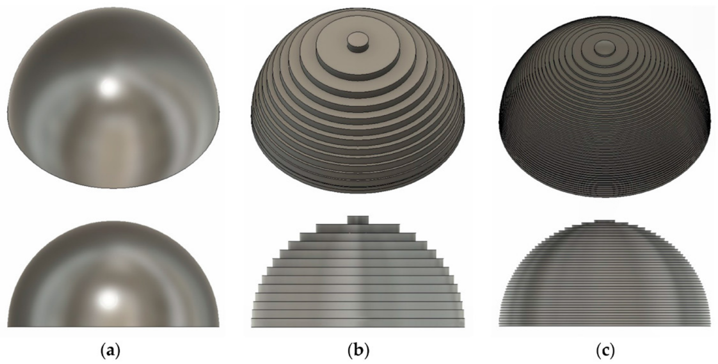


Figure 96 Surface textures with different layer heights and extrusion widths. Source: https://www.mdpi.com/2227-7080/5/3/50/htm

To determine this, the resolution of the human eye must be considered. The human eye has a resolution of about 1 Arc minute (Correll, 1977). 1 Arc minute is equal to 1/60th of 1 degree, which is about 0,017 degrees. Consider an ornament on a ceiling at a height of 4,5 meters and an observer, 1,75m tall, standing directly underneath the ceiling who is looking up at the ornament (see Figure 97). The distance between the ornament and the observer is 2,65 meters (distance Y). The resolution of the observer's eyes is 1 Arc minute, which corresponds to 0,017 degrees (angle O). A triangle can be made between the observer's eye and two adjacent printed layers of the ornament. The question is, with a distance of 2650mm between object and eye and with a viewing angle of 0,017 degrees, what would be the minimum observable distance between two points on the surface of the ornament (distance X). This can be determined with a simple calculation:

$$\tan(0{,}017\ [\text{degrees}]) = (x\ [\text{mm}])/(2650\ [\text{mm}])$$

$$2{,}97 \cdot 10^{-4} = x/2650$$

$$0{,}79\ [\text{mm}] = x$$

So, an observer will be able to distinguish two points on the ornament surface which are separated by approximately 0,8mm. This means required resolution for the **layer height** and **extrusion width** should be **smaller than 0,8mm** for the surface of the 3D printed ornament to appear smooth for the described scenario.

By restoring stucco ornaments in this way, the restored elements will be harmoniously integrated with the whole from a proper viewing distance. However, the from up close, the restored elements will be distinguishable from the original, due to the contoured surface finish. In this way, the restoration work will not falsify the artistic or historic evidence, in accordance to article 12 from the Charter of Venice.

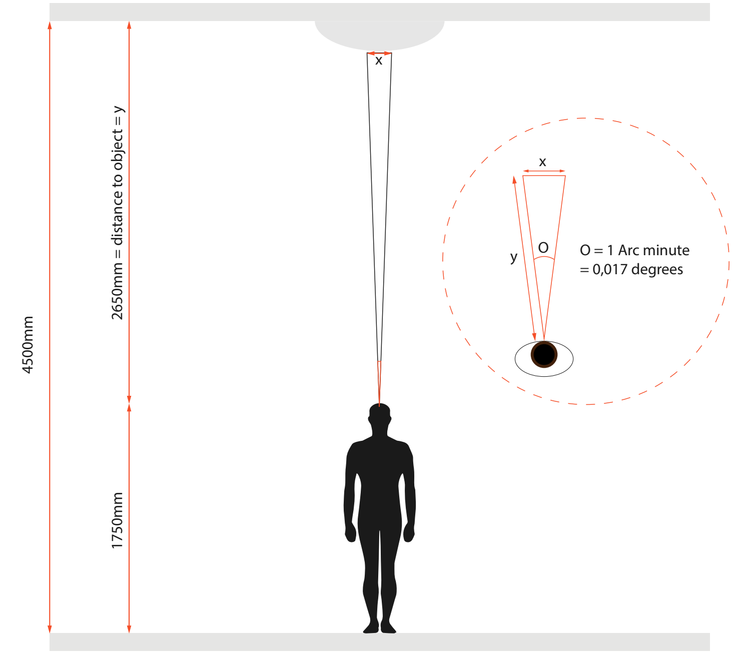


Figure 97 Scheme of visual angle and resolution of oberver. Source: Author.

6.3.2. Technical compatibility

This subchapter gives an overview of the various aspects/criteria on technical compatibility presented in literature for choosing a restoration (mortar) material. Various aspects and assessment methods will be presented and a few of the most relevant aspects and assessment methods will be selected for testing in this thesis.

Porosity & pore size distribution

Gypsum plaster is a porous material, which means it has pores that allow (provided no water repellent has been added to the commercial product) for transport of moisture through it. Due to this, liquid water moisture can be transported by capillarity in the porous network of the gypsum plaster. Therefore, the restoration material should ideally have a similar porosity and pore size distribution as the original material and water repellent additives in the gypsum mixtures should be avoided. If the restoration material would be water repellent, liquid water will not be able to pass through the restored part and this can cause damage to the original substrate. The porosity and pore size distribution of specimen of the restoration material and original material can be assessed by using Mercury Intrusion Porosimeter. This method can give an indication of the distribution of pore diameters present in a tested sample and of the cumulative intrusion volume, which gives an indication of the porosity of the sample (Barbara Lubelli, Timo G. Nijland, 2019).

Moisture transport & capillary absorption

Porosity and pore size distribution are important criteria, because they have an influence on moisture transport and capillary absorption of a material. The capillary absorption at atmospheric pressure can be assessed by immersing a specimen (with the surface which would be in contact with the original material) in water in an environment with a fixed temperature and relative humidity (Barbara Lubelli, Timo G. Nijland, 2019). As the specimen starts gaining weight through capillary absorption of the water, the weight of the specimen can be measured in intervals to get an idea of the rate of absorption; this rate can be characterised by the "Water Absorption Coefficient" (WAC).A compatible restoration material should have a similar WAC to the original material.

However, a simple test can be performed as alternative to give a quick indication on whether the restoration material is water repellent or not by dropping a drop of water on the material of the original substrate, observing the shape of the drop and measuring the time it takes for the substrate to absorb the droplet. This will likely be a matter of seconds, as gypsum is porous. The experiment performed on a sample of the printing material should give a similar result. If the droplet keeps a spherical shape, stays on the surface for a long time, or doesn't get absorbed at all, then the printing material likely contains water repellent additives which can be further investigated. In such a case, the material would likely not be compatible with the original material in terms of moisture transport This method does not generate any scientific data but can be used to give a general indication.

Thermal & hygric dilatations

Materials tend to expand upon heating. The number of meters of linear expansion measured in for a one meter long rod of a material, per unit Kelvin increase in temperature, is expressed as the thermal expansion coefficient α [m/m*K]. For gypsum the thermal expansion coefficient is around 6,7*10^(-6)[m/m*K] (InspectApedia, n.d.). It is important that the restoration material should have a similar thermal expansion coefficient. If not, one material could expand more than the other during temperature changes, which will cause thermal stresses and can lead to cracking and breaking of the gypsum around the interface (A.C. van der Linden, P. Erdtsieck, I.M. Kuijpers-van Gaalen, 2013). Accurate measuring equipment and a precisely controllable heating source is required to assess and compare thermal expansion properly.

Materials also tend to expand as they absorb water, this is known as hygric expansion and the amount of expansion due to water absorption is called "hygric dilation". Hygric dilatation can be assessed by setting specimen in an environment where temperature and humidity can be controlled. The specimen's exact weight and dimensions are recorded before the experiment starts. After placing them in the controlled environment, the relative humidity can be increased in increments and the weight and exact dimensions of specimen can be determined with the use of precise weighing scale and dilatometer (Barbara Lubelli, Timo G. Nijland, 2019). To assess the compatibility in terms of hygric expansion, the Hygric dilatation coefficients of restoration material and original substrate should be similar. Hygric dilation coefficient is expressed as the ratio between linear dimensional change of a specimen measured at various intervals when increasing the relative humidity, compared to the dimensions measured before the experiments.

As gypsum is selected as the main binder for the restoration material, a quite good compatibility between restoration material and substrate can be expected in terms of porosity, pore size distribution, capillary absorption, thermal expansion and hygric expansion. Assessing the compatibility on these criteria be means of tests goes beyond the scope of this thesis but could be done in a further study.

Mechanical strength and adhesion strength

When adding a restored element to a damaged area it is important to consider the mechanical strength of the original substrate and the mechanical strength of the restoration material, in this case the printing material. The mechanical strength of the restoration material should be lower than that of the original material to ensure that if the restored elements are removed, either on purpose or accidentally, that the original substrate is not damaged (Lubelli et al., 2018). Dynamic E module, compressive and flexural strength are considered relevant criteria for choosing a restoration material (Lubelli et al., 2018). When using gypsum-based mixtures for restoration of gypsum substrates, a sufficient compatibility on these aspects can be assumed.

What is more relevant in this case, is the so called "pull-out force". This is the force required to remove the 3D printed restoration material from the substrate. On the one hand this force must be high enough to ensure the printed ornament will remain in place for as long as possible without interventions. On the other hand, when detaching, the printed ornament should not damage the original substrate, e.g. breaking should occur either at the interface or in the 3D printed ornament. Ideally, the weakest link is at the interface between the

printed material and the original substrate. The pull-out force can be determined by performing a pull-out test, which is an experiment where test dollies are glued to printed samples with a strong glue and after drying a pulling force is exerted on the samples until failure to determine the pull-out force and location of breaking (Barbara Lubelli, Timo G. Nijland, 2019). Such a test seems relevant to perform since the adhesion strength of 3D printing a restoration material on a substrate is unknown and is crucial to understand if in-situ AM is to become a viable method for stucco ornament restoration.

Chemical compatibility

Chemical compatibility means that there are not undesirable chemical reactions between the restoration material and the original substrate material. In addition, no harmful by-products should be created and the restoration material should not provide nutrients (mainly nitrates) for biological growth (Teutonico et al., 1996). In context of this research, assessing chemical compatibility can be largely avoided by choosing off-the-shelve products, as these products are already extensively tested on general chemical compatibility with material used in the built environment.

A specific situation in which gypsum could be not compatible, is when magnesium carbonate (MgCO3) is present in the original ceiling (such as in the situation when magnesian lime mortars are used). In this cases using gypsum is unadvisable, as magnesium carbonate and gypsum may react with each other in the presence of water and lead to the formation of damaging salts (magnesium sulfate salts). Magnesium carbonate may be present in lime mortars, if the original limestone from which lime is made contained magnesium carbonate. For example, magnesium limestones are present in some parts in the North of Italy and Switzerland and magnesian lime mortar are sometimes used in those regions. In general, in the Netherlands, magnesian lime mortar are not used and so the use of gypsum stucco should not give chemical compatibility issues.

6.3.3. Conclusions

Key criteria

Aesthetical compatibility:

- Colour similar to substrate material. --> Use white aggregates: marble powder.
- Texture similar to substrate texture. --> Small layer height and extrusion width, as well as fine aggregates should be used.

Technical compatibility:

- Porosity & pore size distribution:
  - Similar porosity & pore size distribution between as substrate material.
- Moisture transport:
  - Similar capillary absorption as substrate material.
- Thermal and hygric expansion
  - Thermal and hygric expansion coefficient similar to substrate material.
- Mechanical strength:
  - Lower than substrate material.
- Adhesion:
  - Adhesion strength between original and restored element should be high enough to keep restored element in place but should be the weakest link in the chain.
- **Chemical compatibility:**
  - Should not undesirably react with substrate material.
  - Should not create harmful by-products.
  - Should not provide nutrients for biological growth.

Assessment methods

Aesthetical compatibility:
- Visually assess colour from appropriate distance.
- Visually assess texture from appropriate distance.

Technical compatibility:
- Porosity & pore size distribution:
  - o Mercury Intrusion test with Porosimeter. (Not within scope of this research.)
- Moisture transport:
  - o Capillary water absorption test. (Not within scope of this research.)
- Thermal and hygric expansion
  - o Measure dimensions of specimen with dilatometer at various intervals after exposing them to increasing in temperature in controlled environment to determine thermal expansion coefficient. (Not within scope of this research.)
  - o Measure dimensions of specimen with dilatometer at various intervals after exposing them to increasing relative humidity levels in controlled environment to determine hygric expansion coefficient.
- Mechanical strength:
  - o Perform 3 point bending test to determine flexural strength. (Not within scope of this research.)
  - o Perform compression test to determine compressive strength. (Not within scope of this research.)
- Adhesion strength:
  - o Determine pull-out force (F_printed) on printed sample by performing a pull-out test.
  - o Determine maximum self-weight F_self
  - o If F_self<F_printed , then adhesion strength is sufficient.
  - o Note where break occurs, ideally it should occur at interface.
- Chemical compatibility:
  - o Various assessment methods possible but are not within the scope of this thesis.
  - o By using off-the shelve tested products issues in chemical compatibility can be largely avoided.

6.4. What is printability?

In the field of large-scale extrusion-based AM, most research is conducted on concrete and clay 3D printing. Gypsum is unexplored as a main binder for AM, which gives the opportunity for this thesis to add to the body of knowledge about gypsum-based AM. Due to the lack of prior research about gypsum application in AM, the approach behind developing suitable cementitious mortars is used to create a framework for developing this gypsum-based AM technique.

To ensure proper workability and printing performance for a new AM technique the design of the printing material must be coordinated with the design of the 3D printer. The last includes the material storage system, the material delivery system, the material deposition system (in this case the extruder), the printing system and the control system for the AM process (Ma et al., 2018).
The material must be designed according to so called **key printing criteria** to satisfy the requirement of good **printability**. These key printing criteria are identified as:

- **Extrudability**
- **Flowability/pumpability**
- **Buildability/strength**
- **Setting time/open time.**

Since the required material properties are in part driven by the printer properties, there are no universally accepted values for key printing parameters (Verian, Verian, Carli, Bright, & Maandi, 2018). Therefore, a unique material recipe must be developed experimentally in coordination with the printer design. Principally, the printing material should be easy to extrude, easily flowable, strong enough to be built up in layers and should have a long open time to be able to generate large freeform geometries with the accompanying 3D printer (Ma et al., 2018). This research focusses on the aspects of the material design as well as the material delivery system, nozzle/extruder design, moving interval and travel control aspects (see Figure 98). In the next sub-chapters, the identified key printing parameters are defined; besides, options on how to control a to achieve certain desired material properties are reported.

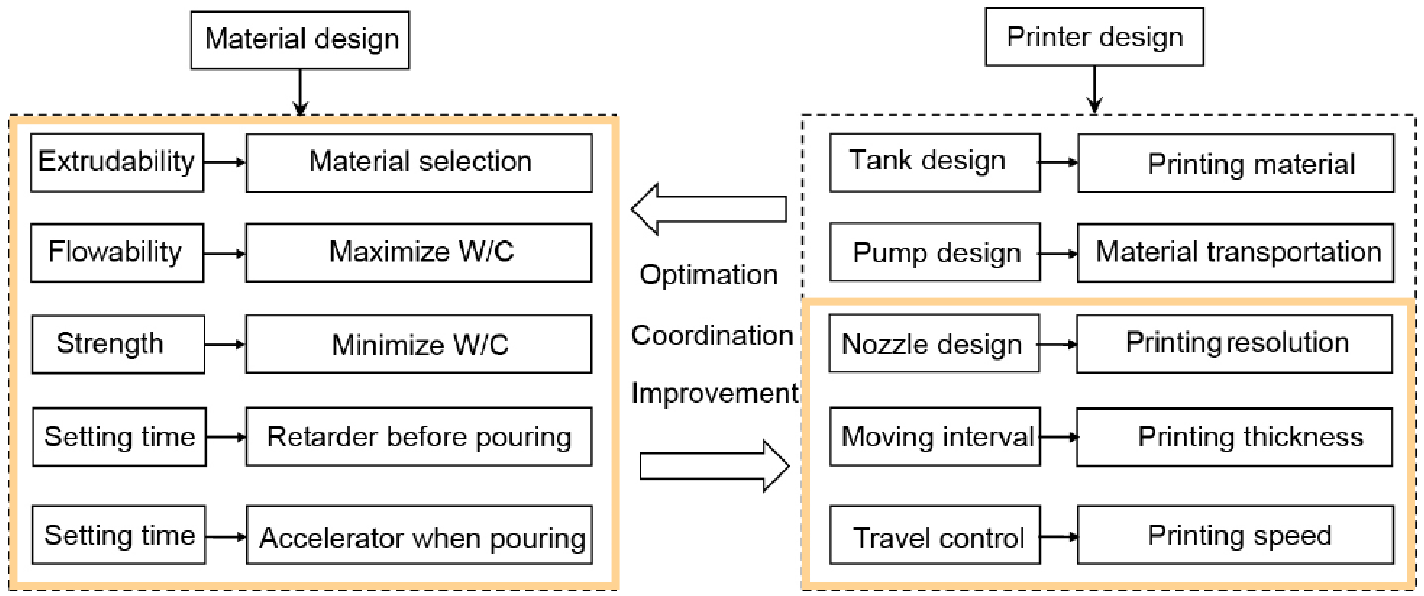


Figure 98 General requirements in the mix design of cementitious mixture for construction-scale 3D printing (Ma et al., 2018).

6.5. Extrudability

Definition: Reliability and ease with which a material can be deposited through a deposition device (Lim et al., 2012).

Extrudability has to do with the ease with which a printing material can pass through the material delivery system, such as material delivery tubes as well as through the printer nozzle (Ma et al., 2018). This key parameter is influenced by the size and smooth grading of the raw materials which the printing material is made up of. Raw materials used in the mixture should have round shapes, as opposed to angular shapes and should be no bigger than 1/10th the size of the diameter of the extruder nozzle (Ma et al., 2018). Large, angular shaped particles have a higher chance of blocking or clogging inside the material delivery system for a given water to powder ratio (Ma et al., 2018). Generally, basic principles of grading design used in for example self-compacting concrete can be applied for printing material design (Ma et al., 2018). This means, a considerable volume of (in this case gypsum) paste can be used to fill voids which form between smooth graded aggregate particles for better extrudability (Ma et al., 2018).

Assessment

To assess the extrudability of a printing material, experiments have been set up by Ma et al. (2018) as well as by Lim et al. (2012). Both experiments involved extruding a material continuously along a set distance (2000mm and 4500mm respectively) through a fine nozzle (8x8mm and 9mm in diameter respectively). A material has good extrudability if it can be extruded through the nozzle along the defined length continuously (i.e. without breaking) and if the material is able to maintain its stability (i.e. without segregating, bleeding or clogging inside the extruder or nozzle) (Verian et al., 2018).

To assess the so called "line continuity" aspect of extrudability of a printing material, an experiment can be setup in which various printing material mixtures are extruded through a nozzle with a fixed diameter. The length of the uninterrupted extrusion line can be measured for each mixture and compared.

To assess the printing resolution possible with a mixture, a created mixture can be extruded through an extruder onto which different nozzles with different nozzle diameters can be mounted. If a mixture can be extruded through the nozzle uninterrupted and without clogging, the chosen nozzle diameter can be used for this mixture. If the mixture cannot be extruded through a nozzle, a mixture with finer aggregates can be tried to be made. This could be done by filtering out larger aggregate particles with a sieve.

Conclusions

Key parameters:
- Binder/aggregate ratio
- Aggregate size
- Aggregate shape

To improve extrudability:
- Use round shaped aggregates
- Use finer aggregates
- Size of aggregate < 1/10 Nozzle diameter

Assessment:
- Achieve a long length of continuous, uninterrupted extruded line.
- Try different sized nozzles for extrusion. Filter out larger aggregates with a sieve.

6.6. Pumpability

Definition: The ease and reliability with which material can be moved through a delivery system (Lim et al., 2012).

Pumpability (also called flowability) is related to the ease with which a material can be pumped through a material delivery system, such as material delivery tubes and extruders (Ma et al., 2018). Pumpability of cementitious mixtures and, in this case, gypsum-based mixtures, is controlled through two main physical parameters: the water to binder ration and the grain size distribution.

The most important parameter is the water to binder ratio in the mixture (Ma et al., 2018). Increasing the water to binder ratio would increase the ease with which the mixture could be pumped through a delivery system. However, a too high water to binder ratio could lead to high porosity in the delivered material, reducing its mechanical strength (Ma et al., 2018). Adding a superplasticizer to concrete mixtures has shown to improve the pumpability, while maintaining comparable or higher mechanical strength (Malaeb et al).

The grain size distribution in a mixture is the second main parameter which governs its pumpability (Ma et al., 2018). Generally, a better pumpability can be achieved through a higher packing density of the mixture, which in turn can be achieved by using a wider distribution of particle sizes (Ma et al., 2018). Smaller particles can fill voids left between larger particles, displacing the water in voids and thus improving pumpability of the mixture (Ma et al., 2018). At the same time, an excess of fine aggregates may increase the viscosity of the mixture, which could lead to an adverse effect (Ma et al., 2018).

Assessment

To assess pumpability, an experiment can be set up in which different mixtures with varying water to binder ratios are pumped through a material delivery tube at a constant pressure with a compressor. Mixtures that can be pumped through the delivery tube without clogging have a better pumpability than mixtures that clog or move without a constant speed inside the material delivery tube at that pressure. Mixtures which have a varying range of particle sizes can be compared in a similar way. Pumpability would be assessed qualitatively, since there is no universally preferred flow rate or desired compressor pressure. Maleab et al. and Le et al. have used slump flow test to assess pumpability of cementitious mixtures for concrete 3D printing after achieving desirable printing results with certain mixtures (Ma et al., 2018). It could be possible to perform a slump flow test on gypsum-based mixtures which show good pumpability results to quantify what is a good flowability for gypsum-based mixtures for AM.

Conclusions

Key parameters:
- Water/binder ratio
- Grain size distribution of aggregate

To increase pumpability:
- Increase water/gypsum ratio
- Improving grain size distribution
- Adding plasticizers

Assessment:
- Pumping mixture uninterrupted at constant speed through tube at constant pressure.
- Slump test (after achieving desirable results)

6.7. Buildability

Definition: Ability of a material to retain its extruded shape under self-weight and pressure from upper layers when it is not yet fully cured (Lim et al., 2012)(Ma et al., 2018).

Buildability is another critical parameter, especially for extrusion-based AM onto inclined surfaces. In common 3D printing practise, buildability refers to the early stage stiffness or compressive strength of an extruded material right after it has been deposited (Ma et al., 2018). This material must be able to bear its self-weight and the weight of the subsequent upper layers which press down. In cementitious 3D printing materials, a higher content of fine aggregates and sand provide a favourable buildability (Ma et al., 2018). Adding a small doses of viscosity modifying agent (VMA) can also improve the buildability of cementitious 3D printing materials (Ma et al., 2018). A higher viscosity means, the extruded material has a higher shear strength and will less likely bleed or deform (Panda, Paul, Mohamed, Tay, & Tan, 2018). Experiments conducted in concrete 3D printing show that the previously mentioned methods can improve buildability, but again there are no universally accepted ratios or values of mechanical strength etc. for concrete AM, let alone that can be translated to ratios and values for gypsum-based AM (Ma et al., 2018). Therefore, the ratios of fine aggregate to binder to water must be experimentally obtained for gypsum-based AM.

Buildability is important for any 3D printed geometry to maintain its stability and its shape. If a lower layer deforms due to poor buildability under the weight of subsequent layers, this would result in the 3D printed object losing stability and geometrical accuracy (Panda & Tan, 2018). Deformations due to poor buildability can create a distance between the printing nozzle and the working surface, resulting in insufficient contact area between layers and could lead to collapse of the printed structure (Panda & Tan, 2018).

Assessment

A method to assess buildability of fresh concrete mortars can be used for gypsum-based AM. According to this method a relationship must be defined between the shear strength of the mixture and the number of layers that can be built up without the occurrence of noticeable deformations in the geometry (Le et al., 2012). For example, a study by Le at al. (2012), showed that the optimum buildability was achieved by a cementitious mixture with shear strength of 0.55 kPa that could be built up to 61 layers without collapsing.

An experiment can be set up where layers of material are stacked on top of each other, while a camera records the growing geometry. After a predefined number of layers are stacked, the video recording can be analysed to find after how many layers major deformations are visible in the geometry. By repeating the experiment with different ratios of fine aggregates (and VMA) favourable ratios of these additives can be experimentally determined for favourable buildability.

Conclusions

Key parameters:
- Grain size distribution
- Viscosity of mixture

To improve buildability:
- Increase the percentage of fine aggregate
- Increase viscosity by adding viscosity modifying agents (VMA)

Assessment:
- Number of layers stackable before major deformations can be observed for a certain mixture.

6.8. Open time

Definition: Time interval in which pumpability, extrudability and buildability are within an acceptable range (Lim et al., 2012).

The previously discussed key printing parameters are both material properties dependant as well as time dependant. For each of the these key printing parameters there is a certain range of values within which they will give preferable printing results and the time frame within which this range of values occur is defined as the open time of the mixture (Verian et al., 2018). The key parameters are time dependant because after mixing gypsum powder with water, the mixture starts to slowly set, which means it will start to slowly harden. Over time, a mixture has three phases: A) Pre-printable phase, B) Printable phase, C) Post-printable phase. In phase A) the mixture is very liquid and has a low viscosity. It may be pumpable and extrudable, however it is too liquid to maintain its shape after extruding. In phase C) the mixture has hardened too much and it is too viscous to be able to be pumped or extruded. Phase B) is the printable phase, in this phase all the key printing parameters are within a desired range. This phase can be defined as the Open time and the goal is to extend the period of this phase as much as possible. The end of the open time is indicated by the disruption in the extrusion process of the printing material, which is indicated by the breaking or clogging of the mixture in the material delivery system (Verian et al., 2018).

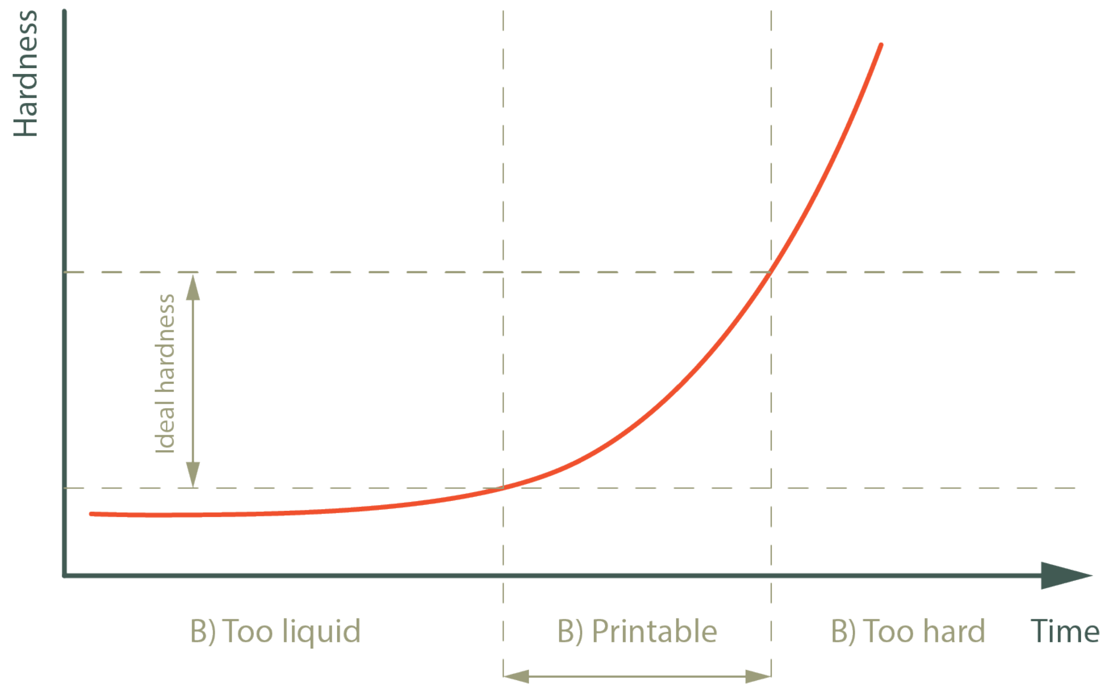


Figure 99 Conceptual graph for three phases of mixture. Source: Author

Primarily, the length of the pre-printable phase is dependent on the water to gypsum ratio: a higher water to gypsum ratio means a longer pre-printable phase, because there is more water which must evaporate before the gypsum can harden. Mixtures that have too much water will flow out of the nozzle uncontrollably and will not be able to support their own weight. Mixtures that are too dry will have a short printable range, as they will rapidly harden. A balance must be found between these extremes.

Retarders are generally used to extend open time of cementitious mixtures in concrete 3D printing (Ma et al., 2018). Retarders can be absorbed on the surface of the binder particles to form an insoluble layer around the binder particles, which delay the hydration of the binder (Ma et al., 2018). Sodium tetraborate was among the most effective retarders which have been tested for concrete 3D printing, extending the open time 3 to 4 times (Ma et al., 2018). As the setting and hardening processes in gypsum are occurring differently than in cement, retarders used for cement might not be effective in the case of gypsum.

Experiments conducted in 1974 at the Institute of Technology in Washington show the effectivity of various retarders used on the setting time of gypsum powder. The induction period and final setting time of pure gypsum without additives were respectively 37 minutes and 76 minutes (R.Clifton, 1974), the induction period and final setting time of mixtures with the various retarders are shown in Figure 100.

Table 2. Effect of Retarders on the Setting Rates of Gypsum Plaster

Additive[a]	Amount (grams)	Induction Period (Minutes)	Final Set (Minutes)	Maximum ΔT[b] (°C/min)
$NaC_2H_3O_2$	1.7	60	110	-
$NH_4C_2H_3O_2$	0.8	70	118	1.1
$Na_2B_4O_7 \cdot 10H_2O$	0.8	178	218	-
Succinic Acid	0.2	213	271	0.5
Tartaric Acid	0.2	61	106	1.0
Gelatin	0.1	-	240	-

[a]The retarders were dissolved in 60 ml of water and then mixed with 100 g of plaster of paris.

[b]Maximum temperature rise in °C for a one minute interval.

Figure 100 Table showing effect of various retarders on the setting time of gypsum. Source: (R.Clifton, 1974)

Additives such as the ones mentioned in Figure 100, must be carefully studied to determine if they are compatible with the original substrate or if they will cause any undesirable chemical reactions to take place. By using off-the-shelve products used in the construction and restoration industry, such compatibility issues can largely be avoided, as these products undergo testing and must be certified for use. Consulting the manufacturer could be an option when using additives that you are uncertain of in terms of compatibility.

Assessment

To assess Open time of a mixture, the mixture could be put into a container, from which it would be pumped to an extruder. Next, the mixture could be extruded in various time intervals. After each extrusion test, the pumpability, extrudability and buildability would be rated qualitatively. The extrusion test in which the material shows signs of poor pumpability, extrudability or buildability, will indicate the end of the Open time. These signs could include clogging, major deformations, poor interlayer adhesion etc.

Conclusions

Key parameters:
- Water to binder ratio

To extend Open time:
- Add suitable retarder after Printable phase has started, e.g. gelatine

Assessment:
- Perform printing tests with a mixture over in time intervals to assess pumpability, extrudability, buildability over time.

6.9. Shrinkage & cracking

Definition: Shrinkage is the process or fact of decrease in size during the setting period due to the evaporation of water from an extruded object; it may be accompanied by the development of shrinkage cracks in the mass of the material.

A relatively high water/gypsum ratio is required in the 3D printing material mix to achieve good extrudability and pumpability of the mixture (Ma et al., 2018). This results in a volume of water present in the mixture which exceeds the required amount for hydration of the gypsum. The excess water evaporates out and may result in shrinkage and cracking during the setting period (Ma et al., 2018). Cracking may occur on the surface of an extruded object since some parts of the extruded object dry faster than other parts. To achieve a smooth surface texture for 3D printed ornaments, it is of paramount importance to minimize shrinkage and cracking. To decrease the amount of shrinkage and cracking several strategies could be used. Decreasing the water to binder ratio and increasing the aggregate to binder ratio are feasible and easy to implement strategies (Ma et al., 2018). Furthermore, adding shrinkage reducing admixtures (SRA) can reduce shrinkage by lowering the surface tension which is induced by evaporation of water (Ma et al., 2018). Experiments with fly ash and calcium sulfoaluminate cement have shown to reduce shrinkage by 80% for cementitious mixtures (Ma et al., 2018). Alternatively, adding fibres such as glass fibres or natural fibres, into the printing mixture could reduce shrinkage and cracking as well (Ma et al., 2018).

Assessment

Shrinkage of a 3D printed object can be expressed as the change in size between its freshly printed state and its state after the final setting time. Therefore, shrinkage can be assessed by measuring the size of an object right after it has been 3D printed and again after the final setting time of the mixture used for 3D printing that object. The shrinkage can then be expressed as a percentage.

Cracking is harder to measure in a meaningful way. Counting the number of cracks per square centimetre at three fixed locations of a 3D printed object could be a method of assessment.
Another method of assessment could by to create a grid of lines on the 3D printed object and to count the number of cracks encountered by these grid lines.
Alternatively, a qualitative visual rating can be given between 1 and 5, with 1 being least cracking and 5 being the most cracking.

Conclusions

Key parameters:
- Water to binder ratio
- Aggregate to binder ratio
- Size of geometry

To reduce shrinking & cracking:

- Decrease water to gypsum ratio
- Increase aggregate to gypsum ratio
- Reduce overall size of individual extruded elements
    - Reduce nozzle diameter for decreased extrusion width
    - Decrease layer height in printer settings
    - Reduce extrusion speed for smaller layer size
- Add reinforcement fibres:
    - Straw
    - Glass fibre
    - Organic fibres
- Add shrinkage reducing admixtures (SRA):
    - Fly ash

Assessment shrinkage:

- Measure main dimensions of object in freshly printed state and after final setting time.

Assessment cracking:

- Qualitative visual rating between 1 (least cracking) and 5 (most cracking).

6.10. Adhesion between printed object and substrate

Good adhesion between printing material and the substrate on which the object is printed is essential for objects printed by traditional 3D printing techniques. If the adhesion between the fresh printing material and the substrate is inadequate, the object could be displaced during the printing process resulting in a poor print quality or even total collapse of the object. Furthermore, a poor adhesion could develop after the printed sample has hardened, which could cause the sample to fall off the ceiling or wall.

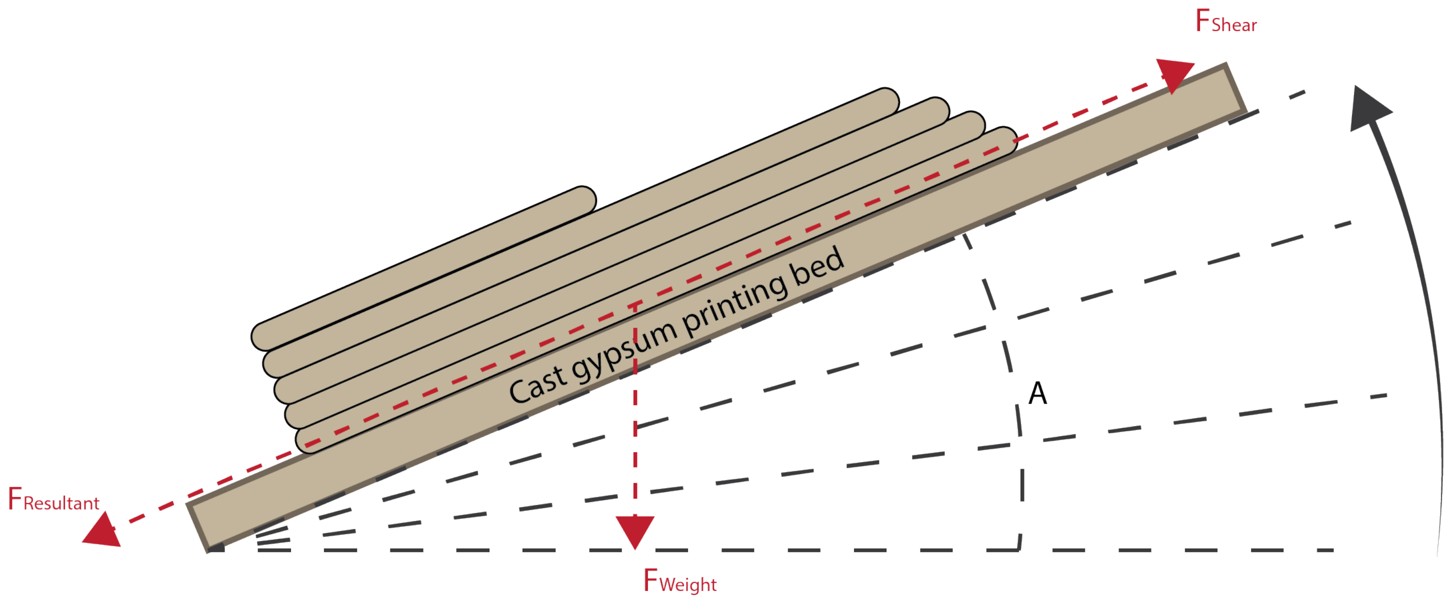


Figure 101 Illustration of relevant forces acting on inclined printing substrate. Source: Author

6.10.1. Printing material manipulation

By inclining the substrate on the which the object will be printed, the weight of the 3D printed object, expressed as F_{Weight} is accompanied by a horizontal component, which results in the combined resultant force called $F_{Resultant}$. To prevent the 3D printed object from sliding down the inclined printing bed, a shear force FShear, must be equally strong as $F_{Resultant}$. This shear force is induced by the resistance of particles from the 3D printed object and particles from the substrate sliding over each other in opposite directions. The shear force between two shearing bodies like these can be increased by increasing the viscosity of the mixture of the 3D printed object (Carlino & Messina, 2018). As viscosity of a fluid increases, it gets a higher resistance to flow. The $F_{Resultant}$ is determined by the weight of the 3D printed object, since it is resulting from the F_{Weight} as well as from the inclination of the angle. It is evident that as the inclination angle increases, the horizontal component become larger, which means $F_{Resultant}$ become larger, reaching its peak at an inclination of 90 degrees, when $F_{Resultant} = F_{Weight}$. This means the adhesion strength between the 3D printed object and substrate must increase with an increase in the weight of the 3D printed object. When printing onto a vertical substrate $F_{Shear} = F_{Resultant}$.

Shear stress is expressed as **б=F/A** where F is force along the sliding plane in Newtons and A is area in mm^2.

This shows there are two parameters and thus two approaches which can be taken to increase adhesion between the 3D printed object and the substrate. The first is to increase the shear strength (F) by increasing the viscosity of the mixture. This can be achieved by using viscosity modifying agents (VMA) (Ma et al., 2018). The second approach is to increase the contact area (A) between the 3D printed object and the printing substrate. This could be achieved by giving the first printed layer onto the substrate an infill density of 100%.

6.10.2. Substrate manipulation

When the delay time between the placement of consecutive layers increases, the interlayer adhesion between those layers decreases (Verian et al., 2018). This phenomenon occurs due to the formation of so called 'cold joints', which can occur if a significant amount of surface moisture of the previous layer is lost due to evaporation and chemical reactions (Verian et al., 2018). Therefore, the inter-layer adhesion strength decreases as the delay time between placing consecutive layers increases (Le et al., 2012). In light of this knowledge, it could be assumed the adhesion strength between a fully set and dried original gypsum substrate and a freshly extruded, moist first layer of a 3D printed ornament would be poor. So, a method to increase this adhesion strength could be to pre-wet the substrate before commencing the printing process.

Another approach could be to increase the surface area of the substrate on a microlevel by making the surface rougher (as opposed to being smooth) for better mechanical interlocking between the fresh gypsum print and the substrate. Roughening of the surface of the substrate could be done with sanding paper before commencing the printing process. The rough surface should theoretically be more suitable for the 3D printed first layer to grip onto than a smooth surface. This should be experimentally assessed.

6.10.3. Printing process manipulation

By manipulating certain parameters of the printing process the adhesion to the substrate can also be improved. The basic principle here is again to increase the contact area between the 3D printed object and substrate. This can be achieved through lowering the printing speed (Hulette, 2019), or in this case, the movement speed of the robot arm. By lowering the printing speed, the material will be placed on the right places with more accuracy, which can increase the contact area (Hulette, 2019). Another method is to increase the extrusion speed, which would result in more material flowing out of the nozzle per unit of time. This would increase the amount of material deposited onto the substrate, which means a larger contact area (Hulette, 2019). Finally, a nozzle with a larger diameter could be used. This would result in wider extrusion lines and thus larger contact area (Hulette, 2019). The last two methods are however unfavourable in the case of ornament restoration, since they would most likely decrease the precision and printing resolution.

Assessment

For fresh state:

A method for the assessment of the adhesion of fresh printed object to the substrate could consist in marking the exact position of a 3D printed object and recording it over time. With a series of photographs or a video/ time-lapse any displacement could be observed.

For hardened state:

After 24 hours of drying, hang a load with a known weight on a printed sample, with the force parallel to the substrate. Keep increasing the force until the printed sample comes off. Record the force exerted when the sample fails to adhere to the substrate.

Conclusions

Key parameters:

- Adhesion strength
- Weight of sample --> Shear strength (Carlino & Messina, 2018)

To improve adhesion:

By printing material manipulation:

- Increase contact area
  - First layer 100% infill density
- Increase viscosity
  - Add viscosity modifying agent (VMA)

By substrate manipulation:

- Prevent cold joints by pre-wetting substrate with water
- Sand substrate to give it a rough finish

By printing process manipulation:

- Increase contact area
  - Slower print speed
  - Increase extrusion speed
  - Larger nozzle diameter

Assessment:

- Mark initial position of 3D printed object and observe possible displacements by means of photographic or video monitoring.
- Keep applying a force which is increased in increments on printed sample perpendicular to the substrate, until the sample disconnects from the substrate.

6.11. Conclusions & discussion

The design of a printable mixture must meet the criteria discussed in the previous chapters of this section. The preparation procedure is summarized in a flowchart in Figure 102. The behaviour of the mixture in its fresh state controls the quality of the 3D printing process (Le et al., 2012). By fixing the raw materials, particle sizes, as well as the water to binder ratio for an optimal extrudability and pumpability, the other criteria can be optimized further with additives (Ma et al., 2018).

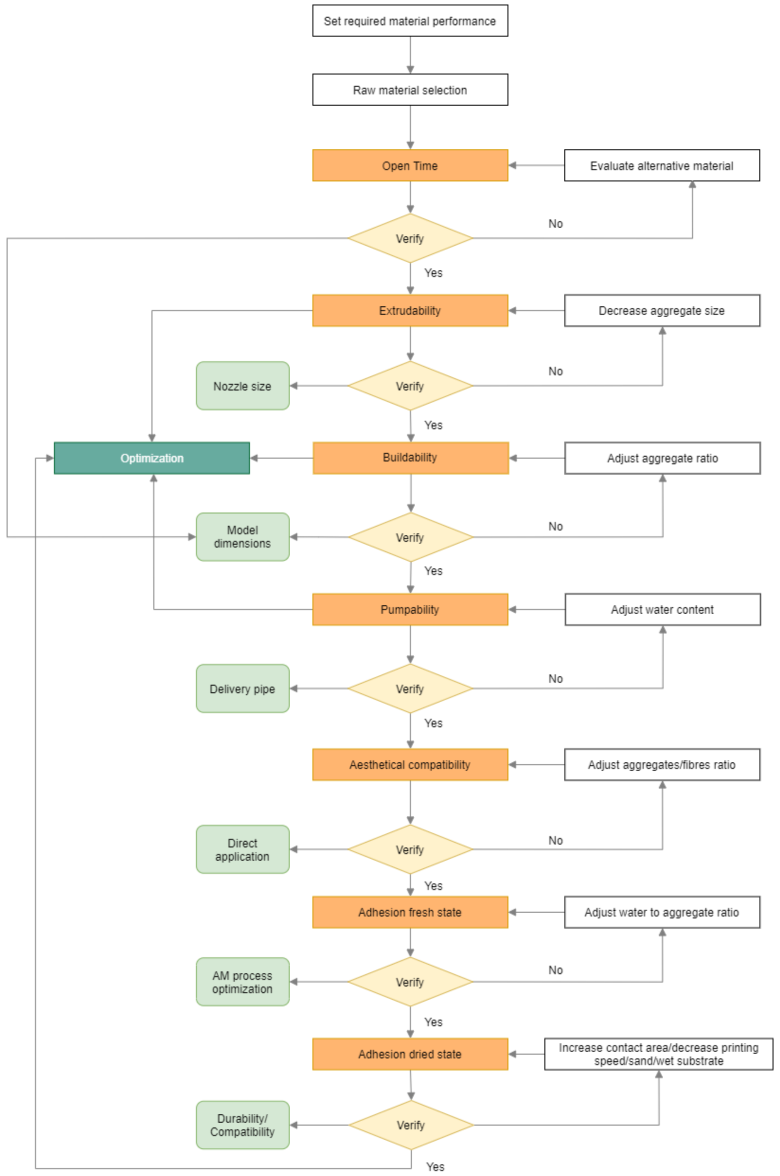


Figure 102 *Preparation procedure for gypsum-based mixture design for restoration by means of AM. Source: Author.*

However, there are two main contradictions in creating optimal mixtures for AM with respect to pumpability, buildability and mechanical strength. Both contradictions are directly or indirectly influenced by the water to binder ratio of the mixture:

Buildability: *Strength to maintain shape --> low water/binder ratio*
Pumpability: *Smooth flowing, good line continuity --> high water/binder ratio*

Pumpability: *Long setting time for continuous uninterrupted flow --> high water/binder ratio*
Buildability: *Short setting time for rapidly gaining strength --> low water/binder ratio*

These contradictions form a dilemma for the mixture design. A compromise may need to be made to find a balance between these contradicting material requirements to satisfy all relevant printing criteria. Another method could be toto solve this contradiction by other means than the water to binder ratio. As presented above, superplasticizer is expected to balance the required amount of water, while accelerators and retarders can help to control setting time in both fresh and hardened state (Ma et al., 2018). By using off-the-shelve products normally used in restoration field with good results, compatibility issues can largely be avoided.

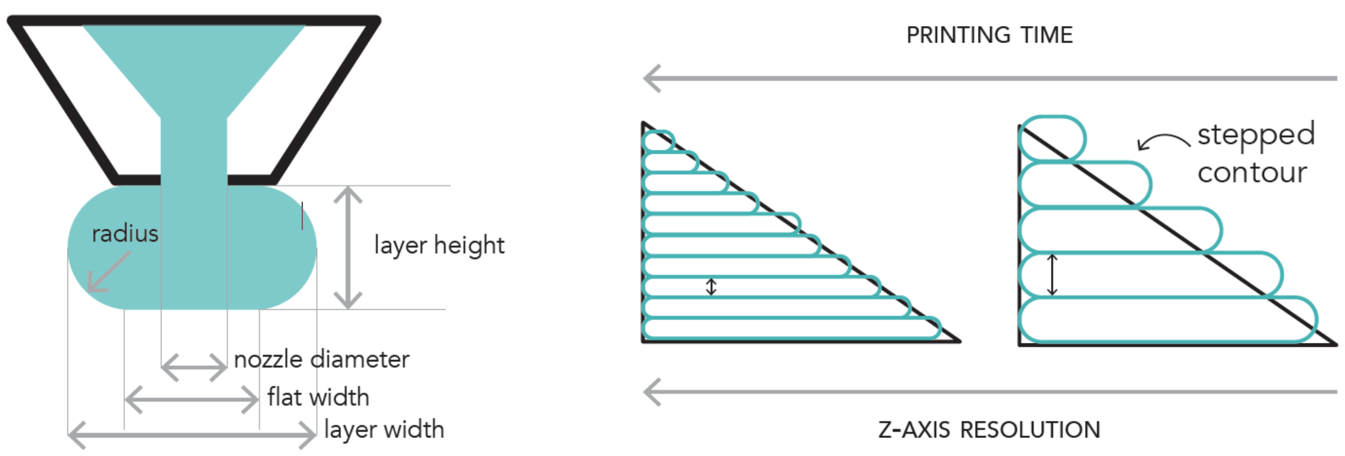


Figure 103 *Relationship between printing time, layer height and extrusion width. Adopted from: Master thesis of Valeria Piccioni (Piccioni, 2019)*

A final dilemma in the material design and printing process of gypsum-based mixtures for ornament restoration must be discussed. On the one hand, it is desirable to have a smooth, or at least “close-to-smooth” surface texture of the printed gypsum ornaments. To achieve this, a high printing resolution is required, which means using a small extrusion width and layer height (see Figure 103). However, by reducing the extrusion width and/or layer height, the printing time of an object increases. This can be a problem if the printing time exceeds the Open time of the mixture. Therefore, depending on the size of the object, the Open time will be a constraint for the printing resolution for that particular object. This dilemma is visualized in Figure 104. Methods to avoid such constraints due to Open time will be discussed in the chapter “Suggestions for improvement”.

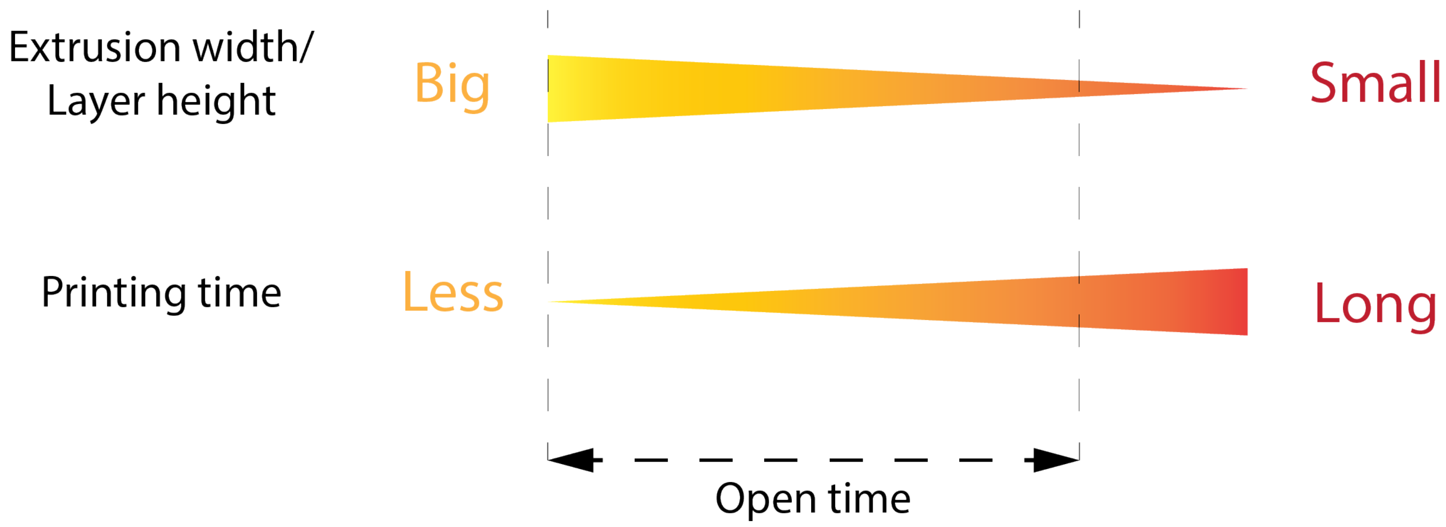


Figure 104 *Relationship and constraint between printing resolution and printing time. Source: Author.*

6.12. Decision-making model

The literature research on designing a mixture for 3D printing in the previous chapters is summarized in the form of a “Decision making model”. The measures that can be taken to change/improve mixture properties based on observations from experiments are described in this model. The methods for increasing or decreasing the value of the measured or observed parameter are arranged in an order of priority (1 highest priority, >1 descending priority). This decision-making model can be used to improve subsequent mixtures during the experimenting phase.

The hierarchy of measures is based on a few pre-determined principles. The first principle is to select off-the-shelve products as these products have usually ingredients used in the restoration field, and these products are most likely to be in line with compatibility criteria. Products with no (or as less as possible, known) additives are preferred; as the effect of additives in a product would complicate the interpretation of the results and lead to lower compatibility with historic materials. The second principle is to prioritize changes in water/binder/aggregate ratio’s over procedural measures and prioritize procedural measures over adding additional additives. Procedural measures are measures which need to be performed by the person preparing the material, such as the intensity and speed of mixing. Finally, if measures taken with respect to the first and second principle do not give the desired results, compatible additives can be used.

Key parameter	Measured parameter	To increase	To decrease
Extrudability, pumpability	Flow rate	1. Increase extruder speed 2. Increase compressor pressure 3. Use finer aggregates 4. Use round aggregates	1. Decrease extruder speed 2. Decrease compressor pressure 3. Use coarser aggregates 4. Use angular shaped aggregates
Extrudability, pumpability	Line continuity	1. Increase water/gypsum ratio 2. Add wider range of aggregate sizes 3. Plasticizer	1. Decrease water/ gypsum ratio 2. Add coarser aggregates
Buildability	Nr. Layers without deformations	1. Add more fine aggregates 2. Increase viscosity by VMA	
Initial setting time	Start of mixing - Start of printable state	1. Mix mixture more intense, for longer 2. Use warmer water (<50 degrees	1. Mix mixture for shorter time 2. Use colder water
Final setting time	Start of mixing - End of printable state	1. Mix mixture more intense, for longer 2. Use warmer water (<50 degrees) 3. Use retarder: Gelatine	1. Mix mixture for shorter time 2. Use colder water 3. Use accelerator: Starch
Open time	Start printable state - End printable state	1. Apply retarder after initial setting time	
Shrinkage & cracking	Dimensions (after 24 hours)		1. Decrease water/ gypsum ratio 2. Increase aggregate/ gypsum ratio 3. Add reinforcement fibres 4. Decrease extrusion thickness 5. Add shrinkage reducing admixture/plasticizer to reduce water/gypsum ratio further.
Printing speed	Printing time	1. Increase extrusion speed	1. Decrease extrusion speed
Adhesion to substrate	Displacement from origi-nal point (fresh state)	1. Decrease print speed 2. Increase extrusion speed 3. Increase/decrease infill density 5. Increase nozzle di-ameter/ 6. Use accelerator after extrusion. 5. Increase viscosity by VMA	
Adhesion to substrate	Force needed for de-tachment in hardened state	1. Increase substrate roughness before printing. 2. Wet substrate before printing. 3. Spray primer over substrate before printing.	

07.

MATERIAL DESIGN EXPERIMENTS

7.1. Introduction

In the section “06. Material Design Research”, key printing parameters and methods to influence these key parameters with the decision making model are identified. In the section “05. Tool Design”, various tools are designed and built that can be used to develop and test gypsum-based printing mixtures for the in-situ AM application. In this section, the knowledge gained in “06. Material Design Research” and the knowledge gained on 3D printing in “04. Digital Fabrication” section will be used in combination with the built 3D printing tools to develop compatible and printable gypsum-based mixtures through various experiments.

A framework is made for the design and assessment of 3D printable gypsum-based mixtures (see Figure 102 on page 105), based on a framework made by Ma et al. 2018 for concrete 3D printing. The printing material is developed with experiments which evaluate: pumpability through determining the required pumping pressure; extrudability through assessing line continuity and printing resolution; buildability through assessing number of stackable layers; open time through assessing the timeframe in which the material is in a printable state; adhesion in fresh state through assessing stability during printing on inclined angles; adhesion in dried state through determining the pull-out force; and aesthetic compatibility through assessing the colour and texture post drying. This is visualized in Figure 105.

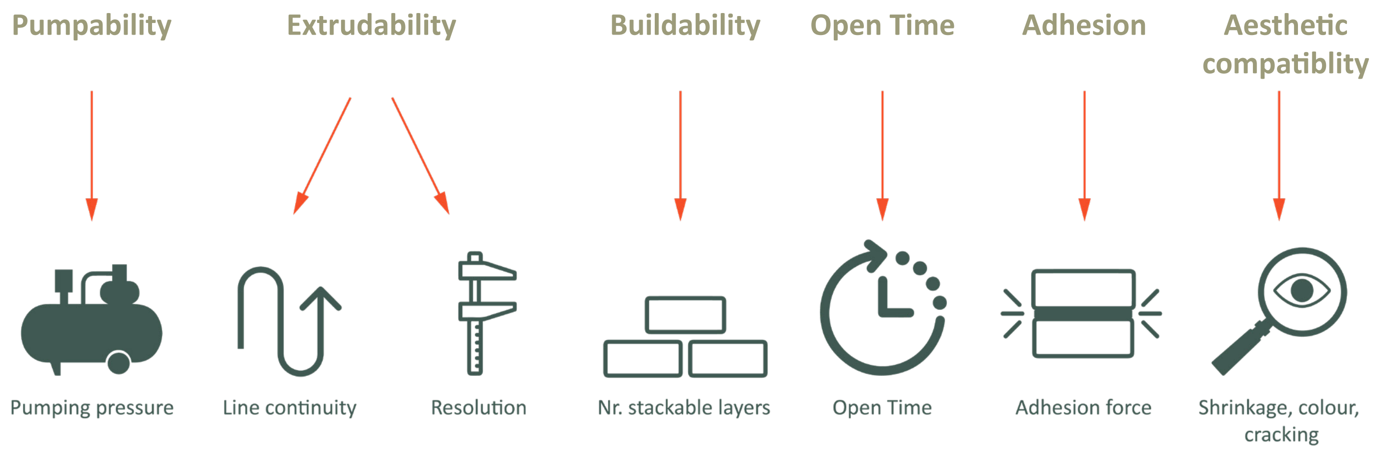


Figure 105 Key printing criteria and assessment factors. Source: Author.

7.2. Material making procedure

Two different gypsum products are tested for the manual experimenting phase. The first is the Molda 3 Normal gypsum, manufactured by Formula Saint Gobain. Molda 3 Normal is often used for restoration of ornaments by Delstuc Stucadoors according to Anton van Delden in personal correspondence. According to the manufacturer this gypsum has a minimum purity of 91% and various chemical-, setting-, physical- and mechanical properties are described (see Appendix H).

The second type of gypsum powder tested is Knauf Rotband, which is sold by Knauf as a construction material for plastering walls. The manufacturer also describes on the package that a mixture made with Rotband can be applied onto a wall immediately after mixing and has a long open time of about 1.5 hours, which seems promising. A safety sheet provided by the manufacturer (see Appendix H) describes about half a dozen additives such as hydrated lime, surfactants, cellulose ether, natural oxycarbonate-acids plasticizers and emulsifiers which are likely responsible for the long described open time. Note: this gypsum was considered after the Molda 3 Normal showed very poor results in the first experiments.

As aggregate/filler material white Carrara marble powder is used from DIY shop De Hazelaar. This marble powder has a grain size smaller than 1mm according to the manufacturer. Marble powder is white, not soluble which means it can help to provide additional strength to the mixture and so it is suitable for this application.

Note: The gypsum products used are not pure gypsum but contain additives. For the Knauf product these additives are mentioned in the previous paragraph. For the Molda gypsum the additives are not mentioned by the manufacturer. For the sake of ease, these products, which are not 100% pure gypsum, will be referred to as “gypsum”.

7.2.1. Mixing procedure

The mixing procedure requires five main tools:

- Bucket
- Measuring beaker
- Plastic cup
- Electric mixer
- Weighing scale

Figure 106 Scale and mixing bucket. Source: Author

Figure 107 Mixing procedure. Source: Author

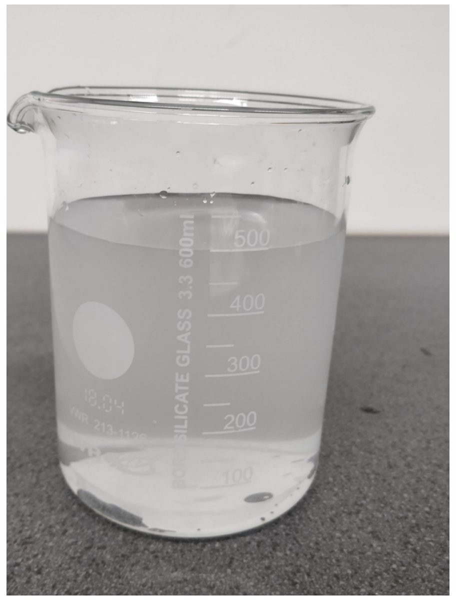


Figure 108 Measuring beaker. Source: author

After calibrating the scale, the water is added first in the desired amount. After this the gypsum is sprinkled in slowly and evenly into the bucket until a heap is formed in the middle. After this, any additional aggregates are added in the desired amount and the mixture is mixed with an electric mixture until a lump-free mixture is created. The mixing takes about 1-2 minutes. This procedure was observed during the visit to Delstuc stukadoors in January 2020.

7.2.2. Tested recipes

Twelve main different mixture recipes are created and tested. The first three are made with Molda 3 Normal and the rest is made with Knauf Rotband. The exact ingredients and ratios can be found in the table in Figure 109. The following chapters will describe the main findings of the experiments.

Sample	Gypsum product type	Water (mL)	Marble powder (g)	Gypsum (g)	Gypsum/ Marble powder ratio (-)	Gypsum/ water ratio (-)
G0	Molda 3 Normaal	500	0	775		1,55/1
G1	Molda 3 Normaal	170	0	300		1,75/1
G2	Molda 3 Normaal	195	150	300	02:01	1,55/1
G3	Knauf Rotband	195	0	300		1,55/1
G4	Knauf Rotband	295	300	330	01:01	1,02/1
G5	Knauf Rotband	200	100	300	03:01	1,50/1
G6	Knauf Rotband	200	50	300	06:01	1,50/1
G7	Knauf Rotband	130	100	200	02:01	1,50/1
G8	Knauf Rotband	130	80	200	2,5:01	1,50/1
G9	Knauf Rotband	130	50	200	04:01	1,50/1
G10	Knauf Rotband	82	0	100		1,22/1
G11	Knauf Rotband	130	67	200	03:01 (sieved)	1,50:1

Figure 109 Table showing the 12 main tested material recipes. Source: Author.

7.3. Open Time

7.3.1. Introduction & experiment setup

The first set of experiments focus on finding suitable water/binder ratios for the printing material and to determine the Open Time of mixtures with different water/binder ratios. The initial ratios considered are the ratios advised by the manufacturer of the respective gypsum products, in this case Molda and Knauf. Subsequently, the ratio water to binder is increased and decreased in different sample mixes to observe the effects of this on the properties of the mixture. The goal of this series of experiments is to qualitatively determine a suitable 'workability' for the mixtures. This qualitative determination of the workability is done by means of manually extruding the mixtures through a syringe with a 5mm nozzle diameter in certain time intervals after mixing of the raw materials has commenced.

Observations on initial and final setting time are recorded in the attached table and are compared to each other. "Preparation time" is the time it takes from the start of mixing until the mixture has reached an extrudable state, which is called "Start Open Time". Note that Preparation Time is a time span and Start Open Time is a time mark. "Open Time" is the time span between the Start Open Time moment and the end of the printable state of the mixture. The end of the printable state of a mixture is indicated by the inability of the material to be extruded out of the extruder with a constant pressure, as it clogs. This principle is visualized in Figure 110.

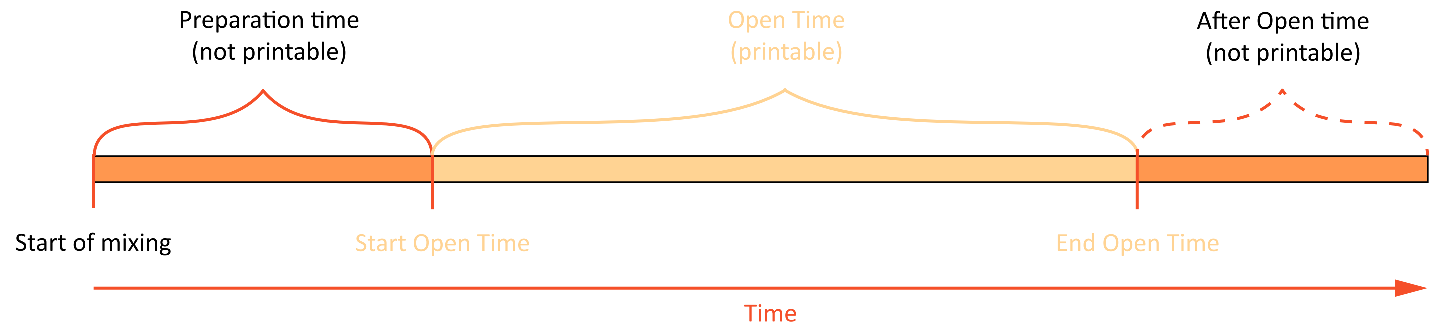


Figure 110 Scheme showing concepts of Open Time. Source: Author.

7.3.2. Results

Initial experiments show that mixtures made with Molda 3 Normal remain too liquid for about 10 to 15 minutes to print. When put inside a syringe, the mixture flows out by itself. After about 10 to 15 minutes, the mixture is extrudable for 1 to 4 minutes, after which it is too thick inside the syringe to extrude any longer. After about 25 minutes the mixtures completely harden out. This behaviour indicates that mixtures made with Molda 3 Normal gypsum have a very short Open Time (1 – 4 minutes) and are therefore unsuitable for AM applications. This type of gypsum is generally used for pouring into moulds, for which 1-4 minutes is a long enough Open Time.

The initial tests with Knauf Rotband give much better results. About 35 minutes of Open Time is determined for mixture. After making some changes in the mixture ratios, Open Time is extended to around 80 minutes for G4, G5, G6 and G11. This is a sufficient Open Time for 3D printing small to medium sized objects. All results are recorded in the table in Figure 111.

Sample	Gypsum type	Start time mixing	Start Open Time (min)	Preparation Time (min)	End of Open Time (min)	Open time (min)
G0	Molda 3 Normal	0	16	16	20	4
G1	Molda 3 Normal	0	9	9	11	2
G2	Molda 3 Normal	0	10	10	11	1
G3	Knauf Rotband	0	5	5	40	35
G4	Knauf Rotband	0	16	16	100	84
G5	Knauf Rotband	0	5	5	83	78
G6	Knauf Rotband	0	5	5	90	85
G7	Knauf Rotband	0	5	5	45	40
G8	Knauf Rotband	0	5	5	50	45
G9	Knauf Rotband	0	5	5	50	45
G10	Knauf Rotband	-	-	-	-	0
G11	Knauf Rotband	0	5	0	85	80

Figure 111 *Table showing recorded Open Time for the tested material recipes. Source: Author.*

7.4. Extrudability

7.4.1. Introduction

Extrudability is the reliability and ease with which a material can be deposited through a deposition device (Lim et al., 2012), such as a nozzle. A mixture exhibiting good extrudability can be reliably and easily, so with constant flow and without clogging, be extruded out of a nozzle during the AM process. There are two main aspects of extrudability which are important to assess for the restoration application: line continuity and printing resolution.

7.4.2. Experiment setup: Line continuity

Line continuity is, as the name suggests, how well a material can be extruded continuously without breaking or interruptions in the flow. To assess this, an experiment is set up in which a mixture is extruded continuously to create rectangles of roughly 30 X 10 cm. The number of times that the line breaks during continuous extrusion is used to give a comparative visual score between 1 (very poor line continuity) and 5 (very good line continuity). A mixture with more broken lines has a poorer line continuity than a mixture with less broken lines. The initial tests were conducted with the syringe and later tests were conducted with syringe, caulking gun and the built robot extruder to compare the results of using different tools.

Figure 112 *Syringe. Source: Author.*

Figure 113 *Robot extruder. Source: Author.*

Figure 114 *Electric caulking gun Source: https://www.hbm-machines.com/producten/hbm-elektrische-kitspuit-compleet-18-volt*

7.4.3. Results: Line continuity

Initial tests conducted with sample G0 with the syringe showed poor line continuity. This improved with G1-G3, but was still showed many interruptions in the rectangle shape (see Figure 115). The Molda gypsum was initially too liquid and would shoot out abruptly, and quickly after that would clog, which is why samples G0-G2 shows poor line continuity.

Mixtures made with Knauf Rotband, which have a much longer Open Time, showed better results in line continuity, as the material could retain the same consistency for a longer period of time. It was observed that a too high gypsum to water ratio resulted in the mixture being too dry and causing the lines to break (see Figure 116). Mixtures that were more liquid showed better line continuity.

Figure 115 Many interruptions in lines for G1, G2, G3 with hand extruder. Source: Author.

Figure 116 More line interruptions in G1-G3. Source: Author.

Figure 117 Hardly any line interruptions for G5, G6 G7. Source: Author

Figure 118 No interruptions in G5, extruded with robot extruder. Source: Author.

After many tests, it turned out that the tools used for extruding the material have an effect on line continuity as well. Tests conducted with the caulking gun and robot extruder showed better results than tests with the syringe. This suggests that a constant flow or pressure is crucial for proper line continuity. Another observation made, was that air bubbles should be avoided in the material reservoir before extrusion. Air bubbles also have to leave the reservoir and when they pop out of the nozzle, they break the extrusion line. A method of avoiding air bubbles is to close the material reservoir and bounce it on the floor with the end from which the material is supposed to flow out from pointing down. In this way, the printing material goes down in the reservoir to fill in gaps left by larger air bubbles.

Mixture G5 showed the best results (see Figure 118) when extruding with the robot extruder. No interruptions were seen in the line, except for one where a large air bubble popped out. The consistency of this mixture, which has a 3:2:1 gypsum : water : marble powder ratio showed the best results. The visual score of all tested mixtures can be found in the table in Figure 119.

Sample	Line continuity (1-5)
G0	1
G1	2
G2	3
G3	4
G4	4
G5	5
G6	4
G7	4
G8	4
G9	4
G10	4
G11	5

Figure 119 Table showing visual score of line continuity for various tested mixtures. Source: Author.

7.4.4. Experiment setup: Printing resolution

Printing resolution has to do with how small the extrusion width and layer height of a mixture can be achieved. The main limiting factor in this is the size of the aggregates, which if too big, can clog inside small nozzles. Layer height cannot be tested without a 3D printer or robot, since precise control of the extrusion speed and movement of the print head is required, so extrusion width will be considered to assess the printing resolution of a mixture. For a given extrusion width, the layer height achievable can be assumed to be roughly 1/3 to ½ the size. The size of the nozzle decides to a certain extent the size of the extruded element (see Figure 120), however the width of the extruded lines can be changed by changing the extrusion speed (see Figure 121). A faster extrusion speed means a wider extruded line and vice versa.

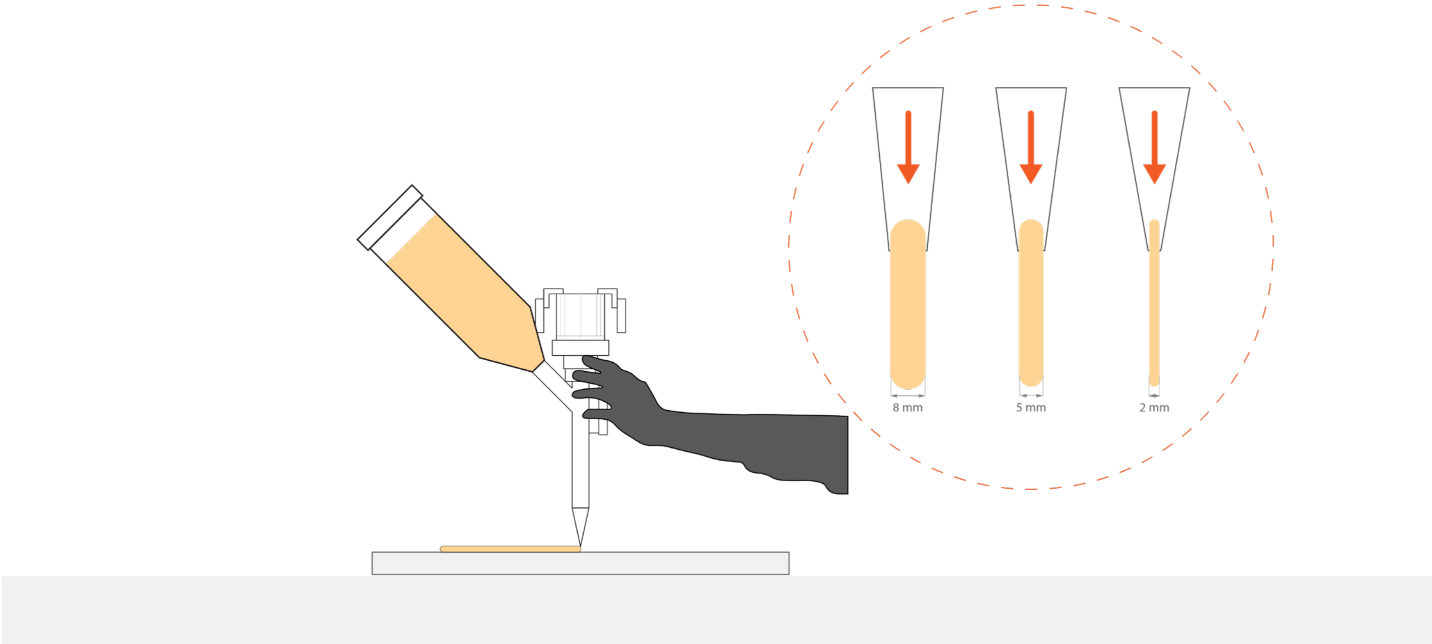


Figure 120 Material takes shape of nozzle when being extruded at a certain speed. Source: author.

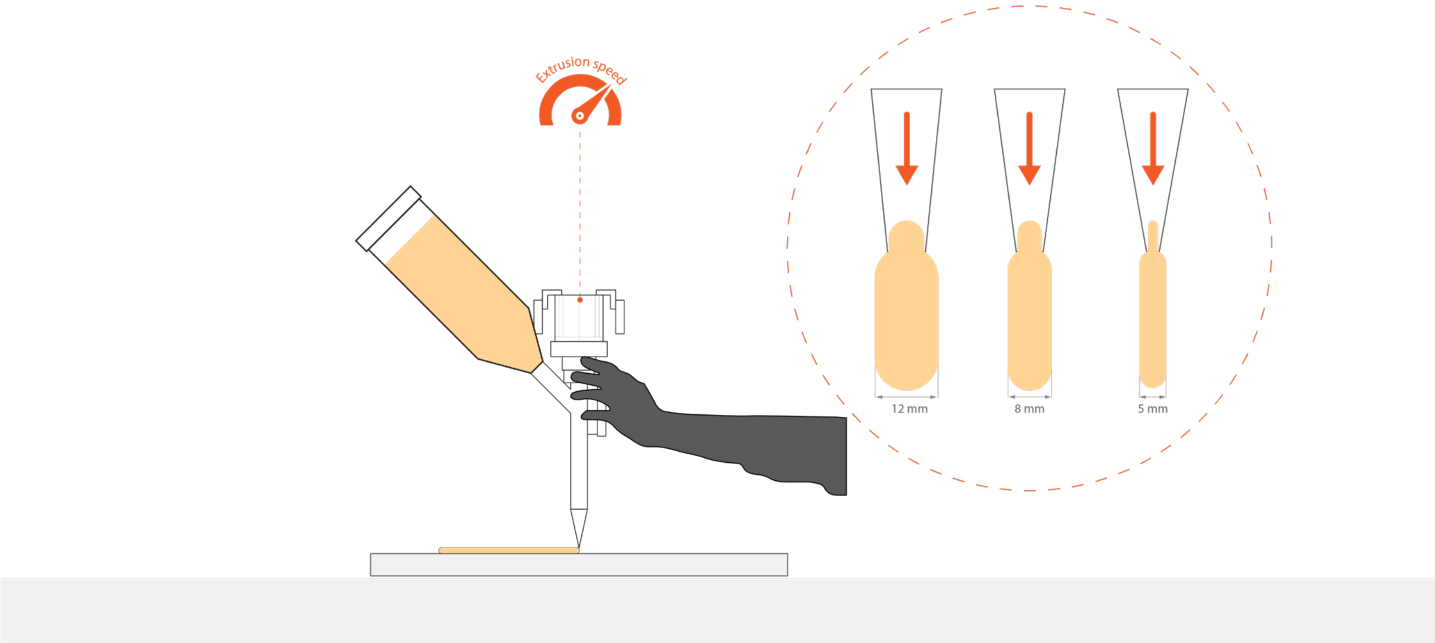


Figure 121 Extrusion width can be changed by changing extrusion speed. Source: Author.

To assess the printing resolution possible with a mixture, the mixtures are extruded through increasingly finer nozzles (see Figure 122) with varying extrusion speeds. Eventually, a mixture will likely clog inside a nozzle which has a diameter which is too small. This limit will be recorded, and the width of the finest lines extruded of a mixture will be measured with a calliper. This will be the minimum achievable extrusion width and the layer height will be calculated as 1/3 – 1/2 of this measurement. Together these figures will determine the printing resolution of a mixture.

Figure 122 Various sized nozzles, between 1 and 5 mm, used for the printing resolution tests. Source: Author.

Note: The experiments on printing resolution were conducted later on in the experimenting phase of the research, so the experiments focus around variations of mixture G5, which was selected for further development due to its good overall printing properties.

7.4.5. Results: Printing resolution

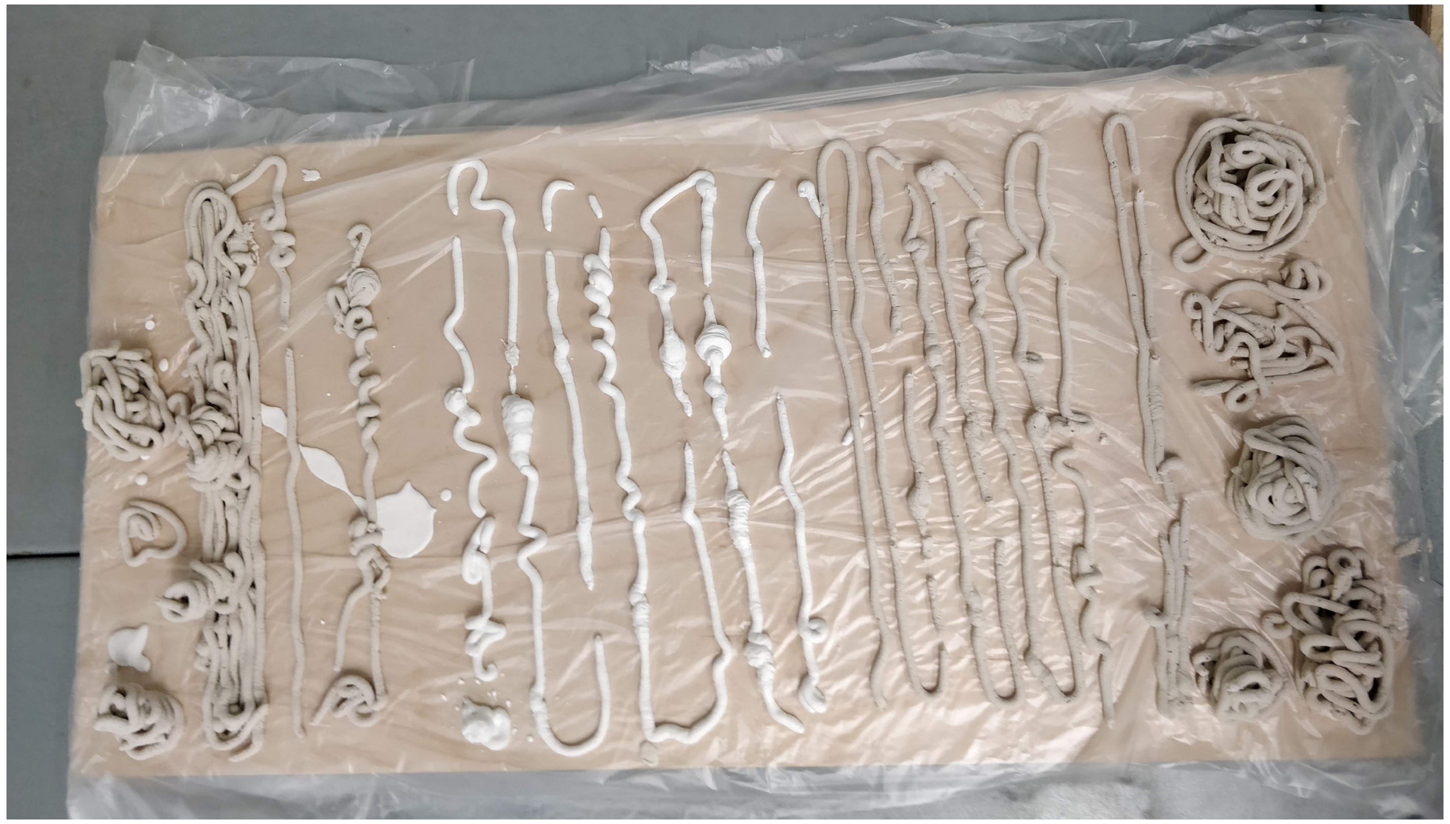


Figure 123 Various mixtures tested. Source: Author.

Nozzle of 4,55 diameter was used initially to extrude the mixtures. All mixtures were extrudable through this nozzle and the extrusion width, depending on the extrusion speed, was a little smaller or larger than the nozzle size. Mixture G3 and G5 were extrudable through a 2,5mm nozzle.

A nozzle of 1,75 mm was also used for extruding the best performing mixtures G3 and G5, but for this nozzle the material was extrudable for a length of about 30 centimetre, after which the material clogged inside the nozzle. The short extruded sample had an average width of 1,7mm. Increasing the extrusions pressure did not result in the material being extruded out of the nozzle, but rather the plastic glue cartridge which housed the mixture was deformed under pressure. Upon closer inspection of the clogged nozzle, many aggregate particles could be seen accumulated inside the nozzle to make the nozzle clog (see Figure 124). This suggests that the larger aggregates are preventing the mixture to be extruded through a smaller nozzle, which is limiting the printing resolution.

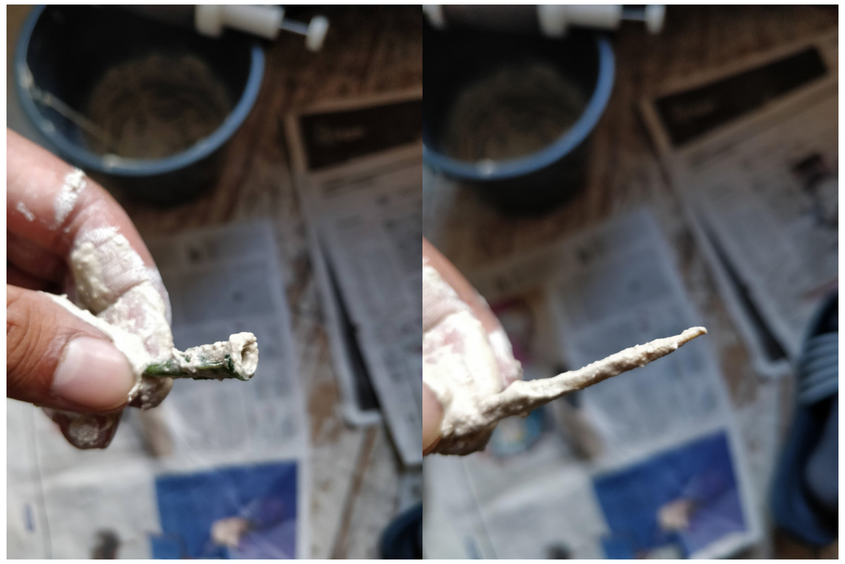


Figure 124 Left: clogged nozzle. Right: stick with aggregate particles removed from clogged nozzle. Source: Author.

To make sure it is indeed the aggregates which is causing the mixture to clog and not the viscosity, an additional experiment was conducted. A more watered down mixture without marble powder, mixture G10 with a 1,22:1 gypsum to water ratio was created for testing. By eliminating the marble powder and watering the mixture down, G10 would have a lower viscosity and if viscosity was indeed the limiting factor, this mixture should theoretically be able to be extruded continuously trough a nozzle as small as 1,75mm.

However, this sample showed similar results to sample G5 when extruding through a 1,75 mm nozzle. The extrusion rate decreased, as the nozzle started to get clogged after about 30-40 cm of continuous extrusion. Upon close inspection of this clogged nozzle, similar observations were made as the nozzle used for the G3 and G5 mixtures. Many small particles were accumulated inside the nozzle again. According to Knauf, the manufacturer of the Knauf Rotband gypsum, Rotband contains light mineral aggregates ("licht minerale toeslagstof"). It is unclear what this aggregate is, but this is likely the cause small nozzles keep clogging and thus the main limiting factor to the printing resolution.

Sieving gypsum powder

After the observations made in previous experiments, it was decided to investigate if a mixture could be extruded through a smaller nozzle if the gypsum powder would be sieved to filter out larger aggregate particles. A sieve with 1mm holes was used to filter the Knauf Rotband gypsum powder. After sieving, particles larger than 1mm were filtered out, leaving a much finer powder behind (see Figure 125).

Figure 125 *Sieving the gypsum with a sieve of 1mm. Source: Author.*

The sieved Knauf powder, which now consisted of particles smaller than 1mm, was used to create a mixture in a 1,55:1 gypsum : water ratio (mixture G11). This mixture was extrudable continuously through a nozzle of 1mm, resulting in samples with an extrusion width of 1mm (see Figure 126 and Figure 127). This experiment proves that by reducing the aggregate size, the printing resolution can be improved. When trying to extrude this mixture through a 0,5mm nozzle, the mixture clogged inside the nozzle. It can be expected that if the Knauf powder is sieved with an even finer sieve, an even higher printing resolution can be achieved. Additionally, this mixture also has a long Open time of 85 minutes. Mixture G11, which has the same recipe as mixture G5, but is sieved through a sieve with 1mm holes, shows the highest printing resolution: **1mm extrusion width**, which means a **0.3-0.5mm layer height** should be achievable. An overview of the printing restolution of all tested samples can be found in the table in Figure 128.

Figure 126 *1mm extrusions of G11 with coin for scale. Source: Author.*

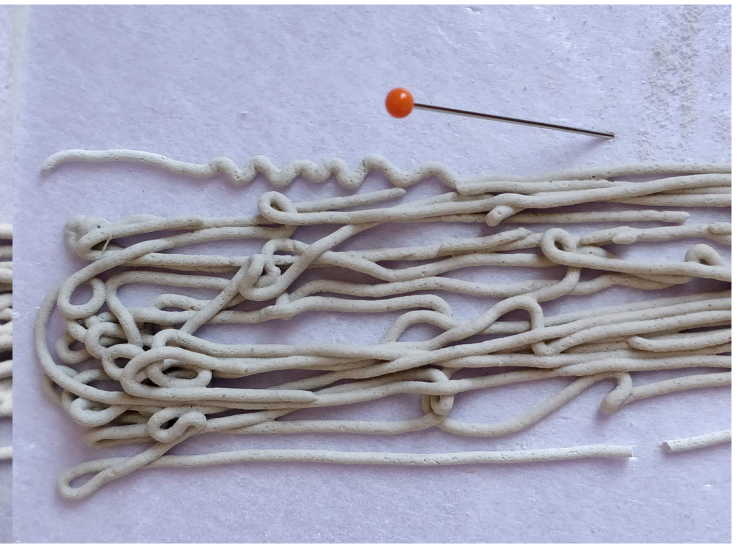


Figure 127 *1mm extrusions of G11 with pin for scale. Source: Author.*

Sample	Nozzle diameter (mm)	Extrusion width (mm)
G0	5	.
G1	5	.
G2	5	.
G3	2,25	2,5
G4	4,55	
G5	2,25	2,5
G6	4,55	5,5
G7	4,55	4,6
G8	4,55	4,8
G9	4,55	4,5
G10	2,5	2,5
G11	1	1

Figure 128 *Table showing printing resolution of various tested mixtures. Source: Author.*

7.5. Aesthetical compatibility

7.5.1. Introduction

Aesthetical compatibility, as described in “06. Material Design Research”, has to do with the colour and texture of the printed object and original substrate. Colour will not be assessed in this research.

7.5.2. Experiment setup: Shrinkage & cracking

To assess shrinkage, straight lines are extruded with the various mixture recipes and are measured in length right after extrusion. The lines are again measured 48 hours after drying and any changes in length is recorded.

If a material dries, it usually does not dry uniformly. This means some parts of the material such as the outside, may dry faster than the inside, which may lead to cracking. Since there is no real unit of measurement to measure cracking, samples extruded with the various mixture recipes will be given a visual score between 1 (least amount of cracking) and 5 (most amount of cracking), which means this will be a comparative assessment.

7.5.3. Results: Shrinkage & cracking

Shrinkage

None of the tested samples with the various mixtures showed any measurable shrinkage. An additional test was conducted by putting bit of a mixture into a small round container and checking if the material would have detached from the sides of the round container after drying. Again, no noticeable or measurable shrinkage was found.

Cracking

Samples made with mixtures G0 and G1 (made with the Molda gypsum) show no visible cracking, they have a pure white colour and a smooth surface (Figure 129). This complies with the desired texture and colour. However, these mixtures were later ruled out because they exhibited very poor overal printing properties.

Samples made with mixtures G4 to G11 show varying levels of cracking (see Figure 130 and Figure 131). An important observation made during the tests is that air bubbles trapped inside the mixture can leave small gaps in the extruded samples, which look like cracks. To avoid this, air bubbles should be removed as much as possible before printing.

Samples extruded with mixture G5 show the best overall results. These printed objects have a smooth, white, crackles surface, as is desired. This can be seen in Figure 132. Results of the visual scores compiled from all experiments from the various tested mixtures can be found in the table in .

Figure 129 G0, G1 and G2 showing a smooth surface. Source: Author.

Figure 130 G4 Showing a lot of cracking. Source: Author.

Figure 131 G8 showing rough surface texture. Source: Author.

Figure 132 G5 showing a smooth, crackles, white surface. Source: Author.

Sample	Cracking (1-5)
G0	1
G1	1
G2	3
G3	2
G4	4
G5	1
G6	2
G7	2
G8	3
G9	2
G10	3
G11	2

Figure 133 Table showing cracking assessment of various tested mixture recipes. Source: Author.

7.5.4. Milling of dried geometry
An additional experiment was conducted to see if 3D printed gypsum objects can be successfully milled. Milling may be a post processing method to create fine details in a printed geometry if the desired printing resolution cannot be achieved.

A sample created with mix G5 was postprocessed by milling it after having dried for a week. The milling was conducted with a rotary multitool with a sanding bit attached. The material seemed easy to manipulate with the multitool and relatively accurate cuts and smoothening seemed possible. Protruding printed parts, which had a small contact area with the rest of the geometry were however dislodged by the rotary tool. This suggests that it may not be possible to mill very thin and long protruding elements as they may break off. However, the test showed that the material can be milled with ease and surfaces consisting of large stepped contour lines resulting from a large extrusion width or layer height may be smoothened out in this way.

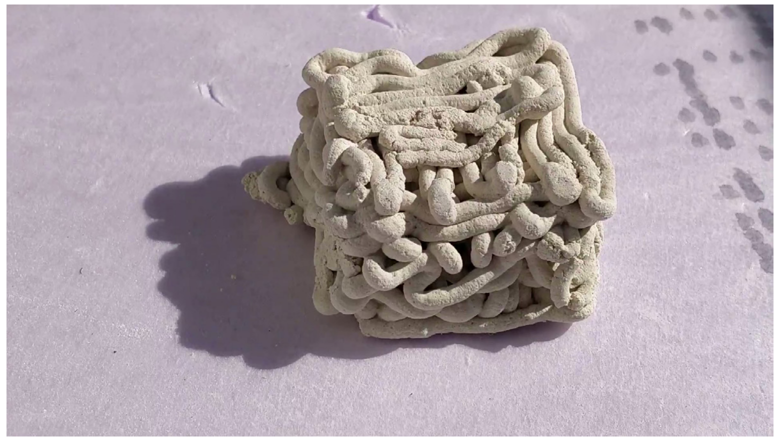


Figure 134 *3D printed gypsum sample before milling test. Source: Author.*

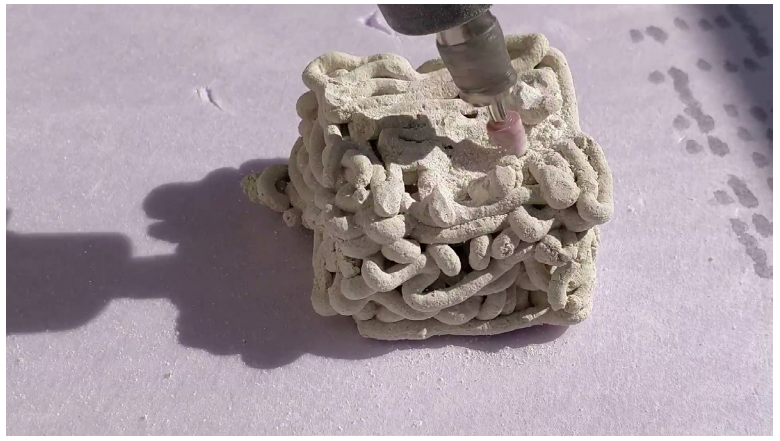


Figure 135 *3D printed gypsum sample during milling test. Source: Author.*

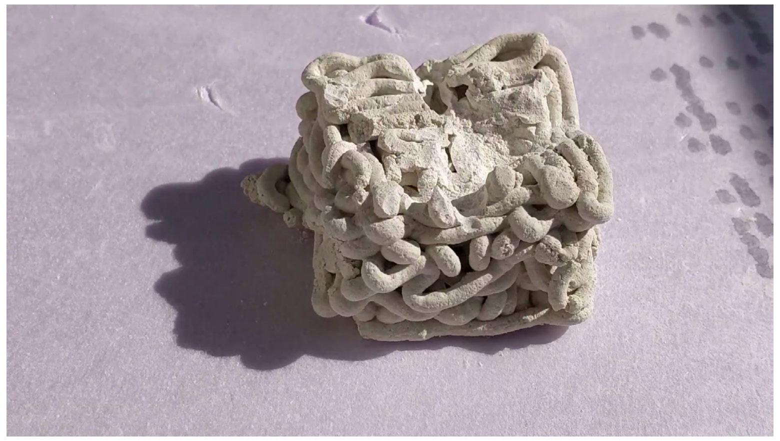


Figure 136 *3D printed gypsum sample after milling test. Source: Author.*

7.6. Buildability
7.6.1. Introduction
Buildability is the ability of a material to retain its extruded shape under self-weight and pressure from upper layers when it is not yet fully cured (Lim et al., 2012)(Ma et al., 2018). To assess buildability, an experiment is set up, based on experiments conducted by Ma et al. 2018 and Lim et al. 2012 on concrete 3D printing.

7.6.2. Experiment setup
Each mixture is tested on how many layers can be stacked on top of each other until noticeable deformations occur the geometry. This can give an indication of how "buildable" the mixture is at a given moment. At least three samples are extruded with each mixture recipe (with the exception of recipe G1 and G2 as these mixtures hardened out before more samples could be extruded). Mixtures with higher number of stackable layers are better than mixtures with lower number of layers. Subsequent tests try to improve the mixture recipes based on observations and the decision making model to improve buildability of the mixtures.

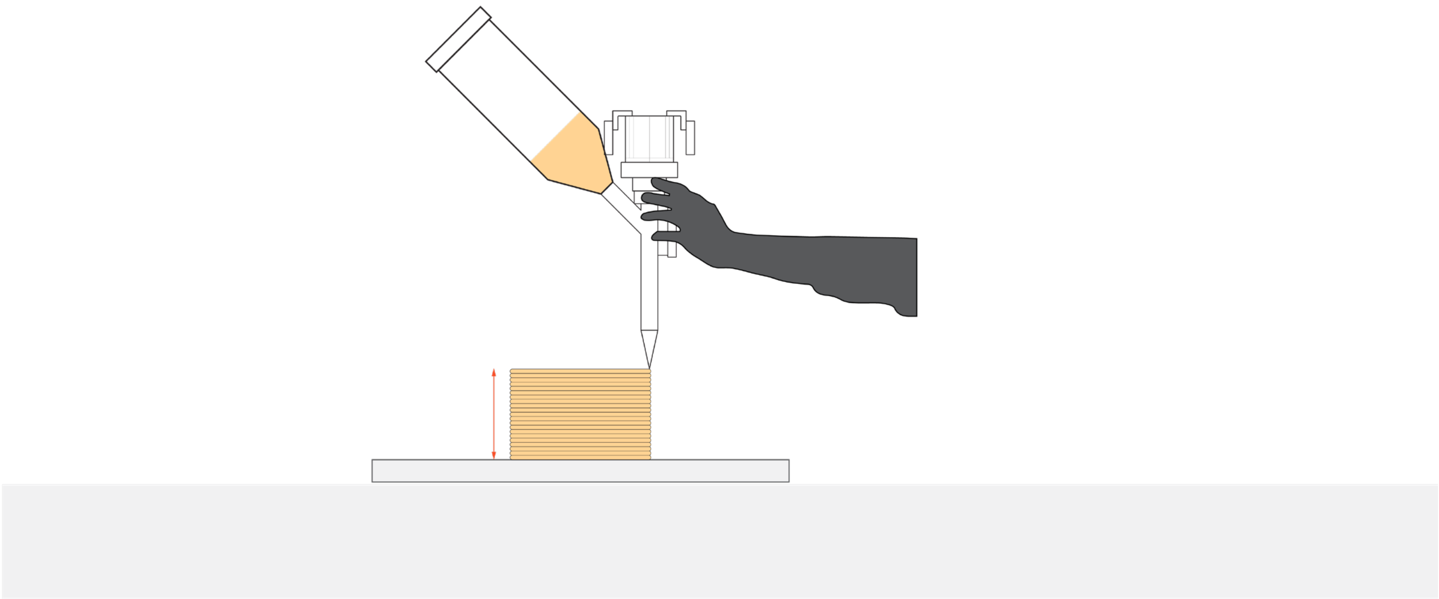


Figure 137 *Scheme of Buildability experiment setup. Source: Author.*

7.6.3. Results
The initial tests performed with Molda gypsum were not successful in creating a buildable material. The printed samples would deform under pressure of the second layer already. Samples tested with G3 and G4, made with Knauf Rotband, were performing better as they were stackable for 5 layers. The introduction of marble powder in varying amounts shows a significant improvement in overall buildability over mixtures without it. Because the marble powder does not dissolve in water, it remains as solid particles in the mixture to help support the weight of additional layers. Furthermore, the marble powder seems to make the mixture less watery, which gives it higher strength after extrusion.

However, too much marble powder makes the mixture too dry and un-extrudable. This was discovered when creating mixture G4 in a 1:1:0,65 ration between gypsum : marble powder: water. This mixture was too dry and thick to be extruded (see Figure 138). Adding more water to this mixture to make the ratio 1:1:1 did make the material extrudable, but it remained too liquid to maintain its shape after extrusion for about 80 minutes (see Figure 139). This experiment shows that a 1:1 gypsum to marble powder ratio is too high.

Figure 138 Mixture with gypsum : marble powder : water in 1.5:1.5:1 ratio. This mixture is too dry to be extruded. Source: Author.

Figure 139 Mixture G4 with gypsum : marble powder : water in 1:1:1 ratio. This mixture is too liquid to maintain its shape. Source: Author.

After these initial experiments, mixtures were created by fixing the gypsum to water ratio at 1.55:1 and varying the gypsum to marble powder ratio between 1:0 and 1:1. Mixtures G4 to G9 are created in this way.

Mixture G5, which features marble powder, at 3:1 gypsum: marble powder ratio, shows a four times higher buildability than sample G3, which has the same gypsum to water ratio, but no marble powder. This suggests marble powder in this 3:1 ratio, improves buildability of the mixture (see Figure 145). By plotting buildability against gypsum to marble powder ratios, there seems to be an "optimum" around a 3:1 ratio between gypsum and marble powder (see Figure 140). All buildability results from the various tested mixtures are compiled in the table in Figure 145.

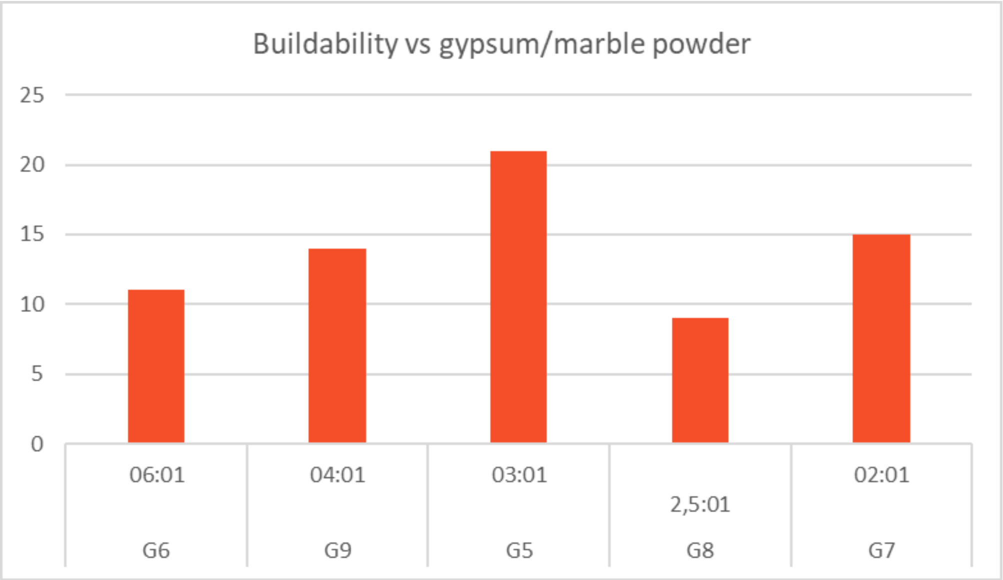


Figure 140 Number of stackable layers vs. gypsum/marble powder ratio. Source: Author

Figure 141 Samples made with mixtures G3 and G4. Source: Author.

Figure 142 Samples made with mixtures G3 and G4. Source: Author.

Figure 144 Samples made with mixtures G5 and G6. Source: Author.

Figure 143 Samples made with mixtures G5, G6 and G7. Source: Author.

Sample	Nr. Of layers without collapse
G	1
G1	1
G2	1
G3	5
G4	5
G5	21
G6	11
G7	15
G8	9
G9	14
G10	-
G11	-

Figure 145 Table showing results of buildability experiments of various tested material mixtures. Source: Author.

7.6.4. Limitations

It is important to mention that buildability is a criterium which is heavily influenced by the precision of the testing procedure. The accuracy with which layers are stacked on top of each other has a big influence on deformation in the geometry, since inaccuracies can lead a printed sample to deform prematurely. Therefore, the values obtained from the experiments, which were conducted manually with a syringe, electric caulking gun or the designed extruder, are an indication of the actual buildability, but are limited by human inaccuracies of the person performing the tests. It is therefore highly recommended that in a further study, these experiments are performed with a robot or 3D printer, as such machines can have an accuracy of up to 0.03mm.

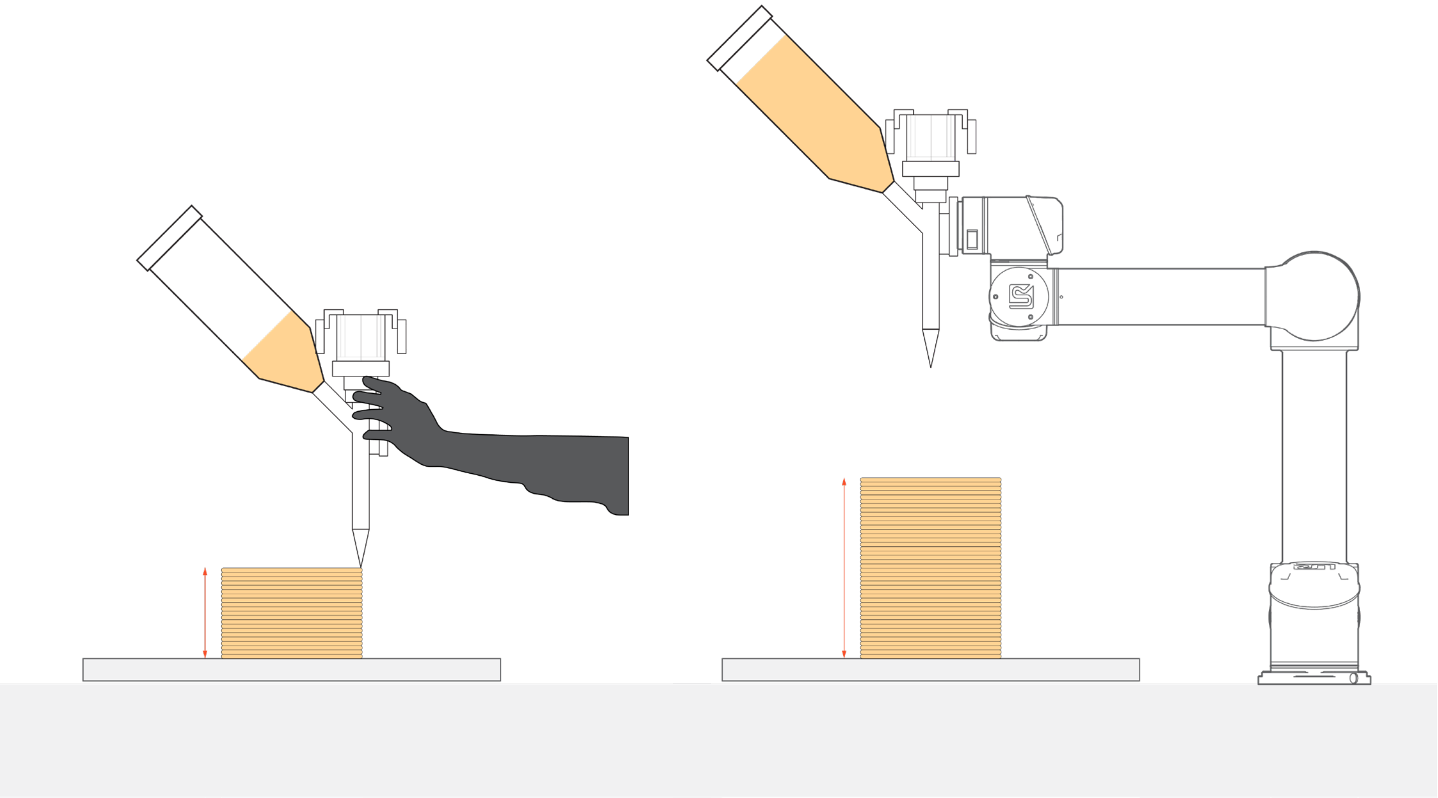


Figure 146 *Scheme showing that performing buildability tests with a robot, will likely yield much better results. Source: Author.*

7.7. Pumpability

7.7.1. Introduction

Pumpability is the ease and reliability with which material can be moved through a delivery system (Lim et al., 2012). This means that a material should be deliverable through a delivery system, homogeneously, so without blocking or clogging. This is important to ensure the right amount of material is delivered consistently from the material reservoir to the extruder during the AM restoration process. Throughout the experiments conducted to determine Open Time, Extrudability and Buildability, mixture G5 showed the best printing properties and was therefore selected for the next set of experiments.

7.7.2. Experiment setup

A simple experiment is setup to assess the pumpability of a mixture. The mixture is put inside the material reservoir, which is connected from one end to the extruder and from the other end to the compressor. The extruder is kept in a flat position, such that the material inside the reservoir or nozzle cannot move out due to gravity. By increasing the air pressure output on the compressor gradually, the material will at a certain pressure slowly start to be pushed out of the extruder due to the air pressure. This would be the required air pressure for the tested material. The lower the required pumping pressure to extrude a material with a good consistency for 3D printing, the better.

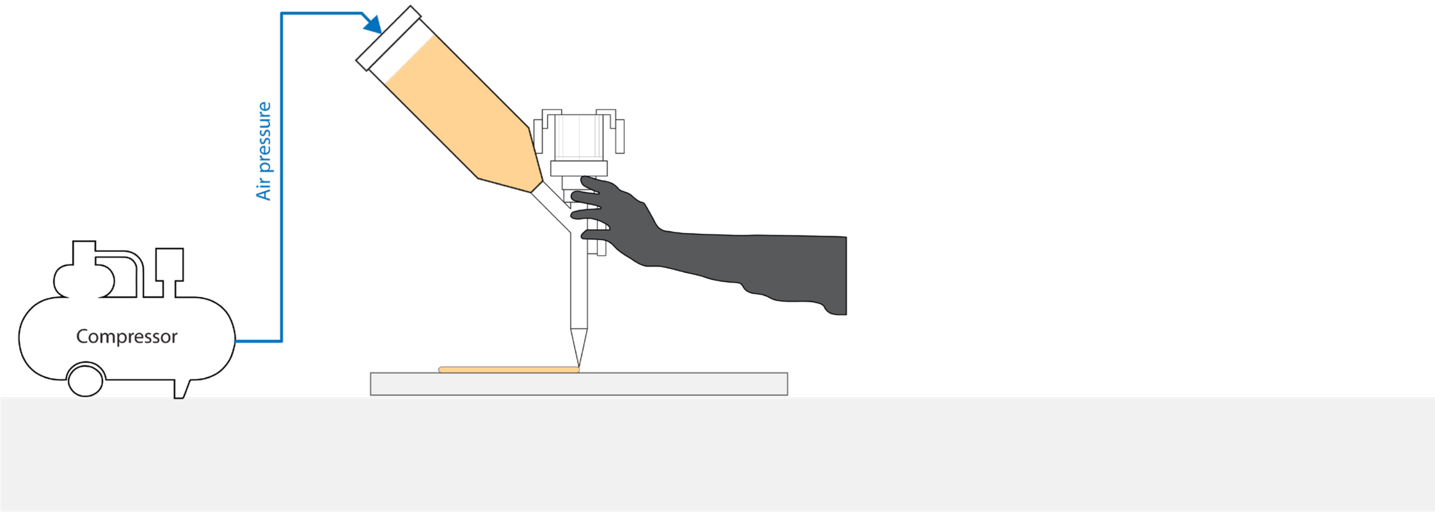


Figure 147 *Experiment setup for pumpability experiment. Source: Author.*

7.7.3. Results

The G5 mixture starts to move out of the extruder at a pressure of about 4 bar. It is already clear which mixture design factors influence the pumpability of the mixture, as discussed in section 6 "Printing Material Design". However, the experiments suggest that the required pressure may vary depending upon the smoothness of the inner surface of the material reservoir, material delivery tube and size of extruder nozzle. A rough inner surface would lead to a higher resistance, thus requiring more pumping pressure. The pumpability is therefore dependant both on the material delivery system and the material. Therefore, the exact pumping pressure required would need to be determined on site right before starting the restoration task. A flowmeter could be used to measure the amount of material passing through per second to determine the flow rate and adjust the pumping pressure accordingly.

7.8. Adhesion

7.8.1. Introduction

Good adhesion between a printed object and substrate is imperative for developing an in-situ AM technique for restoration of stucco ornaments. As mentioned, AM is almost exclusively done by laying layers of material vertically down on top of each other. In this case, material will be extruded on an inclined substrate. Experiments assessing adhesion in the fresh state, focus on assessing to what extent the printing material can be extruded at various inclinations without major deformations in the geometry. Experiments assessing adhesion in dried state, focus on assessing the how strong the adhesion between printed object and substrate is post drying.

7.8.2. Adhesion fresh state

Adhesion between a printed object and substrate during the AM process, so while the material is in a so called "fresh state", must be strong enough to allow the printed layers to stick to each other properly. This is particularly relevant when 3D printing on inclined substrates. At the same time, the material should have enough strength to support the weight of the subsequent layers which exert a force on the printed geometry. For good adhesion in fresh state, the material should be soft so it can stick to neighbouring layers, but too soft so it will droop and deform under pressure of subsequent layers. These objectives, as discussed in the conclusions of the section "Printing Material Design" require properties which are opposite to each other. Therefore, through the following experiments, a material recipe must be created which can balance between these contradicting factors.

7.8.3. Experiment setup: Adhesion fresh state

First, the gypsum printing bed was divided into 16 areas with the help of tape. Next, the gypsum printing bed was placed on the adjustable timber frame. The timber frame could be angled to 30, 45, 60- and 90-degree angles with the help of the steel L profiles drilled into the legs of the frame at set intervals.

A measuring scale was placed on the taped borders during an experiment. A camera mounted on a tripod would record the extrusion experiment in time-lapse mode. By analysing the time-lapse clip after the experiment, any deformations occurring in the geometry during the printing process would

Figure 148 Printing bed divided into 16 sections, placed on frame angled at 30 degrees. Source: Author

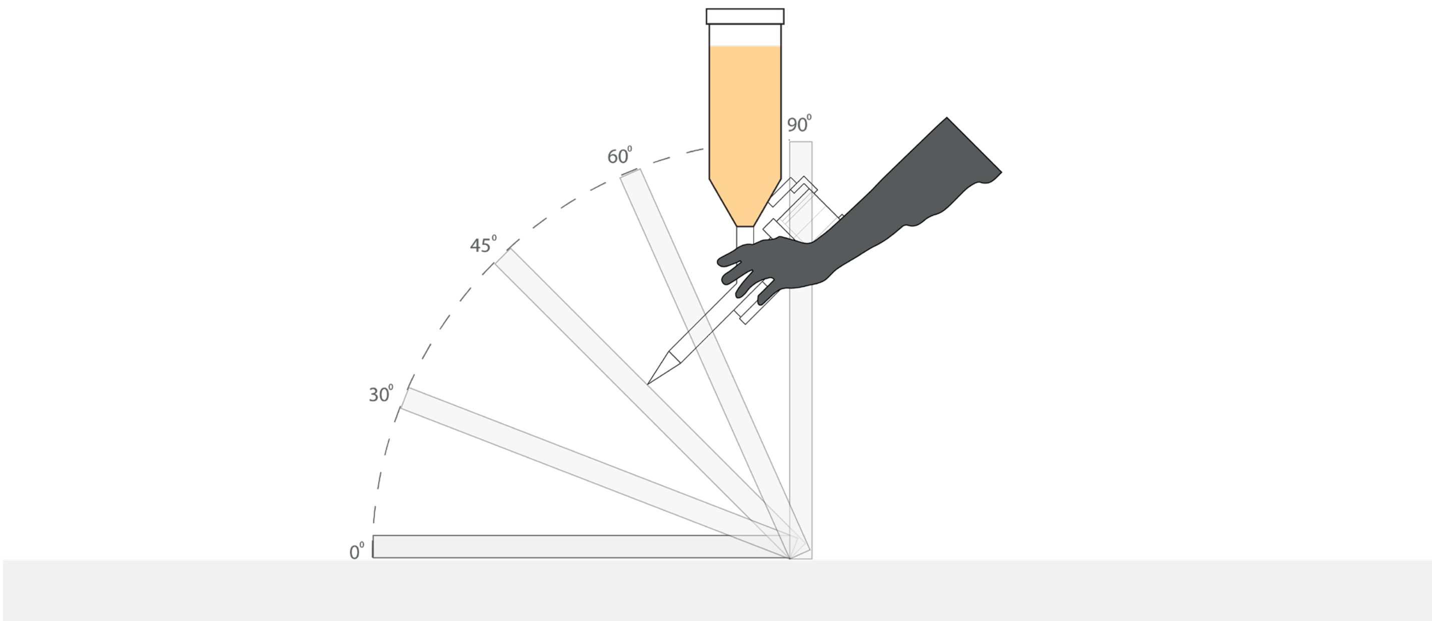


Figure 149 Setup of experiments for printing on inclined substrate. Source: Author

be evident. Each experiment would involve extruding a rectangle of approximately 6 X 5 cm (30cm^2 contact area) consisting of one outer ring and a zig-zag infill of close to 100%. After one layer, the infill direction would switch 90 degrees, and this would be repeated for a total of 5 layers for each sample. The total height of each sample was about 2 cm, making the volume of each sample about 60 cm^3.

7.8.4. Results: Adhesion fresh state

Mixture G5 could be extruded on 30, 45, 60 and 90 degrees of the printing bed without any noticeable deformations for 5 layers. Two additional samples were extruded; one onto an area with was sanded with sanding paper prior to extrusion; the other onto an area which was sprayed with some water prior to printing (see Figure 151). None of the printed samples showed any deformation during extrusion.

Figure 150 Printing bed angled at 90 degrees for adhesion experiments. Source: Author

Figure 151 Above: smooth untreated substrate; below: substrate sanded with sanding paper. Source: Author

Vertical 3D printing

An additional experiment was conducted to see how many layers could be extruded onto the substrate at 90 degrees (see Figure 152). The experiment showed that after 10 layers the sample collapsed under its own weight. Interestingly, the sample did not slide down the plate after the 11th layer, but rather tore off at the sixth layer (see Figure 153). This suggests that the adhesion strength of the sample onto the gypsum substrate was not the weakest link and was not the reason the sample collapsed, but rather that the geometry did not have enough strength to support the pressure of additional layers. As more and more layers are added, an increasing bending moment is created in the sample, resulting in a compressive force in the bottom of the sample and a tensile force at the top of the sample. The recorded clip shows that the sample tears at the top (due to this tensile force) and this tear gets larger and larger as the weight of the outer layers pull the sample apart eventually resulting in the outer layers dislodging from the sample. Interestingly, the first 5/6 layers remained on the gypsum substrate (see Figure 153). This suggests that in this experiment the strength of the geometry played a more crucial role in the collapse of the geometry than the adhesion strength onto the substrate. It also suggests, that the shear strength between the sample and the substrate is higher than the tensile strength of the sample material in fresh state. If the setting of the gypsum could be accelerated just as it is being extruded, the sample may gain enough strength to maintain its shape.

Figure 152 10 layers succesfully printed on 90 degrees substrate without noticeable deformations. Source: Author.

Figure 153 Geometry collapses after 11th layer is added. Source: Author.

Finally, mix G5 was printed upside down onto the printing bed. To do this, the printing bed was put on two tall chairs and the printing was done from below. The material showed good adhesion when printing upside down and it was possible to extrude 5 layers successfully “on top” of each other upside down (see Figure 154 and Figure 155).

One important observation is that when printing upside down, the distance between the nozzle and the printing target (target where the printed material is intended to go, either on the printing bed or on previously printed layers) is an important additional factor to keep in mind. If the nozzle is too far away from the printing target, the material will not touch the printing bed when it is extruded or will very lightly stick onto the printing target, which can result in the printed material falling or deforming downwards. When printing vertically down, as is common practise, and the distance between the nozzle and the printing target is too big, gravity will bring the material down to the printing target. When printing upside down, gravity pulls the material away from the printing target and so the distance between the nozzle and the printing target must be kept maintained constantly. When printing manually, though using an electric powered extruder, it is very difficult to maintain a suitable distance constantly, so it is difficult to create geometries printing upside down, that look like geometries that are printed vertically down or at inclinations up to 90 degrees. Printing with a robot or 3D printer can solve this issue, as the distance between the printing target and nozzle can be programmed into the robot code.

Since it is very difficult to print upside down manually while maintaining a suitable distance between the printing target and the nozzle, experiments could not be conducted to see how many layers can be successfully printed upside down until the geometry would deform or collapse. For such experiments, it is recommended to use a robot or 3D printer.

Figure 154 Upside down printed sample on the top right. Source: Author.

Figure 155 Upside down printed sample in front. Source: Author.

7.8.5. Experiment set-up: Adhesion dried state

The adhesion between printed object and substrate after drying is determined by performing pull-out tests. The goal of such a test is to determine how strong the bond between printed object and substrate is and to compare the strength of this bond to the amount of force there may be exerted on such an object in a realistic scenario. A good adhesion in this case means the adhesion strength is higher than the expected forces which may be applied to the printed object in a realistic scenario. At the same time the interface between the printed sample and substrate should ideally be the weakest link, so if for some reason the printed object must be removed at some point, it will not damage the original substrate.

To assess adhesion strength of the samples to the substrate after the samples have dried, another experiment was set up: a pull-out test. First, an extra, thin layer of G5 mixture was added with a trowel onto the surface of the printed samples and stroked smooth with a trowel to make a smooth surface on the top of each sample. This was necessary to create a flat, even surface for to stick elements onto for the pull-out test (see Figure 157). At least 48 hours after drying of the additional layer, small pieces of wood (60 * 50 * 35mm) were glued onto the top of the samples with Bison Montage Kit glue. Before gluing the wooden pieces, a small steel hook was drilled into each wooden piece (see Figure 158). This would later serve as anchoring point to exert a pulling force onto the sample. The Bison Montage Kit glue claims to be specially made to stick smooth surfaces onto porous surfaces such as brick or natural stone and claims to be able to hold up to 120kg through its adhesive strength, hence it was chosen.

Next, the gypsum plate with the samples prepared as earlier described was placed upside down in between two tall chairs, such that both chairs supported part of the plate and the samples were exposed freely

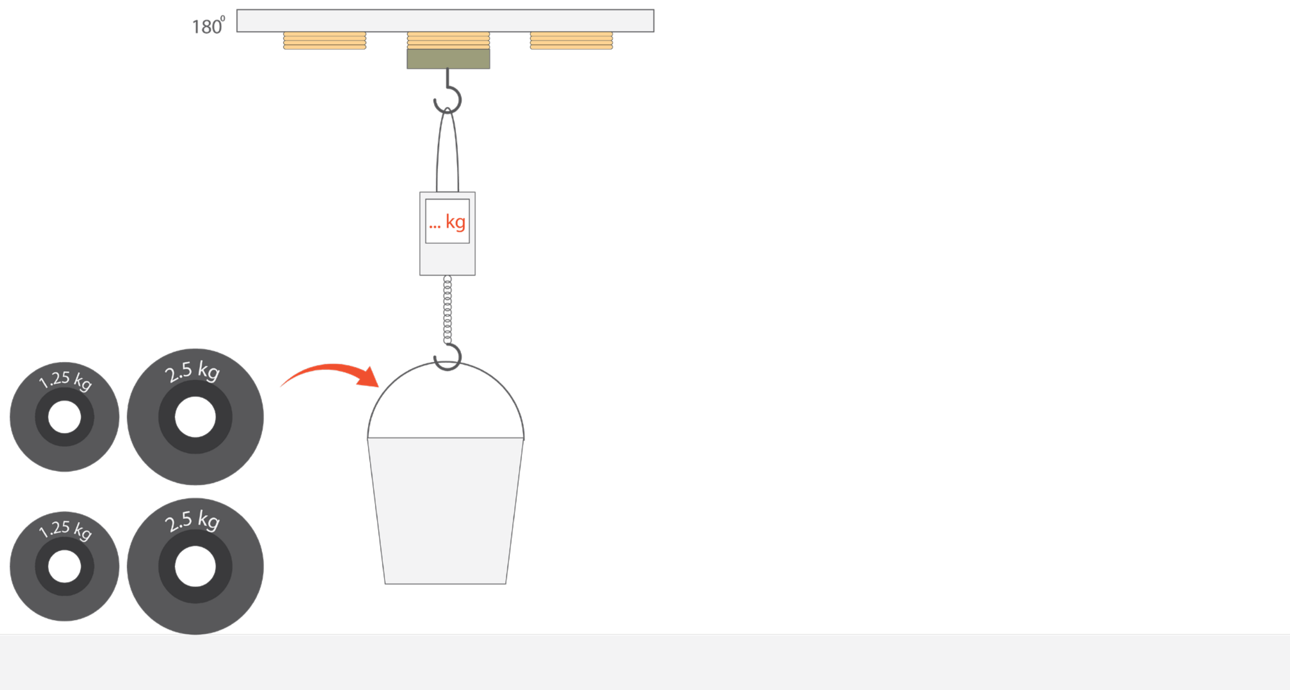


Figure 156 Pull-out test setup. Source: Author

underneath. A bucket filled with several dumbbell disks of 1,25kg and 2,5kg were used to exert a tensile force on the samples. A hanging weighing scale was used to measure the weight of the total load acting on the sample. The hanging weighing scale was attached with one end to the steel hook of a sample and with the other end to the handle of the bucket containing the weights. By adding a dumbbell disks to the bucket, the force pulling on the sample was increased in increments of 1,25 or 2,5 kg at a time. The force at which the sample is dislodged from the substrate can be read off on the weighing scale. The principle of the experiment is shown in Figure 156.

Figure 157 Creating a smooth top on the samples. Source: Author.

Figure 158 Wooden pieces with steel hooks glued onto the samples. Source: Author.

Each sample has a rectangular base of 6cm * 5 cm and a height of about 2cm. This means that with an infill density of 100%, the area of contact between the sample and the substrate would be 30 cm² or 3000 mm² (A_contact). Each sample weighs around 0,056kg, which can be expressed as 0,55N (F_weight). To assess if the adhesion strength between the sample and the substrate would be sufficient, a relationship must be defined between the maximum allowable force, which can be called F_maxweight (so just under the pull-out force), the weight of the sample (F_weight), and the contact area between the sample and the substrate (A_contact). For a sample to have sufficient adhesion strength the adhesion strength (F_adhesion) must be greater than the maximum weight (F_max weight) for a given area of contact (A_contact). Weighing a specimen and comparing this weight to the pull-out force, can give an idea about how large of an object can adhere with a certain contact area. This is defined as adhesion strength and is expressed as force (N) across the contact area (mm²).

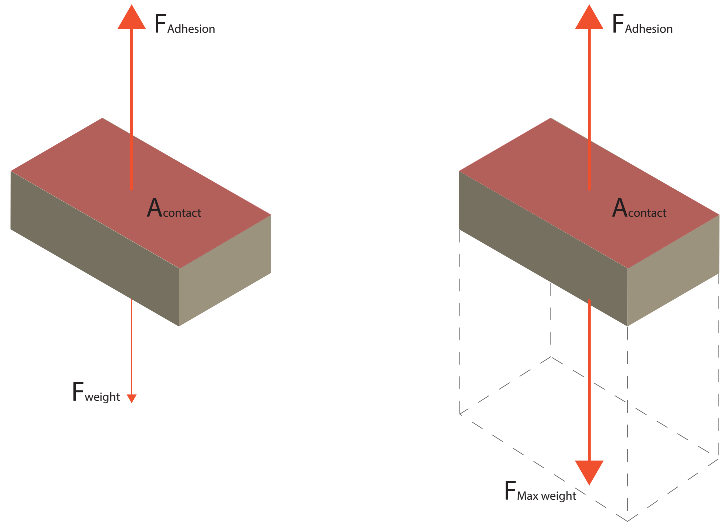


Figure 159 Adhesion strength assessment principle. Source: Author.

7.8.6. Results: Adhesion dried state

Specimen	Fail force (kg)	Failure force (N)	Adhesion (N/mm^2)	Fracture location
G5 R	10	98,1	0,033	At interface
G5 R	10	98,1	0,033	Glue bond
G5 R	12	117,7	0,039	Inside specimen
G5 S	16,5	161,8	0,054	At interface
G5 S (60 deg)	21,25	208,4	0,069	At interface
G5 S	20,45	200,5	0,067	At interface
G5 W	15	147,1	0,049	At interface
G5 W (60 deg)	28	274,6	0,092	At interface
G5 W	22,5	220,6	0,074	At interface
G5 upside down	7,5	73,5	0,025	Glue bond
G5 H1	21,25	208,40	0,070	At interface
G5 H2	20,45	200,5	0,067	At interface
G5 H3	21,25	208,4	0,069	Glue bond & inside specimen
G5 H4	20,45	200,5	0,067	At interface

S = sanded substrate, W = wet substrate, R = regular substrate, 60 deg = inclination during printing

Figure 160 Table showing pull-out force of various tested samples. Source: Author.

The table in Figure 160 shows an overview of the various tested specimens, their respective pull-out force and fracture location. At least three of each specimen type is tested. G5 is the recipe used for all tested specimen. Specimen H1 – H4 are not extruded, but made by hand and smoothened with a trowel, to mimic how a restoration plasterer would apply them on a substrate. The table in Figure 161 shows the average failure force per category and the Standard Deviation. These results are also plotted in the graph shown in Figure 162.

During the pull-out tests, none of the specimens fractured inside the substrate. Instead, most fractured at the interface, while in a few cases the fracture occurred in the glue bond or in the printed sample. This shows that 3D printing with G5 onto a gypsum substrate is a mechanically compatible restoration method.

Surface type	Specimen type	Average pull-out force (N)	Standard deviation
Regular	G5	104,6	9,2
Sanded	G5	190,2	20,4
Wet	G5	214,1	52,3
Regular (hadmade)	G5	204,5	3,9

Figure 161 Table showing average pull-out force and Standard Deviation per tested category. Source: Author.

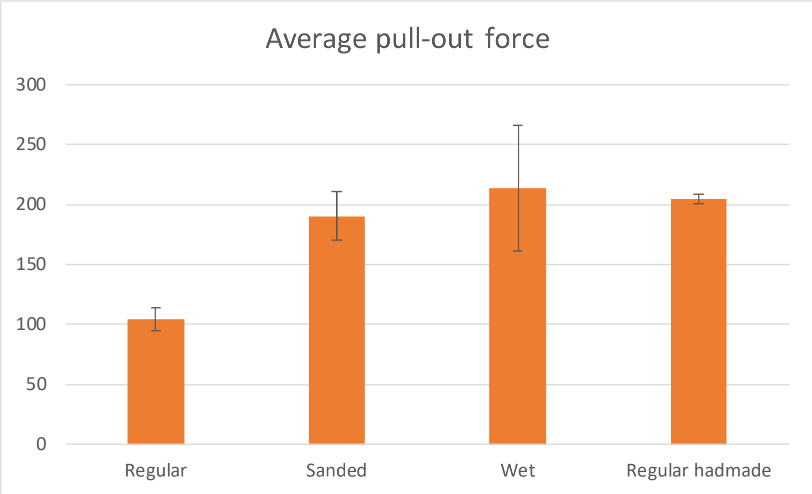


Figure 162 Graph showing average pull-out force and SD per category. Source: Author.

The data from the experiments suggest specimen extruded onto a sanded or wet substrate have around the same adhesion strength as hand-made samples. However, the pull-out forces of the handmade specimen are much closer together as compared to the pull-out forces of the extruded specimen. This can be seen through the Standard Deviation. Specimen extruded on regular, untreated substrates exhibit about half the adhesion strength of hand-made specimen and specimen extruded onto sanded or wet substrates. Extruding the mixture on an inclined plane of 60 degrees does not seem to affect the adhesion strength in a negative way, however only two specimen were made in this way.

The average weight of the specimens is about 56 grams and the contact area between specimen and substrate is about 30 cm^2. The highest pull-out force recorded was 274,6 N, which is roughly 28000 grams. This suggests that the adhesion strength for a contact area of 30 cm^2 can support the weight of a sample which is 2000cm tall. The lowest measured pull-out force from the tests was 73,5N, which is roughly 7,5kg. This sample, though only one could be tested, was extruded upside down. Considering this adhesion strength, a sample with a 30 cm^2 contact area could be over 350 cm tall. Realistically, no stucco ornament will protrude 350cm down from the ceiling and no stucco ornament weighing 10kg will be connected to the ceiling with only a 30 cm^2contact area. Therefore, the adhesion in dried state achieved through 3D printing with G5 seems to be sufficient.

Due to the limited time available for these experiments, the effect of extruding at different angles on the adhesion strength could not be studied properly. It is recommended that at least three samples are

extruded on a regular, wet and sanded substrate at 60 degrees, 90 degrees and upside down. This could give an indication whether extruding samples on an inclined plane reduces the adhesion strength. The results obtained so far do not suggest this.

7.8.7. Limitations of the pull out test

Printing accuracy, printing speed and the distance between the substrate and nozzle are all factors that can play a role in the final adhesion strength between a printed sample and the substrate. The slower the material is printed, the better it can be accurately laid down on the substrate, which may increase the contact area between the sample and substrate. Furthermore, if the nozzle is closer to the substrate, it may be able to push the material in place, which is also expected to improve adhesion. These factors cannot be properly controlled or fixed when printing manually. Although the results seem to suggest that wetting or sanding the substrate increases adhesion in dried state, the above mentioned factors were not fixed during the experiments. It would be recommended to perform these tests again with a proper tensioning machine after samples have been printed with the same extruder, same printer settings and toolpath.

7.9. Conclusions on printing material

Over 10 different material recipes were created and tested on their printability over the past half year. Recipe G5, which features a 3:1 gypsum to marble powder ratio, showed the best overall results and was refined and tested further to evaluate its printing performance by looking at various criteria. Experiments performed with recipe G5 have shown that the mixture has good pumpability and can be easily moved through a material delivery system at 4 bar pressure. The mixture can be extruded out of a nozzle with a diameter of 1mm and can achieve a minimum extrusion width of 1mm. In the 3D printing process, the layer height can be adjusted to about half that size by regulating the extrusion speed and printing speed, which sets the printing resolution for G5 at 0,5mm. It has been determined in the subchapter “Aesthetical compatibility” that at a viewing distance of 2,65m the human eye cannot distinguish objects closer than 0,8mm to each other. 0,5mm would therefore be a sufficient resolution to give a close to smooth surface. In cases where the viewing distance is much smaller, for example in buildings with low ceilings, this resolution cannot give the close to smooth surface. In such cases, sieving with a sieve that has finer holes may help reduce the particle size. Alternatively, some post-processing techniques can be used to create a smoother texture.

Material specs	Value
Bulk density [kg/m³]	1000
Shrinkage [%]	-
Buildable layers	21
Min extrusion width [mm]	1
Min. nozzle width [mm]	1
Min. layer height (theoretical) [mm]	0,35
Pumping pressure [bar]	4
Open time [minutes]	78-83
Adhesion fresh (comparative) [1-5]	5
Adhesion dry [N/mm²]	0,025

Figure 163 Table showing performance values of various printability criteria for mixture G5. Source: Author.

G5 can be stacked for 21 layers without deformations in the geometry when printing vertically down. The experiments suggest that the addition of marble powder in the 3:1 ratio contributes to this increased buildability as compared to mixtures that do not contain any marble powder. Assessment of buildability for printing upside down would be advised in a further research on this topic. It is highly recommended to use a robot or 3D printer for the buildability experiments, as it is imperative that each layer is properly placed relative to the previous layer to avoid inaccuracies in the geometry, which can severely compromise the stability of the printed object and thus give inaccurate results on the actual buildability of the tested sample.

Further experiments show that it is possible to 3D print G5 at inclinations of 30, 45, 60, 90 and even upside down. 10 layers can be printed perpendicular to the printing surface at 90 degrees without noticing mayor deformations, which shows high potential for 3D printing onto walls. Manual experiments have shown that printing upside down is possible. Even with major inaccuracies in extruding the mixture upside down by hand, the printing material sticks for at least four layers to the substrate. The distance between the nozzle and substrate should be fixed to successfully print upside down, which cannot be ensured when printing manually. Therefore, further investigation is required with the use of a robot or 3D printer, which provide much more control in the printing process to achieve usable results. This is also the case with testing for buildability.

Because the mixtures can be made with off-the-shelve products, which are widely used in construction today, the material likely does not contain hazardous contaminants or chemicals which would lead to damage onset, ensuring chemical compatibility. By adding marble powder as fine aggregate, the mixture comes very close to the colour of Molda 3 Normal gypsum which is currently used in restoration. By adding some white pigment, this white colour should be able to be matched. The adhesion between samples, printed on any inclination, and the substrate has proven to be more than sufficient for supporting the self-weight of printed gypsum samples, ensuring the bond between the printed sample and the substrate is durable. Furthermore, the average adhesion strength of extruded samples is similar to hand-made samples. After performing pull-out tests, it is evident that detachment, when this occurs due to the application of high loads, occurs almost exclusively at the interface between the substrate and the printed element. This means the restoration method and printing material provide mechanical compatibility with the original substrate.

Finally, it is noteworthy that G5, which shows good printing properties, can be created with off-the-shelve and relatively inexpensive products. Knauf Rotband costs 49 cents per kilogram at hardware stores and marble powder costs 85 cents per kilogram and can be bought at hobby shops. This means the printing mixture costs about 77 cents per kilogram and the ingredients can be bought in any hardware store and hobby store, making it easy to implement into practise. For further research I would recommend to contact the manufacturer of the gypsum, Knauf, to get more insight into the additives that are present in Rotband.

7.10. Suggestions for further improvement

The experiments conducted in this thesis were limited by time and available tools and facilities. The observations made during the experiments have been discussed and conclusions have been drawn on the different aspects of printability of the gypsum-based mixtures in the previous chapters. Although the printing mixture shows sufficiently good properties for application of in-situ AM for restoration of stucco ornaments, the efficacy with which this restoration method can be done must still be proven with experiments conducted with a multi-axis robot. A number of further improvements can be made to the restoration method and printing process to achieve good results and are discussed in the next subchapters.

7.10.1. Cured-on-demand material delivery system

Buildability is important for any 3D printed geometry to maintain its stability and its shape. If a lower layer deforms due to poor buildability under the weight of subsequent layers, this would result in the 3D printed object losing stability and geometrical accuracy (Panda & Tan, 2018). Deformations due to poor buildability can create a distance between the printing nozzle and the working surface, resulting in insufficient contact area between layers and could lead to collapse of the printed structure (Panda & Tan, 2018).

Two approaches are suggested for dealing with this issue by a team of researchers at Laticrete International Inc.: 1) dynamic adjustment of the nozzle height during printing (Lim et al., 2012); 2) Increase hardening rate of the printed material (Verian et al., 2018). Dynamic adjustment of the nozzle may help to prevent collapse of the geometry, but in the case of highly precise printing of ornaments, major deformations in the geometry are not acceptable, therefore this approach is unsuitable. The second approach can potentially be achieved

through injection of accelerators to the mixture just prior to extrusion. By doing so, the hardening process of the material will be accelerated after it has been extruded and increase the materials mechanical properties to prevent collapse (Verian et al., 2018). Paradoxically, the interlayer adhesion decreases if an extruded layer would rapidly gain mechanical strength, by curing and thus losing moisture through evaporation, before the next layer is printed onto it (Panda & Tan, 2018).

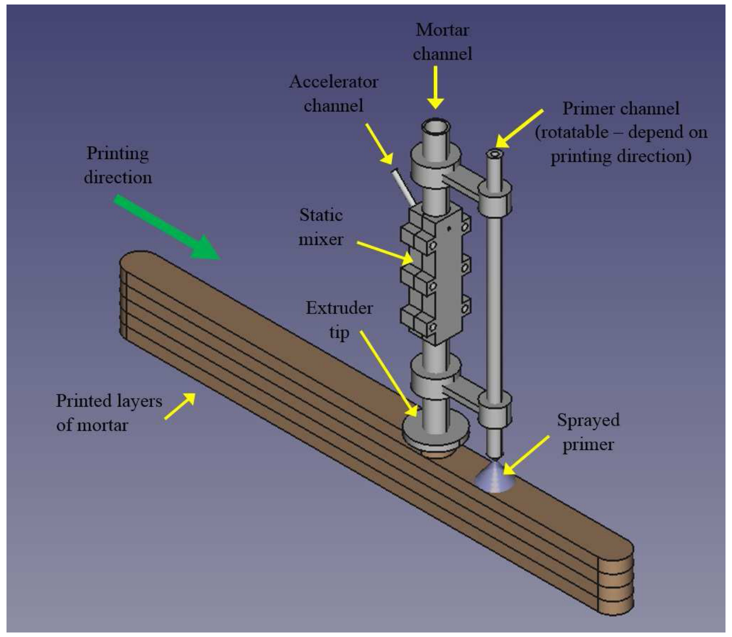


Figure 164 *Cured-on-demand material delivery system. Adopted from (Verian et al., 2018)*

To solve this, a team at Laticrete International Inc. has developed a custom end effector which has a secondary inlet to deliver an accelerator which is mixed with the cementitious mixture close to the nozzle. By mixing the cementitious mixture with the accelerator just before extrusion, the mixture cures rapidly after extrusion, increasing the buildability of the mixture (Verian et al., 2018). The custom end effector has another channel which sprays a primer, a liquid chemical which increases the interlayer adhesion, on top of the previously extruded layer just before the next layer is deposited (Verian et al., 2018). In this way, a solution is proposed to increase mechanical strength of the 3D printed geometry, without compromising on interlayer adhesion, resulting in an improved buildability. If a compatible accelerator and primer could be developed, such a system could be suitable for gypsum-based AM onto inclined surfaces, since such a system has the potential to increase both buildability, interlayer adhesion as well as adhesion to the inclined printing surface. The assessment of the feasibility of the system developed by the team at Latrice International Inc. is still ongoing. Such an approach could be further investigated for the in-situ restoration application as well by developing an end effector with a similar secondary inlet and secondary nozzle for spraying a primer.

7.10.2. Post processing for smooth surface

A two-step restoration approach could be considered in case Additive Manufacturing alone would not be able to achieve the desired resolution to create a near to smooth surface. This may occur in buildings with low ceilings where the ornaments are close to the viewer.

Milling

First, the rough shape could be printed onto the ceiling or wall with a large nozzle. By printing the rough shape with a large nozzle, the printing process can be short, and both the Open time and aggregate size would not be as severe limitations. It is important that wherever the rough geometry has an offset from the more detailed final geometry, that this offset is set outward. This means that to get the final, detailed shape, material must be removed rather than added to this rough shape. After the rough shape has completely dried up, this rough geometry must be scanned again with a 3D scanning technique. The scanned model of the rough geometry can be interpolated with the 3D model of the final detailed CAD model. After doing this, all the parts of the scanned rough shape that are not within the final detailed shape should be marked as parts to be removed. Next, a milling program will be created to remove all of these parts from the rough shape. The extruder on the robot will be swapped for a milling tool for the milling task and the robot can mill details into the rough shape to create the final detailed geometry.

Although this two-step approach may be able to create a very high level of detail on the surface of the printed ornament, there are also several disadvantages to such an approach. Firstly, a 3D scan would need to be made twice instead of once, which is time consuming and expensive. Secondly, the scan could only be made after the rough printed shape is completely dry, so you can be sure that it will not change due to the drying process anymore and this can take a few days. Thirdly, the robot would need to be recalibrated as well after the end effectors have been swapped and this is also a time-consuming task. Overall, this approach would take longer than if only AM could be used, however, this approach would solve the problem of the visible layering-effect.

Smoothening in wet state

Another method of creating a smooth surface is brushing along the printed geometry right after printing to "dissolve" the layer contours into each other. Using a wet brush to stroke fresh stucco objects in order to create a smooth surface is a method used by restoration plasterers when restoring or creating ornaments manually. Several tests were conducted to see if a wet brush could blend the layer contours into each other to create a smooth looking surface of printed samples. The wet brush can indeed smoothen out the surface of the 3D printed layers.

An important note is that a human can feel real-time feedback from the printed object when brushing along the surface: If I brush too hard, the object will deform, if I brush too soft, the surface will not get smoothened. The robot must also be able to receive feedback between the printed object and its smoothening tool. This will be further elaborated in the chapter about the In Situ Fabricator.

Figure 165 Left: Sample letter "A" extruded through a 2,25mm nozzle. Right: post smoothening with a wet brush. Source: Author.

The advantage of this method of smoothening is that it can be done right after AM process is done. The robot can remain in the same place, and this process could start right after the end effector is swapped. This means the total working time on site is relatively shorter than for a method such as milling, which requires the material to be completely dried. This advantage is however also at the same time the disadvantage of this method. The material must be fresh and soft to be able to brush it, once it hardens too much, it cannot be smoothened with a brush any longer.

7.10.3. Coordinated continuous mixing procedure

The Open time of the printing mixture creates a time constraints within which the AM process must be completed. This not only sets constraints on the maximum printing time, but also on the maximum size of any geometry that can be produced in one go. If by decreasing the robot movement speed, the printing accuracy can be improved, then the Open time also indirectly creates a limitation to the printing accuracy. One approach to deal with this constraint is to produce larger ornaments, which may take longer to print than the Open time of the mixture, to be printed in smaller parts which can be printed within the time limit.

Another approach could be to create a continuous mixing process to create the printing mixture simultaneously with the printing process. A container holding a mixture of gypsum powder and marble powder in the suggested 3:1 ratio can continuously keep pumping this mixture to a mixing tank. This mixing tank could simultaneously and continuously be fed with water in the desired ratio as well. In this way, the gypsum powder and marble powder can be mixed shortly in the mixing tank with water and the desired mixture can be pumped to the extruder to be extruded onto the working area continuously. The speed at which the ingredients are fed to the mixing tank can be regulated by the extrusion speed, to ensure the right amount of printing material is always available for the printing process. Such a process would eliminate the time constraint imposed by the Open time of the mixture and nor the size of the geometry to be printed, printing speed or printing accuracy would be constrained.

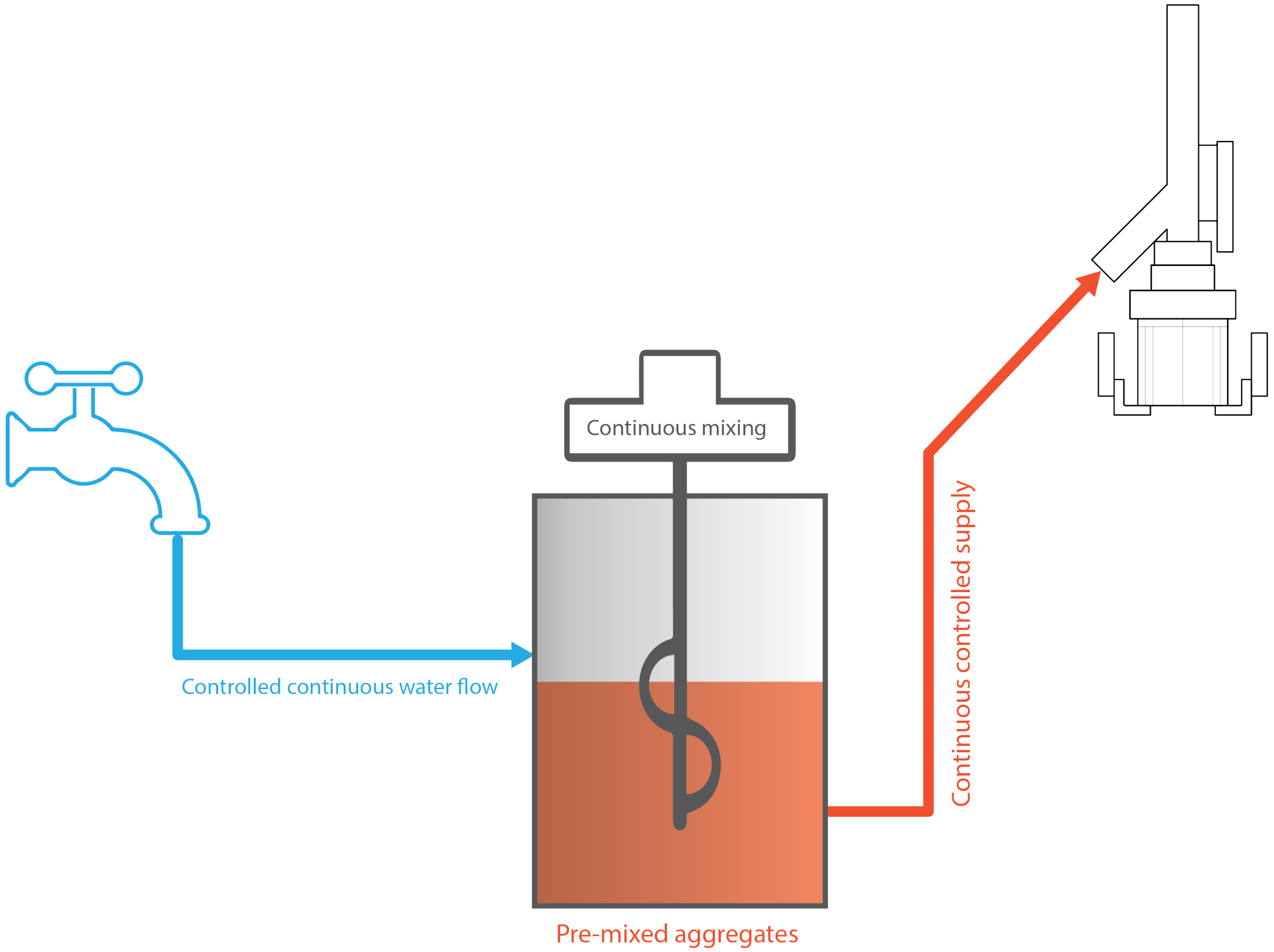
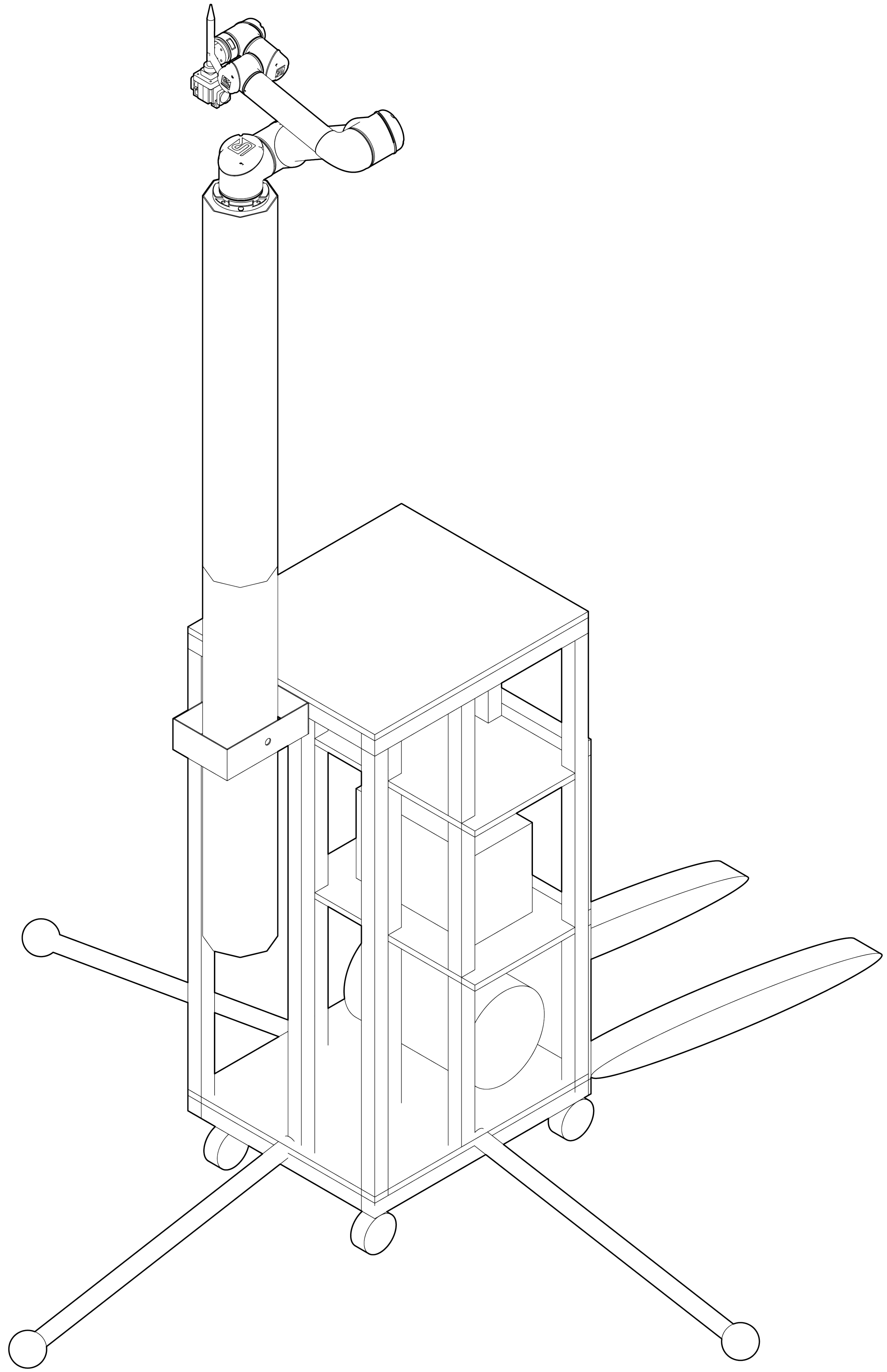


Figure 166 Principle of coordinated continuous mixing procedure. Source: Author

08.

RESTORATION ROBOT PLATFORM



8.1. Introduction

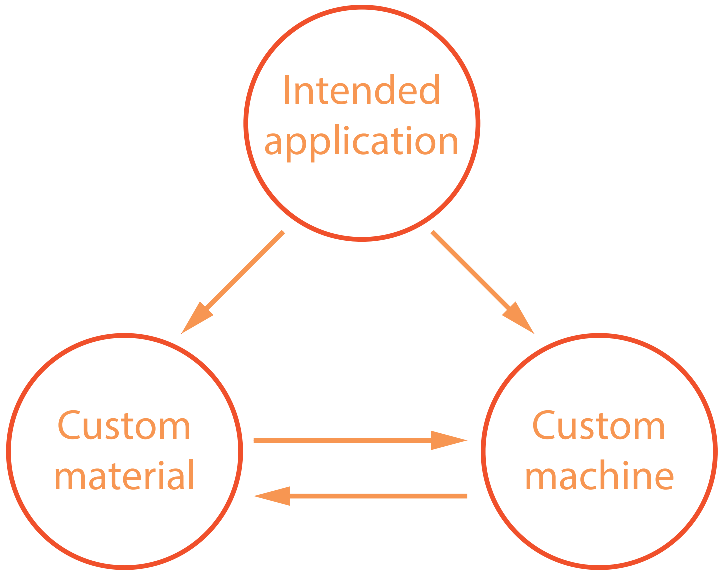


Figure 167 Relationship and influences between intended application, material and machine development. Source: Author

The fields of architecture, restoration and construction, are all relatively "traditional" in their working methods. Innovations take time to adopt and much of the work involved, especially in restoration and construction, is still performed manually on site. Developing a new methods of construction or restoration, require a certain technical infrastructure to be able to be adopted in practise. In the case of adopting in-situ AM as a method for restoration of ornamented stucco ceilings, technical infrastructure is required in the form of a robotic platform, which can be used in old buildings. Such a machine currently does not exist, as AM is not a construction or restoration method that is used for on site applications. Therefore, when developing new construction or restoration materials and methods, the simultaneous development of a machine which can use this method and this material is also required. The intended application, the used material and the machine are intertwined with each other. The intended application sets requirements for the new material and the machine, which in turn influence each other's development. It is evident that this increases the complexity and calls for a multi-disciplinary approach.

ETH Zurich has acknowledged this need for a multidisciplinary approach for innovation in construction and has set up a building on their campus where researchers from various technical backgrounds such as mechanical engineering, electrical engineering, computer science and architecture work together to develop new construction materials, construction techniques and construction machines. One such construction machine developed at ETH Zurich is the In situ Fabricator, which will be investigated as a case study. Through the case study, key design aspects are identified which must be considered when designing a robotic platform for in-situ applications. The following chapters will use these key design aspects to investigate the design requirements for the development of a Restoration Robot Platform (RRP). The final chapters in this section will use the developed requirements to design a prototype of a RRP with off-the shelve components. A further study could then be done in the future by building the prototype and use it for testing the in-situ AM method. Testing such a platform could lead to a better understanding of the requirements for the in-situ restoration application and findings could lead to the development of a customized machine in the future.

8.2. Case study: In situ fabricator

The In situ fabricator (IF1) is a prototype designed and built by the Gramazzio Kohler Research Group at ETH Zurich in 2014. The machine is intended for manufacturing, assembly and digital fabrication tasks on the construction site. Today we find machines in many different size on the construction site: from large cranes carrying supplies, till electric drills and hammers. According to the Grammazzio Kohler Research Group, it is expected that if robots would be introduced in large scale on the building site in the future, that there would be various sized robots similarly to these various sizes of machines seen today on the construction site. The IF1 is defined as an intermediately sized robot, capable of operating within a local portion of a construction site (Giftthaler et al., 2017).

The In situ Fabricator has been used in two main research projects so far at the ETH Zurich, one dealing with construction of an undulated brick wall with discrete elements, the other dealing with in-situ welding of steel reinforcement rebar to create a self-supporting wall. It can navigate a site by creating a basic image of its surroundings by using an on-board LIDAR scanning system and thus is not limited by the reach of its arm. The robot also requires limited human interaction once it has been programmed to perform tasks.

8.2.1. Robot development guidelines

Gramazzio Kohler Research Group defined guidelines and criteria in five different domains for the In situ Fabricator:

1. Control and state estimation:

- Provide 1 to 5-millimetre positioning accuracy at the end effector.
- Can operate within a local portion of the construction site. Moving obstacles, humans, and changing scenes outside of this area should not impact performance.
- Is mobile in non-at terrain with obstacles and challenges as found on a typical construction site.
- Can operate with limited human intervention. The machine alone should offer the modality for achieving the overall accuracy of the building task.

2. Size and workspace constraints:

- Can reach the height of a standard wall.
- Can fit through a standard door (in our case defined as a 80 cm wide Swiss standard door).
- Can be loaded on a pallet/van.

3. Versatility and customisation:

- Can be equipped with different tools or end effectors to perform a wide range of building tasks.
- Have a sufficient payload to handle heavy and highly customised digital fabrication end effectors.
- Can work in confined non-ventilated spaces.
- Are protected against dust and water ingress.

4. Power supply:

- Can be plugged into standard mains power.
- Has sufficient on-board power for phases of construction where no external power supply is available (e.g. during transportation to and from the construction site).

5. Usability and integration:

- Can provide required information to the architectural planning and control environments, e.g. current robot location, building state, etc.
- Provides interfaces for interaction with an operator who is not a robotics expert (Giftthaler et al., 2017, p. 2-3).

8.2.2. IF1 features

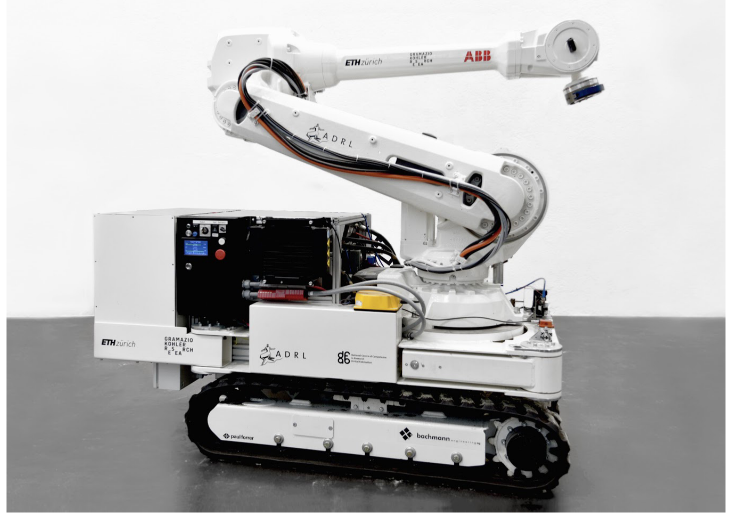


Figure 168 IF1 prototype. Source: (Giftthaler et al., 2017)

The IF1 consists of an ABB IRB 4600 arm, which has a 2,55m reach, weighs 440kg and has a maximum payload capacity of 40 kg (Giftthaler et al., 2017). The robotic system is electric powered and carries four packs of Li-Ion batteries which allows it to operate for 3-4 hours without being plugged into an external power source (Giftthaler et al., 2017).

The IF1 also carries a custom-made hydraulic system on board to power its tracks for mobility, as well as to power any tools mounted on the arm such as a gripper. The core components for this hydraulic system are a compact AGNI DC electric motor which is attached to a pump delivering hydraulic pressure up to 150 bar (Giftthaler et al., 2017, p. 9).

Additionally, depending on the task, IF1 can be equipped with exteroceptive sensors for localization or vision. All on-board sensors are driven by an on-board computer which processes the localization data to navigate the robot, while computationally more demanding tasks may run on an external computer and can be sent to the IF1 wirelessly (Giftthaler et al., 2017).

8.2.3. Limitations and lessons learned

The development and use of the IF1 in research projects have shown several shortcomings to be successful as an in-situ construction robot, which can be used to design an improved IF2. The main two lessons, which are relevant for the research of this thesis are presented below.

Self-weight and Payload to Weight Ratio

Standard industrial robots often use heavy-duty electric motors and gearboxes to move their joints and are designed for maximum stiffness in order to achieve a high positioning accuracy (Giftthaler et al., 2017). Because of this, these robots tend to have a low Payload to Weight Ratio (PWR), in the case of the In situ Fabricator this ratio is 40 kg: 440kg, which is about 0.09 (Giftthaler et al., 2017). This would mean, that theoretically to carry 1 kg of extra weight, this robot itself would require to be 11 kg heavier. The heavier the robot gets, the stronger the driving motors need to be to move the robot and the more power they would require, thus the heavier the batteries will get as well. While the base of the robot needs to be heavy in order to prevent the robot from tipping over, it is desirable to keep the overall weight of the robot as low as possible. Weighing 1,4 tons, the IF1 is already too heavy to access some standard building environments (Giftthaler et al., 2017).

Feedback between tool and workpiece

According to the research team, purely position based robotic arms are by design unsuitable for advanced manipulation tasks, since they lack any interaction between the tool and the workpiece (Giftthaler et al., 2017). This means that robots such as the IF1 cannot adapt to any feedback they get from the workpiece they are working on. If for example a purely position-based robot would be moving a smoothening tool around the surface of a 3D printed object to smoothen the surface of the 3D printed object out, it would not be able to adapt to how the object reacts to the smoothening. The object may be a little tougher in some spots, where the robot may require using a bit more force, while other spots may be softer, which may require less force from the robot. A human worker can feel this through the feedback he/she senses between the tool and the workpiece, but a purely position based robot only follows a fixed set of instructions, without the ability to react to such feedback. A multi Degrees of Freedom or multi-axis force-torque sensor (see Figure 170) attached at the end of the end effector could provide a solution for this issue, as such a device could provide the necessary feedback required for the robot to adapt to the object it is working on (Giftthaler et al., 2017). Such sensors can detect linear and torque forces and bending moments along multiple axis, which makes it possible to register feedback between a tool and workpiece in three linear axis and three rotational axis (HBM, n.d.) (see Figure 169). Such sensors are already widely used in robotics and aircraft manufacturing.

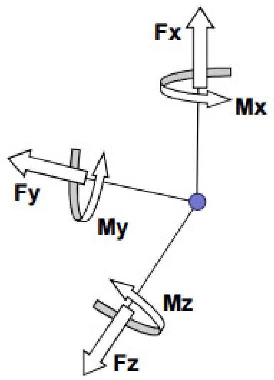


Figure 169 Linear forces along three axis and bending moments around these axis can be measured. Source: https://www.hbm.com/en/7115/how-does-a-multi-axis-sensor-work/

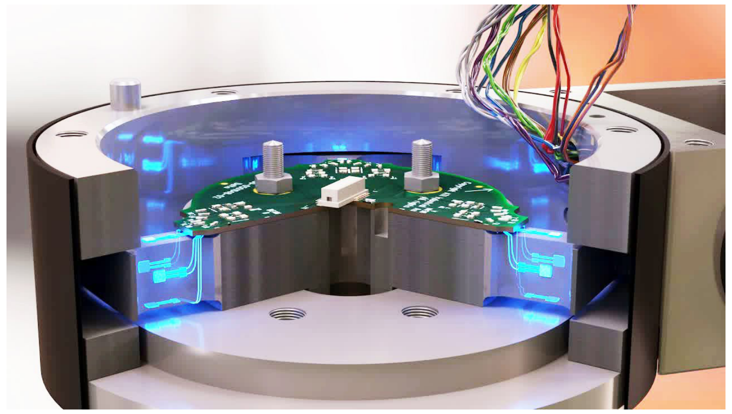


Figure 170 Example of a multi-axis force torque sensor. Source: https://www.ati-ia.com/products/ft/sensors.aspx

8.2.4. Developing the next generation In situ Fabricator

The IF1 project is imperative to understand the limitations of payload to weight ratio that current generation industrial robots have. Using robots inside a building sets hard weight and size restrictions on them, while the chaotic nature of a construction site advocates for a high level of manoeuvrability. With such insights in mind, the team at ETH has started conceptualizing a second generation In situ Fabricator, IF2 (see Figure 171). Robotic arms used on IF2, would use novel hydraulic vane actuators, which have built in sensors, electronics, processing, data bus and slip rings to make the overall system more compact and smarter (Giftthaler et al., 2017). Hydraulic actuation is preferred in this case over electrical actuation, since this hydraulic actuation has a higher power-density, which is useful when creating compact machines (Giftthaler et al., 2017). IF2 will be a more modular design, allowing to “plug-in” multiple robotic arms at once. To achieve a greater manoeuvrability, the IF2 would be equipped with legs that have wheels on them, which allow IF2 to walk, drive and allow hybrid movement.

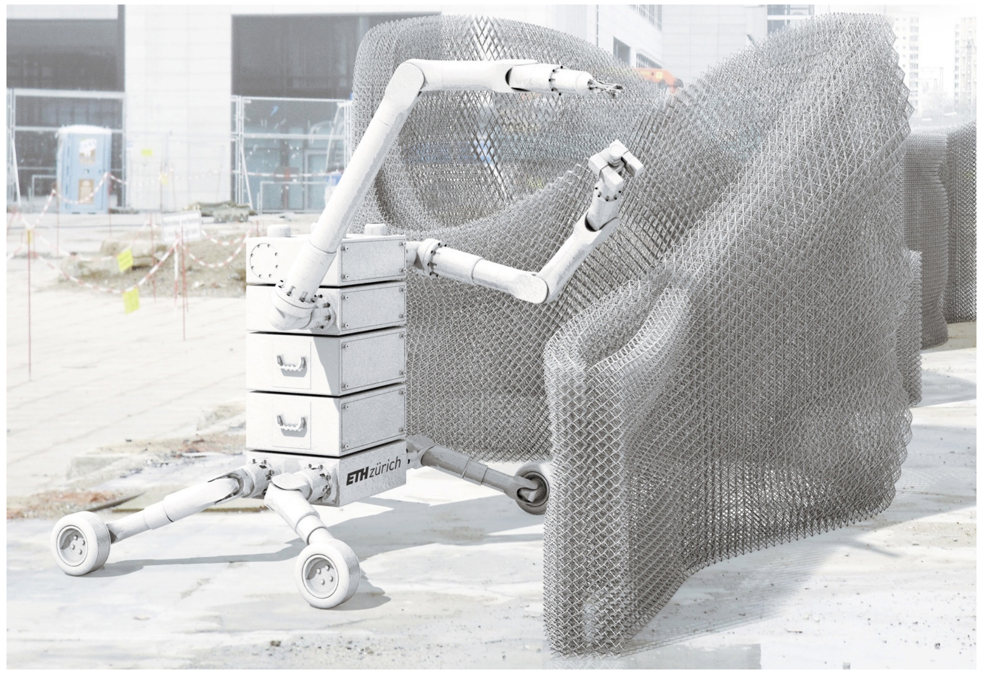


Figure 171 Concept image of IF2. Source: (Giftthaler et al., 2017)

8.2.5. Lessons for Restoration Robot development

Much can be learned from studying the IF1 and IF2 research projects. The types of criteria setup for designing the robotic platforms are a useful start for the development of a Restoration Robot. Even though the goal for the Restoration Robot is not necessary to have autonomous mobility capabilities, the sensing and mobility strategies used for the IF1 can be considered for the further development of autonomous Restoration Robots in the future. PWR will be an even more critical aspect for Restoration Robots, as the context in which they will work will likely support a lower maximum load on the floors. In addition, a Restoration Robot will also have more severe dimensional constraints, because it must be able to be moved in and out of old buildings, which may have narrow doors, corridors and may not have elevators. Finally, the feedback between the tool and workpiece is an interesting aspect to consider if Restoration Robots would be implemented for any post-processing techniques such as milling, smoothening or brushing, but may not be directly relevant for AM.

8.3. Spatial & physical constraints

Restoration Robots would operate in old (Cultural Heritage) buildings. Putting a modern, automatically moving and powerful steel machine in such sensitive contexts requires careful consideration of the various spatial and physical constraints in which the Restoration Robot would operate. Many buildings featuring stucco ornaments in the Netherlands were built or refurbished in the 18th, 19th and early 20th century (Prins, 2013). Guidelines for the dimensions and weight requirements for the Restoration Robot platform can be defined by identifying basic spatial and physical constraints of these type of buildings.

8.3.1. Spatial constraints

A concept must be developed about what such a Restoration Robot Platform would be like. How will it arrive on site, how will it be moved and by how many people? Delstuc stukadoors arrive on site in a company van, which transports both the restoration plasterers as well as the equipment they require. The platform should fit inside a standard transporter van and should ideally be moveable by one worker, so another worker could bring other equipment to site. If we consider a Volkswagen Crafter transport van, which is commonly used transport van, the platform should fit within 1780mm (width) * 2600mm (length) * 1650mm (height) (see Figure 172) (Auto Express Team, 2016), leaving space for other equipment as well.

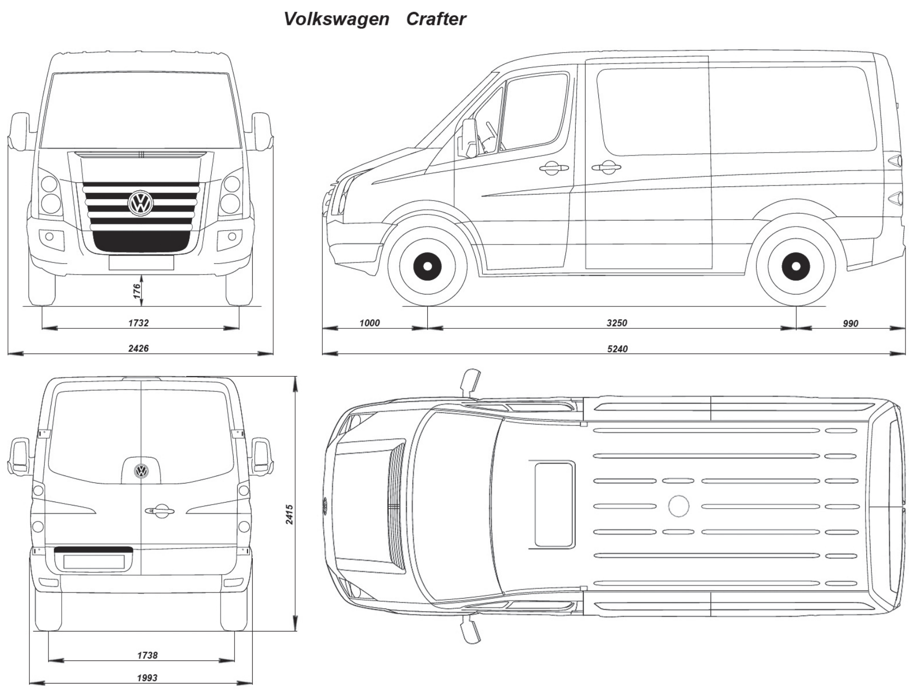


Figure 172 Volkswagen Crafter van dimensions. Source: https://drawingdatabase.com/volkswagen-crafter-2006/

Any machine brought into a building must fit through the smallest free passageway of that building, which usually means it must fit through the doors of the building. According to the Dutch building codes (Bouwbesluit 2012 article 4.22 subsection 1), door openings must be at least 0.85 meters wide and 2.30 meters tall. Since this is a building code from 2012, it does not represent the particular building stock in question. A door width of 80% of this modern building code is considered as minimum width of doors in these older buildings and thus 0.7m would be the maximum width of any machine going through a door.

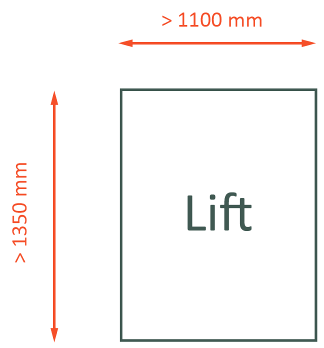


Figure 173 Dimensional constraints for lifts. Image souce: Author.

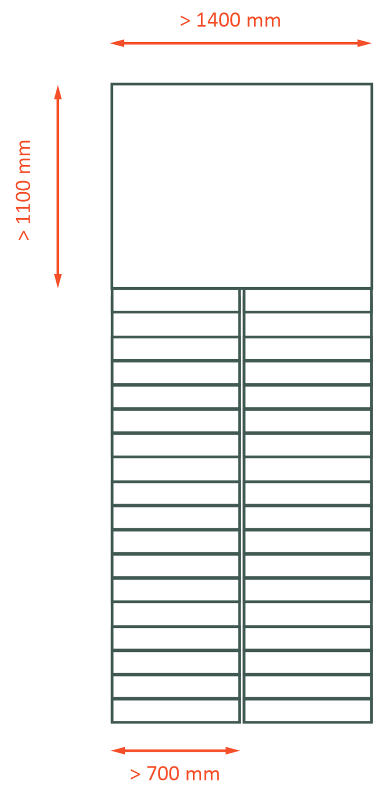


Figure 174 Dimensional constraints for stairs and landings. Image souce: Author.

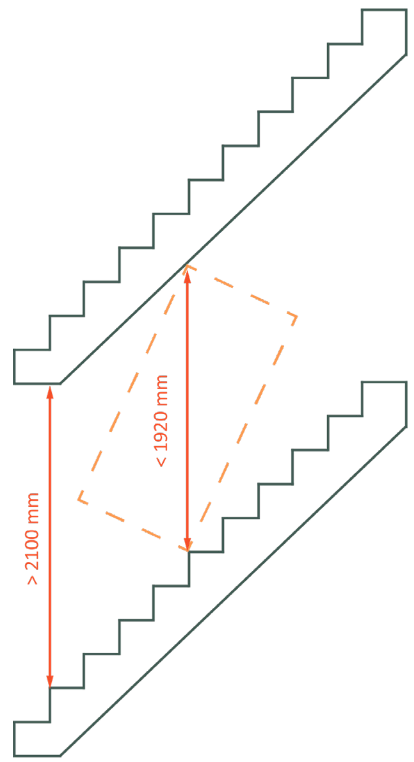


Figure 175 Dimensional constraints for stairs height. Image souce: Author.

If the Restoration Robot platform fits through the door and must go straight to a room on the ground floor, there would be no major constraints for the length of the platform. However, when the platform must make turns in (narrow) hallways, move up flights of stairs or fit inside lifts there will be constraints for the length and height of the platform as well. According to the Bouwbesluit 2012 article 2.39 staircases in existing buildings must be at least 0.7 meters wide and article 4.15 from the older Bouwbesluit 2003 states circulation areas must be at least 1.1 meters wide and 2.1 meters high (see Figure 174 and Figure 175). Furthermore Article 4.28 states from Bouwbesluit 2012 states the minimum dimensions of a lift must have a footprint of at least 1.1 meter by 1.35 meter (see Figure 173). These building codes may not be present during the time of construction of the building stock in question, however these building codes are meant for existing buildings, so existing buildings must comply with them. To fit through a door, to fit inside a lift and to make a turn in a passageway, an object must be within 0.7m* 1.1m*2.1m. It may occur that even if a hallway is 1.1m wide, the platform may need to make a cramped turn into a room in such a passage. Therefore, the horizontal diagonal dimension of the bounding box must be smaller than 1,1m instead of the length. Using Pythagoras Theorem, we find that the corrected length of the platform should be: $\sqrt{(1.1^2)-(0.7^2)}=0.85$m. By correcting the height of the bounding box by setting the 2.1m constraint for the vertical diagonal instead of the height and again using Pythagoras Theorem we find $\sqrt{(2.1^2)-(0.85^2)}=1.92$m. So, a **bounding box of 0.7m *0.85m*1.92m** can be made within which the Restoration Robot platform must fit. Naturally, the platform must be made with some margins on all sides, so the actual bounding box may be a few centimetres smaller in all dimensions.

Conclusion:

- The robotic platform must fit inside a bounding box of 0.7m *0.85m*1.92m.

8.3.2. Vertical reach

Buildings which feature wall-and ceiling-mounted stucco ornaments are mostly public buildings like churches, libraries, museums, palaces, but also homes of wealthy people. These types of buildings often have a high floor to ceiling height. Public buildings for large groups of people tend to have large spaces with tall ceilings to accommodate those large spaces. An example is the +-12-meter-tall main hall of the Teyler's museum in Haarlem built in 1784 as the first public museum in the Netherlands. The ceiling and walls of this main hall are richly decorated with stucco ornaments (see Figure 176). Homes of wealthy people also tended to have richly ornamented and tall ceilings, as these were symbols of luxury and wealth. Villa Dijkzicht (which today hosts the Natural History Museum of Rotterdam), built in 1852 as a summer villa for the family Van Hoboken (Natuurhistorisch, n.d.) features +-4.5 meter-tall ceilings richly decorated with stucco ornaments (see Figure 177).

Figure 176 Main hall of Teyler's Museum Haarlem (1784). Adopted from: https://www.teylersmuseum.nl/

Figure 177 Richly ornamented ceiling in a room of the Natuurhistorisch Museum Rotterdam (1852). Image source: Author

It is evident that ceiling heights to be considered are much higher than is current practice in residential construction and that these heights vary greatly as is evident in the two presented examples. The largest industrial robot, which is sold commercially is the FANUC M-2000iA/2300 (see Figure 178). It has a reach of 3734mm, can lift 2300kg and weighs 11000kg (Robot Worx, 2019). Even the largest industrial robot would not be able to reach a 4/5-meter-tall ceiling. Furthermore, this 11 ton machine would not be able to be moved inside or be supported by old buildings with wooden floors. Therefore, using a robot with a very long reach is not a suitable strategy, since the weight of the robot also increases as its size increases.

Figure 178 FANUC M-2000iA/2300 lifting a car. Adopted from: https://www.robots.com/robots/fanuc-m-2000ia-2300

To reach such ceilings a different strategy should be implemented. A smaller, lighter robot could be used and for example mounted on a telescopic camera crane, used for video shooting. Camera cranes come in various sizes and strengths. The cranes in Figure 179, Figure 180 and Figure 181 can be used with a payload of 35kg, 15kg and 80kg respectively, reaching heights of 12.2m, 8m and 4m respectively (https://www.proaim.com/). The UR5 robot for example is 20kg, so it could theoretically be mounted onto the cranes in all three of the cranes in the figures above. These types of cranes can have built in gyroscopic stabilizers for taking steady video shots, which is a feature very useful for stabilizing a moving robot arm. Furthermore, the cranes in figures above also feature stabilizing legs to keep the platform perfectly still, which is a useful feature as well when mounting a robot on the end. In its fully retracted state however the crane must fit within the 0.7m *1.1m*1.78m bounding box.

Figure 179 Camera crane 12.2m reach, 35kg payload. Source: https://www.proaim.com/

Figure 180 Camera crane 3.2m reach, 25kg payload. Source: https://www.proaim.com/

Figure 181 Camera crane, 4m reach, 80kg payload. Source: https://www.proaim.com/

Conclusions:

- A camera crane could be used to allow a relatively light robot to reach high ceilings up to 12 meters.
- Camera cranes can lift payloads of as much as 80kg.

8.3.3. Stability

Figure 182 Temporary supports underneath a stucco ceiling. Adopted from: https://www.ornamenten-restauratie.nl/ornamenten-plafond-vastzetten/

It is important that the platform is completely stable during the AM process to avoid inaccuracies of the printed geometry. However, mounting a moving robot arm at the end of a camera crane is likely to cause some vibrations or movement in the crane arm. These kind of camera cranes are made to hold the deadweight of a camera at the end, which means the camera itself does not move, but rather the entire crane arm moves or even the entire platform moves during filming. A robot which is 3D printing at the end of such an arm cannot be considered a deadweight as it is moving while printing. Granted, the robot will not move very fast, so dynamic loads or the bending moment which is generated at the end of the crane arm will not be very large. Nonetheless, strategies must be discussed to keep the crane stable and stationary while printing. Many camera cranes have built in "pan locks" or even gyroscopic stabilizers. By activating a pan lock, the crane is locked in its current orientation at the base point (see Figure 183). A gyroscopic stabilizer actively counters any deviations from the resting position of an object to keep the object (in this case the camera) in its resting position (see Figure 184). Gyroscopic stabilizers are widely used and can help to stabilize a wide variety of loads. Segway vehicles for example use gyroscopic stabilizers to balance the weight of a human being riding the vehicle, but even large ships use gyroscopic stabilizers to keep the ship stable at sea.

A third option could be to anchor the robot itself at its base to additional supports which rest directly on the ground. In some cases, temporary supports are placed underneath a damaged ceiling to support it during reparations (see Figure 182). It could be possible to mount these types of supports underneath the robot at the end of the crane to support the robot while printing. Alternatively, if such temporary supports are used for supporting the ceiling, rods or cables could connect the robot to these supports for extra stability, much like how a Delta printer works (see Figure 185).

Figure 183 Pan lock is activated by turning the screw on the right side. Adopted from: https://tinyurl.com/tjepctu

Figure 184 Gyroscopic hand-held camera stabilizer. Adopted from: https://www.photographyblog.com/news/flashpoint_zerograv_2_axis_digital_gyro_stabilizer

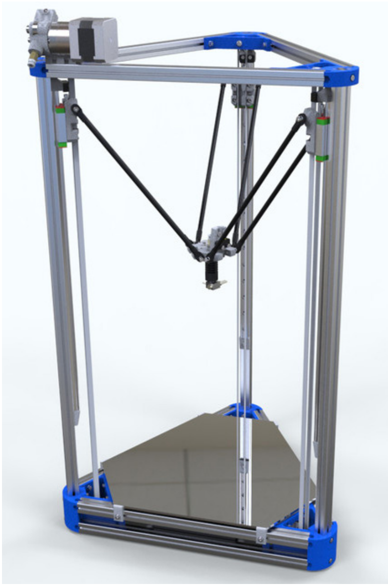


Figure 185 Delta 3D printer, which supports the movement of the nozzle on three arms. Adopted https://tinyurl.com/vrg8l3k

Conclusions:
To stabilize the limited dynamic loads and bending moments induced by the moving robot at the end of a camera crane various strategies can be implemented, such as:

- Pan locks
- gyroscopic stabilizers
- Additional external supports

8.3.4. Weight constraints

It is hard to give a clear numerical guideline about the maximum allowable weight for the robotic platform, since there were no building regulations about structural strength of beams, columns and floors in the 18th and 19th century. The weight of the robotic platform should be kept to a minimum to avoid overloading any structural elements inside the buildings For floors of contemporary office buildings, a deadload of 3.0 – 3.5 kN/m^2 (about 300 – 350 kg/m^2) is considered (Dijkman, 2005). To account for the older floors in the building stock in question, 80% of 325 kg/m^2 = 260 kg/m^2 is considered as the maximum allowable weight for old buildings. Assuming a footprint of 0,85m * 0,7m = 0,60m^2, this would mean the maximum weight of the robotic platform cannot exceed 260kg/m^2 * 0,60m^2 = 155kg.

To move the platform horizontally, wheels could be used. Since buildings built pre-19th century are unlikely to have lifts, it is plausible the robotic platform may need to be moved up stairs. To move the platform up a staircase, either the weight of the entire platform must be kept under the maximum weight a person can lift by law or the platform must have electric/hydraulic power to be moved up and down stairs. According to the Dutch labour laws written in the "Arbobesluit 5.2" a worker can lift a maximum of 23 kg (F. H. G. de Grave, J. M. M. Ritzen, H. F. Dijkstal, H. F. Dijkstal, A. Jorritsma-Lebbink, W. Sorgdrager, J. C. Gmelich Meijling, 1997). This weight restriction cannot be met since for example the UR5 robot & robot controller together already weigh over 35kg. There are some alternative trolley solutions which can be used to move heavy items up and down a staircase, known as so called "stair climbing hand trucks/trolleys".

Figure 186 Power Mait Stairclimbing Hand Truck, with max load of 680kg. Adopted from: https://www.youtube.com/watch?v=nuYX5FYTwQU

Figure 188 Stairclimbing trolley on tracks. Adopted from: https://www.pngitem.com/

Figure 187 DW11-A Electric stair climbing trolley, with max load of 310kg. Adopted from: www.dragon-iec.com/product/dw-11a-electric-stair-climbing-handcart.html

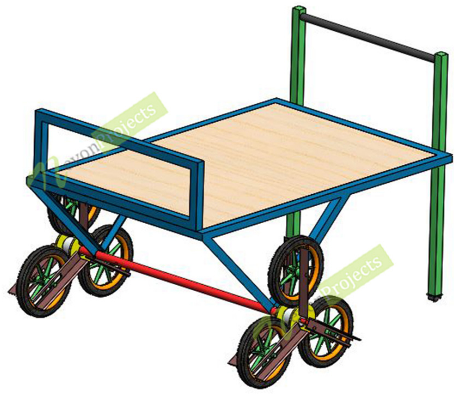


Figure 189 Concept for large staircase climbing trolley. Adopted from: https://nevonprojects.com/solidworks-design-simulation-of-staircase-climbing-trolley/

If such an electric or hydraulic powered trolley system is used, the weight restriction will not be based on the maximum lifting weight of a person, but on the power output of the trolley. The DW11-A model from Figure 187 for example has a self-weight of 30kg and can lift payloads of 310 kg up staircases according to the manufacturer.

Conclusions:
- The maximum allowable weight for buildings where the platform will be deployed is estimated at 260kg/m^2.
- The weight of the robotic platform must not exceed 155kg.
- An electric powered trolley could be used to haul the platform up and down a staircase and can haul weights exceeding the maximum allowable robotic platform weight.

8.3.5. Autonomous mobility

Autonomous mobility would give the Restoration Robot platform some big advantages. The working range of the robotic arm which will be used will not be a major constraint for the area which the robot can operate in one go without being repositioned. The repositioning procedure normally would require human intervention and requires the robot to be recalibrated in its new position.

The In situ Fabricator uses a compact AGNI DC electric motor attached to a pump which outputs hydraulic pressure up to 150 bars to power the hydraulic motors of the tracks for it to move around as well as any tools attached to the robot such as a vacuum gripper.

To power the wheels and tracks of a stairclimbing trolley as discussed in the previous chapter, a hydraulic system may be unnecessary. The IF1 weighs 1,4 tons and the ABB IRB 4600 robot arm alone weighs 440 kg, so the tracks of the IF1 require a lot of power to move such a heavy machine. In the case of the Restoration Robot platform, the weight of entire platform should be kept below 155kg, so the wheels and tracks of the trolley would require much less power. Unlike the IF1, the Restoration Robot platform would be constantly powered by an external 220 Volt power source, which means it will not need to carry any heavy batteries for long operations, as is the case with the IF1. Instead, only one smaller battery would be required to power the trolley when moving it to site from a van and back. Therefore, an electromotor, built into the trolley itself for moving the platform up and down stairs, could be used to drive the platform autonomously on site when printing. Though such a solution may seem promising, it must be further researched to find the exact requirements for autonomous movement of robots while they are 3D printing. For example, the platform would need to accelerate and decelerate very slowly to avoid the robot from shaking too much and to keep the platform balanced. Studying the development of the IF1 and IF2 may be a good place to start such a research.

8.4. General guidelines for robot selection

To select a robot for the Restoration Robot Platform, it must comply with several criteria specific to its tasks in this specific type of context. Firstly, the robot must have at least 6-axis of freedom: three axis for movement in x, y and z direction as well as three rotational axis around the x, y and z axis. This is necessary since the geometry of a broken/damages surface on a ceiling or wall may be uneven and the robot must be able to print to 3D print onto these uneven surfaces from any angle required. Secondly, the robot must be able to be powered by a standard 220 Volt power supply, as a high voltage power supply may not be present on site. These are hard defined criteria which will apply to a robot selected for any in-situ AM restoration task. The additional criteria listed below, which are to be considered when selecting a robot for an automation task (Xiao, 2016), will be further elaborated. Note: Movement speed and rotation speed of the robot are often also mentioned as selection criteria, however for this application these are not important. Cost is not considered either in these comparisons.

Criteria for robot selection:
- Working range
- Self-weight
- Maximum payload
- Repeatability
- Protection 1: Solid objects & Dust
- Protection 2: Liquids

8.4.1. Working range

It is difficult to give a general guideline for what an ideal working range is when performing ornament restoration tasks. When performing such a task manually, the restoration plasterer is usually standing on scaffolding on which they can move around to reposition themselves when needed. The 'working area', or 'reach', of the restorer is roughly the reach of his/her arm length. Robots also have a working area, which is defined by the area within which the robot can operate from its stationary position. This range is roughly determined as a sphere around the robot, in which the radius is the distance between the TCP and the base of the robot. A robot, unlike a human, must not be moved around, because when the robot base is moved, the robot would need to re-calibrate itself for the next task and this time-consuming action should be avoided as much as possible. Therefore, as a rule: the larger the working area of the robot, the less often the entire platform must be moved and recalibrated, thus the better.

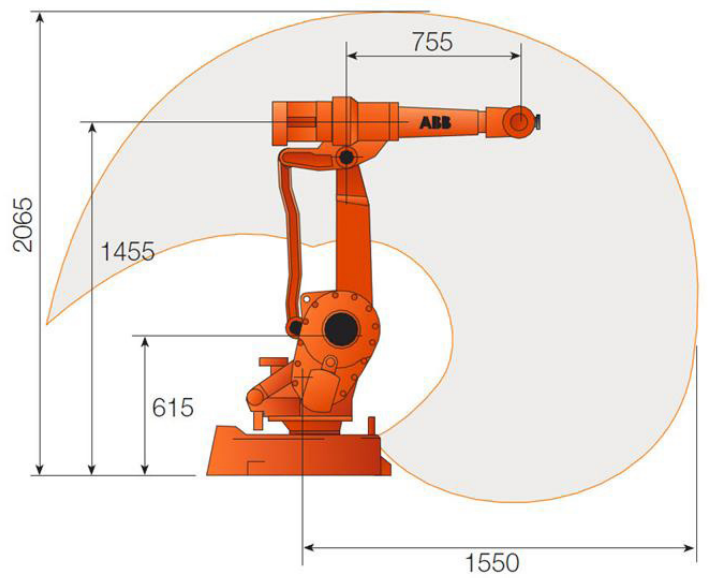


Figure 190 Figure 139 Robot working range indicated with the highlighted area around the robot. Adopted from: https://new.abb.com/

To get an idea of what a suitable working range might be, we can revisit the ornamented ceiling of the Natural History Museum Rotterdam (Figure 177 on page 151). This ceiling features a large ceiling rose in the middle with a diameter of about 1,5 meters. If the robot with a reach of more than 750mm would be positioned directly under this ceiling rose, it would be possible for it to reach any point of the ceiling rose above. Since 750mm is the required reach in a X-Y plane, an additional 100mm will be added to accommodate for the vertical distance of the robot from the ceiling. This means, the robot would require a minimum working range of 850mm.

8.4.2. Self-weight

A larger working area tends to come with a cost: the larger the working area of a robot, the larger and the heavier the robot. The weight of the robot must be kept as low as possible. On the one hand to allow it to be mounted on a camera crane so it can reach high ceilings; on the other hand, because the maximum weight of the robotic platform must not exceed 155kg as established earlier. If we consider the previously discussed camera arms/cranes, the maximum weight of the robot cannot exceed 25kg, 35kg and 80 respectively. Considering a crane with a +-3m reach, which would suffice for the robot to reach ceilings up to 4.5-5 meter, the weight may not exceed 25kg. Additionally, a robot requires a robot controller box to be operated. This controller must also fit into the bounding box of the robotic platform and its weight must also be considered.

8.4.3. Maximum payload

As discussed in the case study on the In situ Fabricator, the higher the Payload to Weight Ratio (PWR) is, the better. The ABB robot used for the IF1 had a PWR of 0,09. When selecting a robot, as a general rule: the self-weight of the robot must be within the 25kg limit and the higher PWR, the better.

The robot must be able to lift and move around the weight of the extruder, material delivery tube and the forces exerted on the robot by the compressor and the printing material moving through the material delivery tube. By weighing the extruder and material delivery tube when they are both filled with the printing material, the maximum (static) payload can be determined. To account for the forces exerted on the robot by the compressor when the material is moving through the tube (dynamic payload), a margin of an additional two kilograms is considered.

The entire extruder and the robot connector part designed and built for the robotic experiments at the LAMA, together with the material delivery tube, weigh under 3kg. Considering an additional 2kg to account for the force exerted by the compressor and moving material in the tube, give a total of 5kg to be the maximum payload in this case.

8.4.4. Accuracy

Repeatability, or Repeated Position Accuracy is the margin of error within which a robot will reach the same location when repeating a movement (Xiao, 2016). These margins are usually small, around 0.1-0.02mm (Xiao, 2016). The repeatability mentioned by robot manufacturers refers to “point repeatability”. Point repeatability is important when programming with waypoints. As mentioned in the Chapter “Robot movement”, the robot will use a linear movement (MoveL) between two waypoints, so the more and the closer waypoints are, the higher the printing accuracy can be achieved. Certain robots and robot programs, such as welding robots, are programmed with so called “path accuracy”. When welding, like with AM, it is not just the accuracy with which each waypoint is reached that is important, but the accuracy of the entire path between waypoints is important. Therefore, some welding robots are programmed in a different way, namely with curves, rather than points.

In 3D printing, the accuracy of the robot, whether it is repeatability or path accuracy, will only be a significant factor if layer heights and or extrusion widths are extremely small, smaller than 0.5mm. This is because most

robots have a very repeatability, usually between 0.1 and 0.03mm. With a layer height and extrusion width of 0.5mm or larger, a path accuracy and repeatability of 0.1 or lower will probably suffice.

8.4.5. Protection

Depending on the environment in which a robot is deployed, it must be protected to a certain degree against hazards. This protection is indicated by a so called ‘IP’ rating, which consists of two numbers, range between 0 (least protected) and 6 or 8 respectively (highest level of protection) (Xiao, 2016). The first number behind the ‘IP’ indicates how well the robot is protected against solid objects and the second number indicates how well the robot is protected against liquids (Xiao, 2016).

First number (Protection against solid objects)

0 No protection
1 Protected against solids objects over 50mm (e.g. accidental touch by hands
2 Protected against solids objects over 12mm (e.g. fingers)
3 Protected against solids objects over 2.5mm (e.g. tools and wires)
4 Protected against solids objects over 1mm (e.g. tools, wires and small wires
5 Protected against dust - limited ingress (no harmful deposit)
6 Totally protected against dust

Second number (Protection against liquids)

0 No protection
1 Protected against vertically falling drops of water
2 Protected against direct sprays up to 15o from the vertical
3 Protected against direct sprays up to 60o from the vertical
4 Protected against sprays from all directions - limited ingress permitted
5 Protected against low pressure jets if water from all directions - limited ingress permitted
6 Protected against strong jets of water e.g. for use on shipdecks - limited ingress permitted
7 Protected against the effects of temporary immersion between 15cm and 1m. Duration of test 30 minutes
8 Protected against long periods of immersion under pressure

Figure 191 *IP ratings and their meaning. Adopted from: https://www.sooyeerobot.com/new/9-Parameters-for-Choosing-the-Right-Industrial-Robot-Model-Type.html*

The robot will be deployed on a building (restoration) site and will be 3D printing upside down. Printing material or broken off pieces from the ceiling could potentially fall onto the robot. Furthermore, there will be a dust and gypsum powder in the air on site, which could potentially get inside the robot. So, for the first number, at least a protection of 5 is required for the restoration robot. The robot is less likely to get in contact with water on site. At most dripping water from a leaking pipe or from a roof leakage could fall onto the robot. Therefore, the second number should be at least 1.

Additionally, a variety of protective coverings are commercially available to protect the robot for various purposes. The simplest of such coverings are disposable slip-on style covers, which protect the robot from axis 1 to 6 against fluids & dust, while maintaining full robot articulation (see Figure 192) (Robots, n.d.-b). Other types of coverings, such as the Airskin cover from Universal Robotics (see Figure 193), have built in pressure sensors that can give feedback to the robot if it collides with any object and initiates the robot’s safety brakes to protect the robot 9 milliseconds after detecting a collisions (Robots, n.d.-a). For the in-situ restoration application, the first type of covering may suffice to protect the robot from any falling gypsum, dust or liquids. Before printing on site, the robot’s printing paths can be thoroughly checked in the robot programming software to avoid collisions. Robot programming software such as RoboDK has a collisions checking feature, so this can be done during the programming phase. In general, the second type of covering may not be required for the in-situ restoration application. Even so, if restorers would be doing other work simultaneously in the same room as where the robot is working, the site becomes more dynamic with new external factors and a protective cover such as the Airskin may be worth considering.

Figure 192 UR10 Robot with disposable protective cover. Source: www.universal-robots.com/plus/urplus-components/accessories/disposable-style-robot-covers/

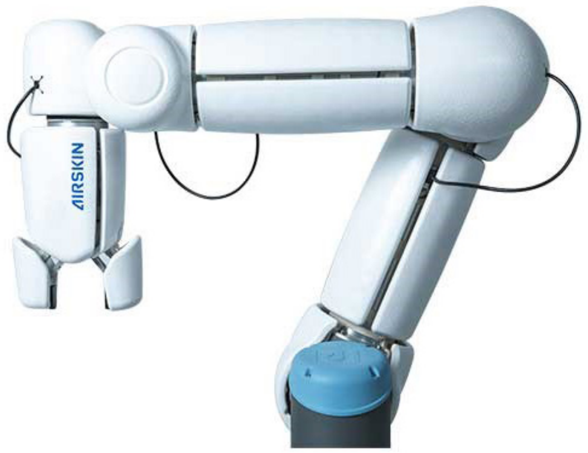


Figure 193 Airsoft protective cover for UR robots. Source: https://www.universal-robots.com/plus/urplus-components/accessories/airskin-ple-certified-safety-skin-for-ur5-and-ur5e/

8.4.6. Safety

Safety for humans and the environment around the robot is extremely important when working with robots. Industrial robots typically do not have any safety-rated sensors built into them (Thaler, 2017). To make an industrial robot safe to use in an automation task, several types of safety equipment such as fences, motion sensors etc. are required and the total cost of the robotic platform increases three (Thaler, 2017) to four times (Robotics, 2017). Collaborative robots have built in safety-rated sensors and are therefore safe to work in collaboration with humans (Thaler, 2017). Typically, industrial robots are larger, stronger and faster than collaborative robots (Thaler, 2017), but this also makes them bigger, bulkier and more dangerous to work with humans.

For the restoration task it may be plausible that initially, the robot would work side by side with restoration plasterers. Certain tasks in ornament restoration, such as finding and scratching off loose material from the ceiling, can be still done by a human worker (for now), while the extremely labour-intensive tasks which require dealing with high geometrical complexity can be done by a robot. Since it is also established the robot would not require to carry heavy loads (payload of around 5kg), a reach of around 850 mm, a low self-weight and must be able to work with humans, a **collaborative robot** seems more suitable than an industrial robot.

8.4.7. Suitable robots

As an example, 10 different robots are compared to each other with the previously discussed criteria. These robots were found through the websites www.directindustry.com and comparison tool of www.cobottrends.com/ which allows a user to search for robots by applying various filters and compare them. Filters used to find this list of robots were:

- Collaborative robots
- 6-axis or more
- Possibility to be powered by 220 Volt power source.
- Working range between 700mm-2000mm
- Payload of 5kg – 15 kg
- IP rating of IP51 or higher
- Repeatability of 0.1 or lower

Note: When comparing collaborative robots in this way, the cost, quality and availability of support & repair services are not considered.

Robot name	Manufacturer	Self-weight (kg)	Controller weight (kg)	Payload (kg)	PWR (-)	Working radius (mm)	Repeatability (mm)	Total weight (kg)
UR5	Universal Robotics	20,6	15,2	5	0,24	850	0,03	35,8
UR10	Universal Robotics	33,5	15,2	10	0,30	1300	0,05	48,7
HC10	Yasakawa	47	?	10	0,21	1200	0,1	>47
HCR-5	Hanwha Techwin	20	20	5	0,25	915	0,1	40
HCR-12	Hanwha Techwin	53	21	12	0,23	1300	0,1	74
I-5	AUBO	24	20	5	0,21	924	0,05	44
I-7	AUBO	32	20	7	0,22	1150	0,05	52
I-10	AUBO	37	20	10	0,27	1350	0,05	57
KR1205	Kassow Robots	25	?	5	0,2	1200	0,1	+-45
KR1805	Kassow Robots	38	?	5	0,13	1800	0,1	+-58

Figure 194 Table showing various collaborative robots which fullfill the requirements for the Restoration Robot Platform.

In the table shown in Figure 194, some robots stand out with their large working range such as the Aubo I-10 and Kassow Robots KR1805. Other robots such as the UR10 (0,30) stand out for their high PWR. Remember the ABB IRB 4600 robot arm used for the In situ Fabricator of ETH Zurich had a PWR of 0,09. Considering this, it appears Collaborative Robots have much higher PWR than standard industrial robots. Some of these robots do exceed the 25kg camera crane payload capacity, so if they are to be used, a stronger camera crane would need to used. It is evident there is not one best robot for the task. The choice of robot would need to be made on basis of further investigation into the restoration tasks and further development of the entire platform, which will give more insight into the total weight of the platform, among other aspects.

For the experiments in this research the UR5 robot was set out to be used, as it is available in the Laboratory for Additive Manufacturing in Architecture of TU Delft. Though the UR5's reach may be modest, it does fulfil all other criteria.

8.5. Software integration

In the previous chapters, several hardware elements of the Restoration Robot Platform were explored. A set of design guidelines is formulated for the design of a prototype of a Restoration Robot Platform with almost entirely off-the-shelf components. To apply such a platform in practise, the data associated with the chosen hardware components for this robotic platform, as well as the gypsum-mixture printing properties must be integrated within a streamlined workflow for robotic fabrication. Therefore, the material properties as well as the design strategy for the platform are compiled in a proposed plug-in, called “Robotic Restoration”. This plug-in will contain all necessary data and additional digital tools required for the use of the Restoration Robot Platform in practise.

The plug-in will have to be installed for two types of software, a robot programming software and a 3D printing slicer software. For this thesis, the robot programming software RoboDK is used and for 3D printing, the Cura slicer is used.

8.5.1. RoboDK plug-in

For RoboDK the plug-in will have four main features:

- Context tab as an additional station element.
- Restoration Robot caddy as an interactive object.
- Online library of camera cranes and other type of arms.
- Custom extruders and nozzles as RoboDK Tools

Context tab

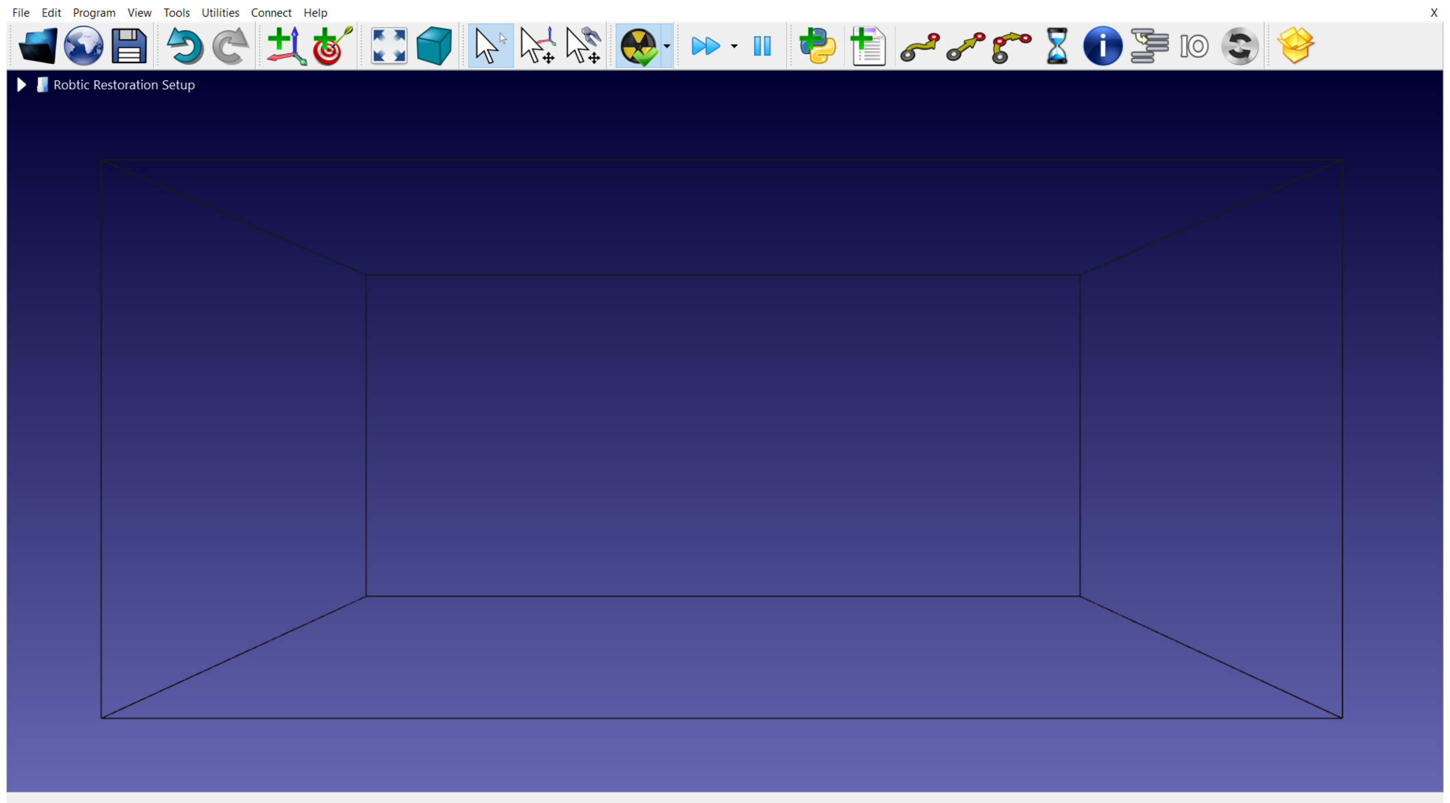


Figure 195 *Impression of room and ceiling loaded into RoboDK as collision objects. Source: Author.*

The first new element is a “context tab”, which will be a new station element. A rough 3D scan of the room in which the robot will operate, including three physical calibration markers on the ceiling, is converted into a CAD file as described in the chapter “Point cloud to mesh transformation”. This CAD file is imported into RoboDK and will be assigned as a “context” element. By assigning it as a context element, the geometry will be recognized by RoboDK as a collision element, so RoboDK will always check if the robot or extruder will collide with this element when creating a toolpath. Furthermore, when loading the 3D printing file of the ornament into RoboDK, it will be possible to assign the ceiling of the context file as a parent object onto which the ornament can be placed. Now that both context and 3D printing object are loaded into RoboDK, the next steps are to load in the transport caddy, choose a robot, extruder and crane.

Restoration Robot Caddy

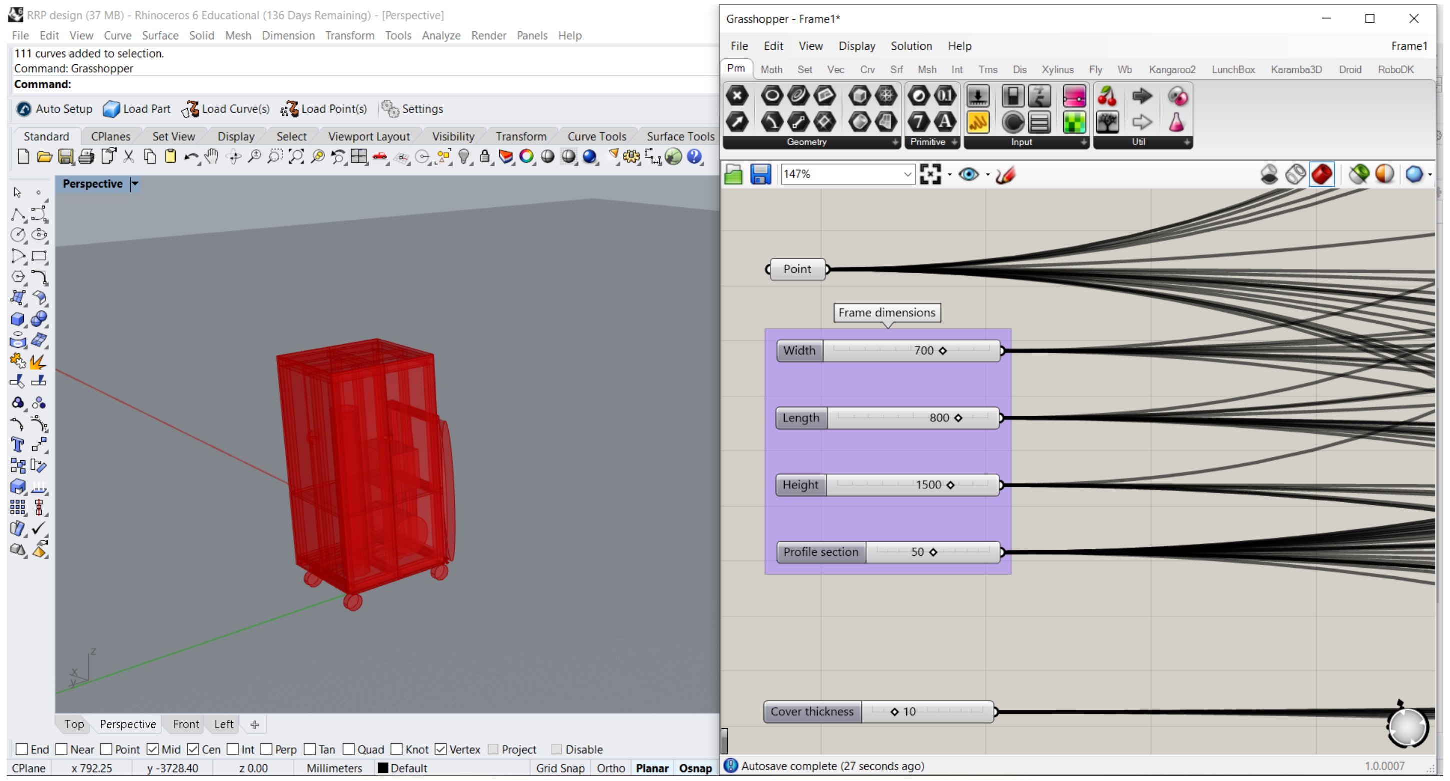


Figure 196 *Screengrab of parametric model of caddy made with Grasshopper parametric design tool. Source: Author.*

The second element in the plug-in is a model of the caddy in which the robot is moved to site. This caddy can be imported as a parametric model, in which the user can change the dimensions of the caddy to their preference. The caddy will come pre-loaded in the size described in the previous chapters. When choosing a robot and or crane that is too large for the currently chosen caddy, RoboDK will generate a pop-up and suggest a suitable dimension for the caddy in which both Robot and crane will fit. A parametric model is created for the caddy using Grasshopper parametric design software, which can be used to change the dimensions of the caddy to the user’s preference. This model could be transformed into a format that is compatible with RoboDK.

Figure 197 *Logo of Robotic Restoration plug-in. Source: Author*

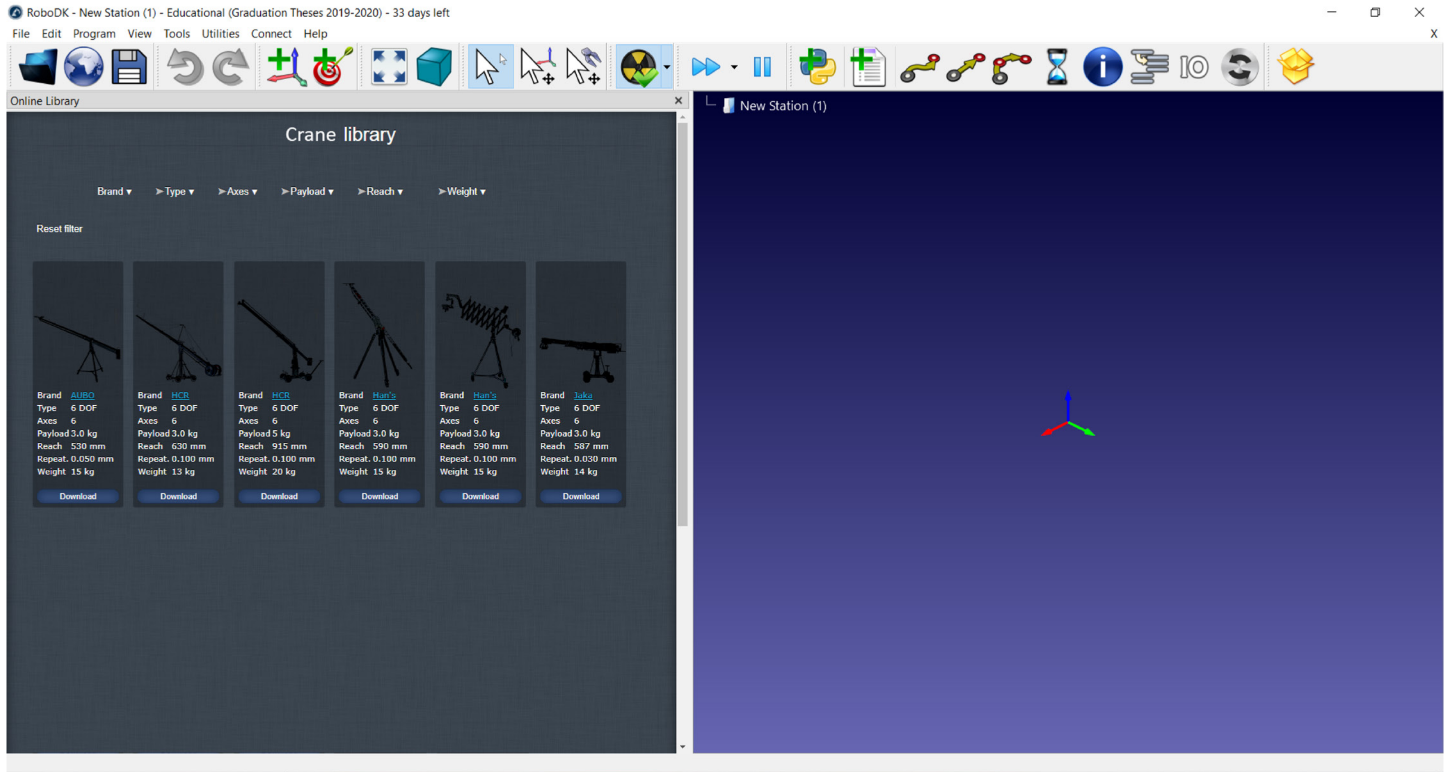


Figure 198 *Impression of an online crane library in RoboDK. Source: Author.*

Online crane library

The third element is the online crane library (see Figure 198), which will be similar to the online robot library that RoboDK currently features (see chapter “RoboDK workflow”). Users will be able to select from a wide variety of cranes accessible through an online database. The cranes, much like the robots, can be chosen by applying various filters such as self-weight, maximum payload, reach, etc. For example, in the case of the Restoration Robot Platform described in the previous chapters, the Kite-11 crane could be selected based on its self-weight, allowable payload and reach. Once the crane is loaded into the programming station, users will be able to move the crane arm into position from the “Kite-11 panel” (see Figure 199) by double clicking on the name, much like they can move robots in the robot panel.

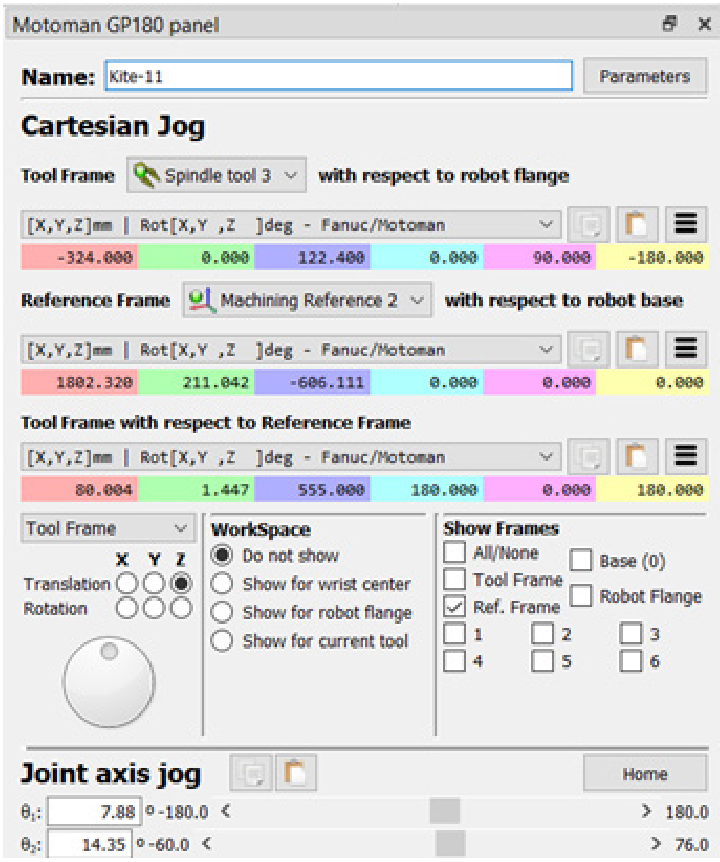


Figure 199 *Cartesian-as well as rotational-movement options for the crane. Source: Author*

If the user has chosen a robot first, the library will tell the user which cranes can lift a payload greater than the chosen robot. Similarly, if the user chooses a crane first, the robot library will tell the user which robots are within the chosen cranes payload capacity. If there is any surplus in lifting capacity for the crane, this will also be shown to give the user an idea of how much additional weight, such as an end effector, can be mounted onto the crane.

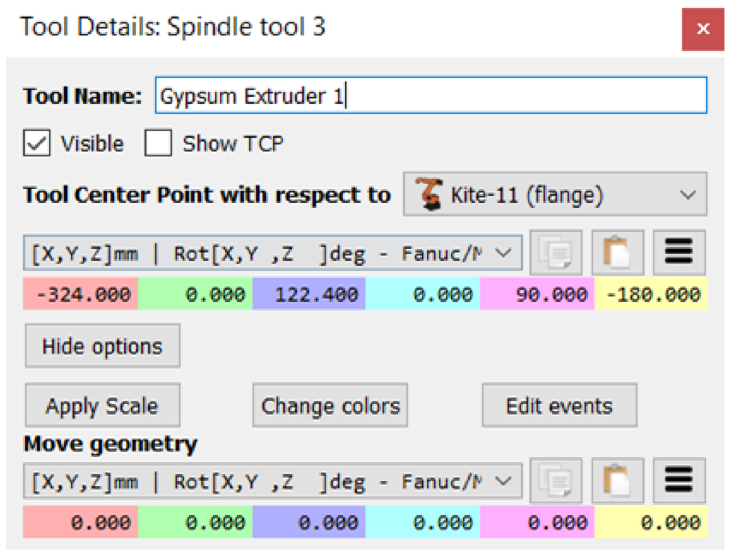


Figure 200 *Tool details menu, from which different nozzles can be simply adjusted. Source: Author.*

The custom built extruder will also be part of the plug-in and will be available as a “RoboDK Tool” file. This tool can be added into the programming station and assigned to the chosen robot as described in the chapter “RoboDK workflow”. By double clicking on the tool, the tool details menu will pop up. Through this menu, the nozzle diameter as well as the nozzle length can be adjusted to accommodate for different nozzles, which may have a different length and or diameter (see Figure 200). The role of the tool in RoboDK is to determine the new Tool Point Centre for a chosen nozzle and to act as a collision object when creating a toolpath.

With these elements integrated into the RoboDK workflow, the Restoration Robot Platform can be programmed by anyone who can work with RoboDK and CAD software such as Rhino and Grasshopper. This means architects, engineers and even restoration plasterers, after a free Rhino crash course from TOI-pedia and RoboDK crash course from RoboDK itself, could work with the Restoration Robot Platform, without the need to learn robot programming.

8.5.2. Cura slicer plug-in

The Cura slicer is one of the most widely used 3D printing software and it has a very user friendly interface, which is why this is the slicer chosen to describe the to-be-developed plug-in. Naturally, this plug-in could also be created for other slicers and would work in a similar way in these slicers.

The Cura plug-in will feature:

- Extruder (with relevant characteristics)
- Library of compressors (with relevant characteristics)
- Printing material (with relevant characteristics)
- Recommended slicer profiles

The first feature for the Robotic Restoration plug-in for Cura is the extruder. The user must select a 3D printer from one of many 3D printers pre-loaded in Cura. In this menu, the user will be able to find the extruder under the name “Gypsum printer_01” (see Figure 201). After selecting this extruder, Cura will have all the necessary data about this extruder, such as the extrusion speed range of the motor, and the volume of printing material which it can move per revolution of the motor.

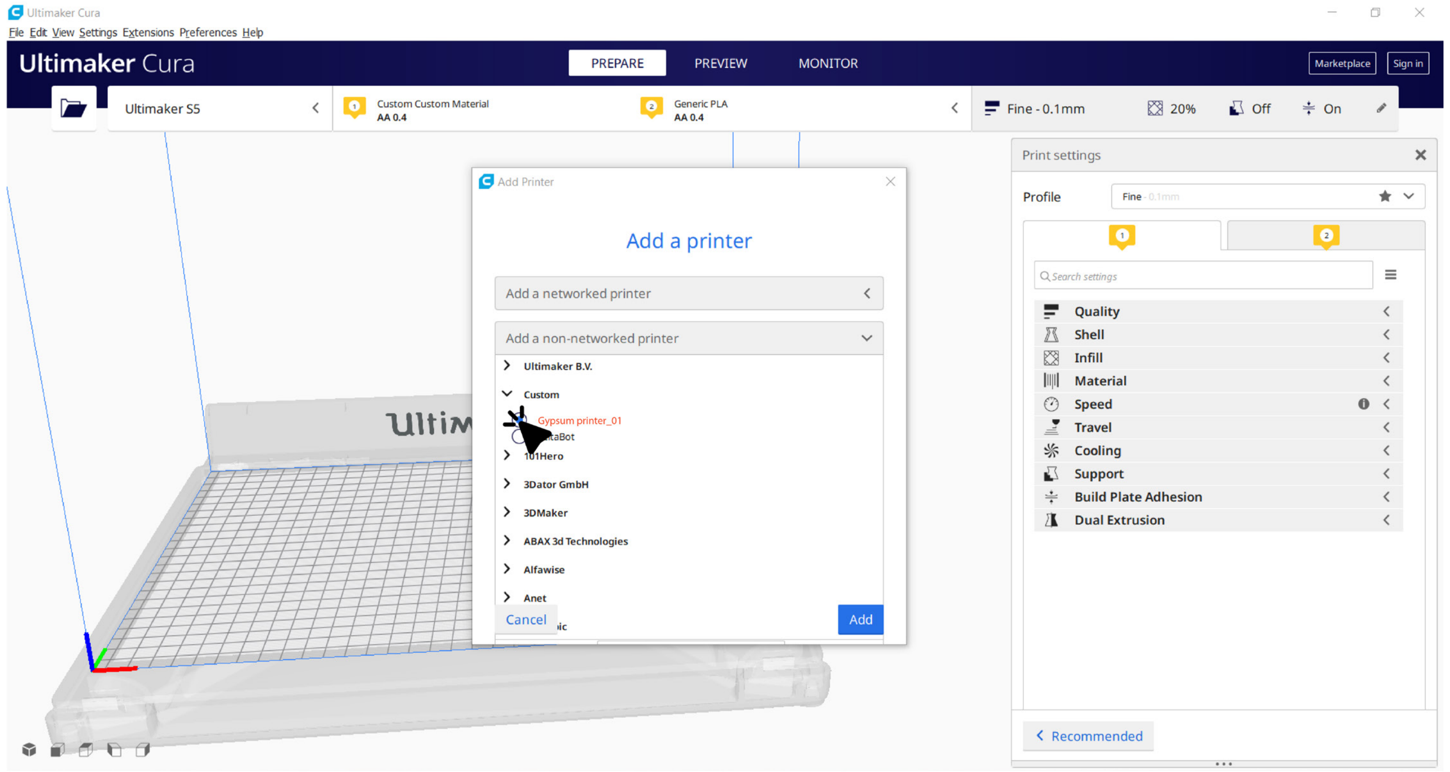


Figure 201 *Choose the extruder in the "Add a printer" menu. Source: Author*

Compressor library

The second feature from the plug-in for Cura will be the option to select a compressor. Similar to the how the extruder is selected, now an additional tab will be available where the compressor which the user is going to use can be selected from an online database of different compressors (see Figure 202). After selecting a compressor, the relevant data of this compressor is imported into the software settings menu. This data includes information such as the power, capacity and output pressure range of the compressor. From the "Print settings" menu, the user can change various parameters for the slicing and printing procedure. After selecting a compressor, the compressor settings tab will automatically appear in this printer settings menu. Here the user can change the compressor's output pressure.

Printing material

The third feature from the plug-in is the printing material. Under the same "print settings" menu, the user can select the printing material (see Figure 203). A new material section called "RRP" (Robotic Restoration Platform) will be available through the plug-in. The user can choose one of the pre-loaded mixtures, such as the G5 mixture. Information about the material, such as minimal extrusion width, required pumping pressure, particle size, maximum stackable layers, etc. will be imported as well when selecting a material.

Recommended slicer profiles

The final feature of the plug-in for Cura will be a set of recommended slicer profiles, which give a set of default settings in Cura. These settings will be based on the material properties, extruder and compressor specs as well as the 3D printing geometry. Some of these recommended default settings are determined from experiments conducted in this thesis such as the minimal extrusion width, open time and required pumping

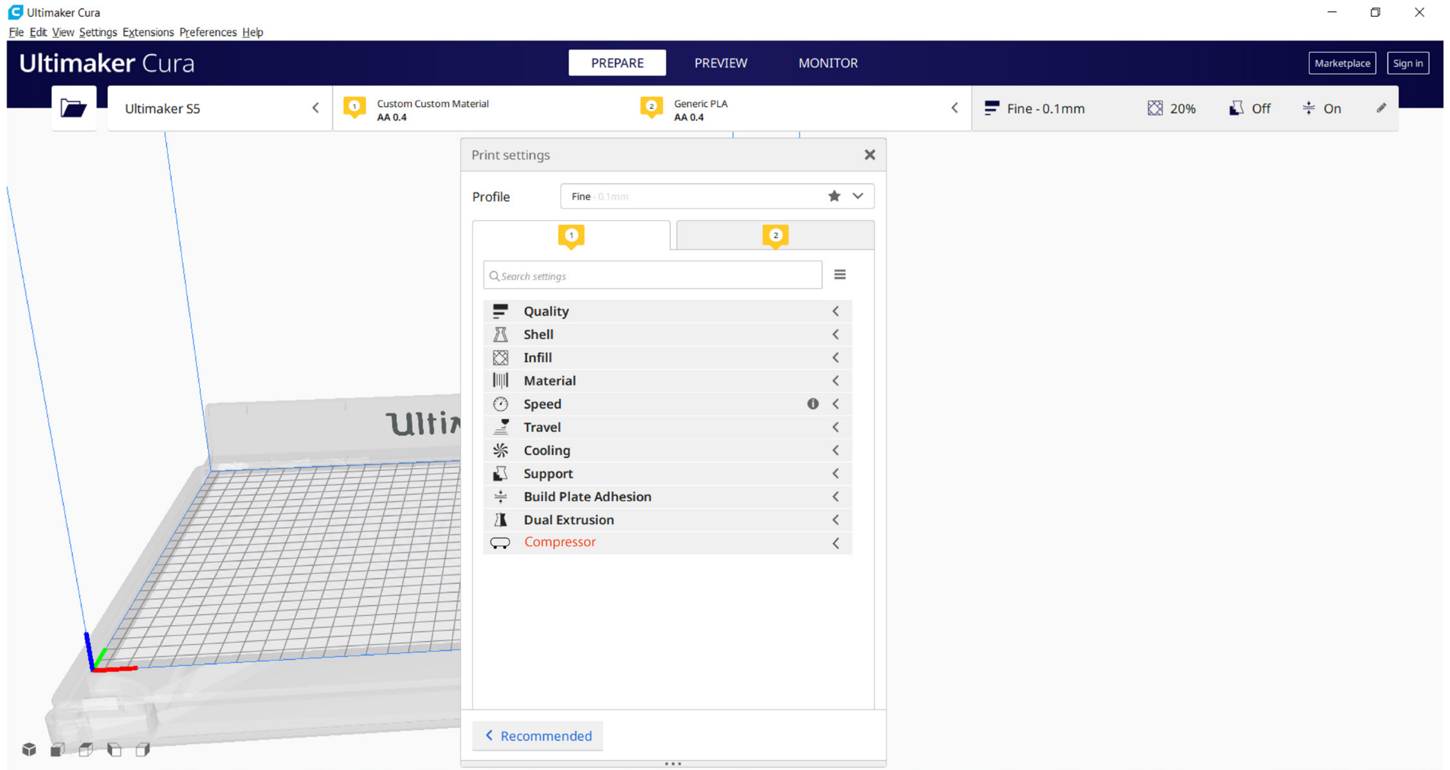


Figure 202 *Compressor settings added in Cura. Source: Author.*

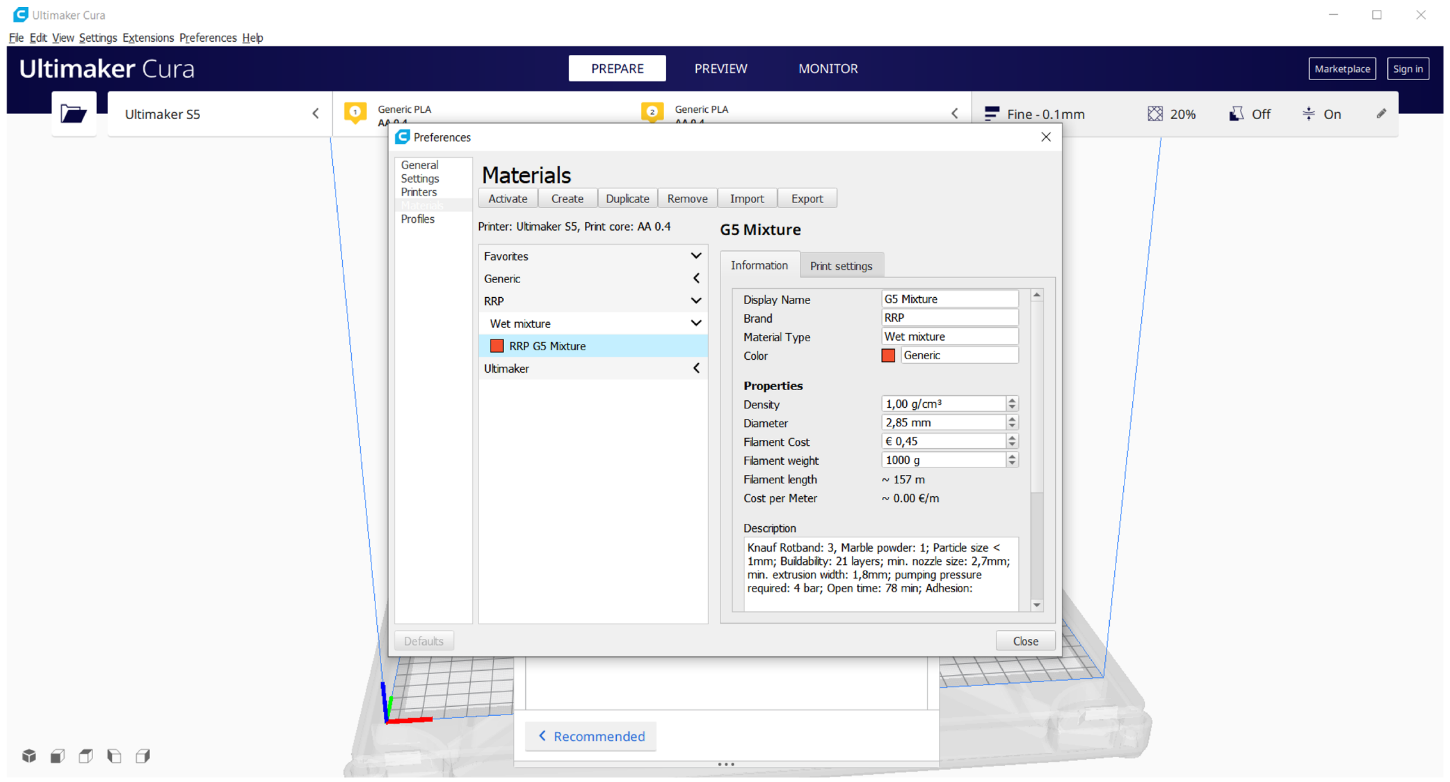


Figure 203 *Printing material selection in Cura. Source: Author.*

pressure, while others are yet to be determined by conducting more experiments.

The required data about the crane, extruder, nozzles and compressor for the plug-in can be found in appendix D. The data about material characteristics of mixture recipe G5 can also be found in Appendix D.

8.6. Maintenance
The following set of criteria are defined to ensure proper maintenance of the RRP:
- Extruder should be easily removable with a single tool. --> Attached M6 with bolts
- Extruder, material reservoir and material delivery tube should be easily detachable and cleanable with water and cloth.
- Robot should be bought with an extensive service plan, as it has a higher probability of getting damaged during transportation and installation on site.
- Software plug-in should be maintained online by software developers.
- New research in the field of restoration with gypsum-based mixtures should ideally be made open source, to keep software tools up to date with the latest knowledge.

8.7. Summary
In the previous chapters several constraints and requirements are discussed for the development of a Restoration Robot Platform. These aspects can be used as a general guideline towards the further development of such a robotic platform. The various constraints and requirements are summed up per category in the list below.

8.7.1. Guidelines summary

Weight & dimension constraints:
- Entire platform does not exceed 155kg.
- Fits inside a bounding box of 0.7m *0.85m*1.92m for transportation.
- Robot can reach the height of 5 meters.
- Platform can be loaded into a van.

Working range & accuracy:
- Robot can work within a range of at least 850mm.
- Robot can provide 0.1 millimetre positioning and path accuracy at the end effector.

Versatility and customisation:
- Has at least 6-axis of freedom.
- Can be equipped with different tools or end effectors to perform a wide range of restoration tasks (e.g. 3D printing, milling, smoothening, etc.).
- Has a sufficient payload capacity (5kg or higher) to carry various custom end-effectors.

Protection & safety:
- Is protected against dust and water ingress (IP151 or higher).
- Can work safely with human workers on site.

Power supply:
- Can be plugged into standard mains power of 220 Volts.

Usability and integration:
- Integrate crane library and context import as plug-in into Robot programming software.
- Integrate printing materials and extruder as plug-in into current slicer software.

8.7.2. Design suggestions
In addition to the requirements and constraints, the previous chapters also offer some off-the-shelve suggestions to fulfil the constraints and requirements for the development of the robotic platform. These suggestions are summed up in the list below.

Weight & dimension constraints:
- Build lightweight aluminium chassis within the 0.7m *0.85m*1.92m bounding box to fit all equipment inside for safe transportation.
- A camera crane could be used to allow a relatively light robot to reach high ceilings up to 12 meters.
- Use electric powered stairclimbing trolley to move the platform.

Stability:
- Use crane arm with padlock to lock orientation.
- Use a crane arm with built in gyroscopic stabilizer.
- Attach robot at base to an external support such as a scaffolding pole.

Robot selection:
Select collaborative robot as they have many advantages for this application:
- Lightweight
- High PWR
- Safe to use with human workers.
- Generally powered by 220V.
- Fulfils working range requirement
- Fulfils point- and path-repeatability requirement.

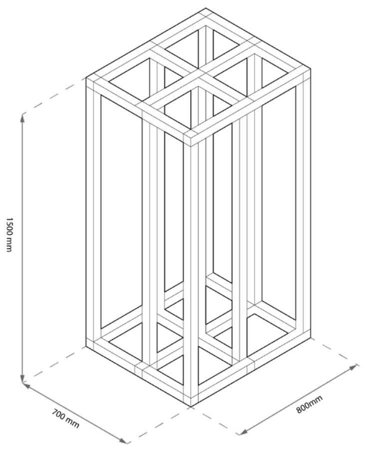
Select a collaborative robot such as:
- UR5
- UR10
- HC10
- HCR-5
- HCR-12
- AUBO I-5
- AUBO I-7
- AUBO I-10
- KR1205
- KR1805

Protection & safety:
- Use disposable slip-on sleeve to provide additional protection for robot against dust & liquids.

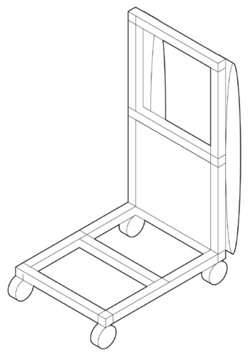
Usability and integration:
- Integrate crane library and context import as plug-in into RoboDK software.
- Integrate printing materials, compressor specs and extruder as plug-in into Cura slicer software.

8.8. Restoration Robot concept design

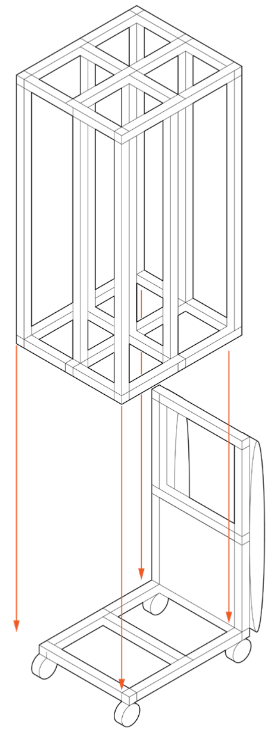
Aluminum frame
Dimensions: 0.7m*0.8m*1.35m
Self weight: 10kg
Total weight: 10kg



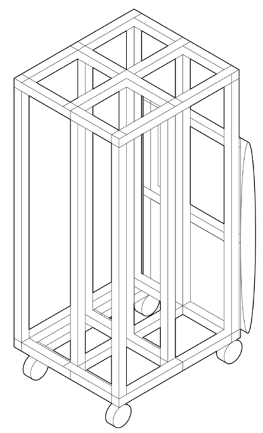
Aluminum frame
Payload: 310kg
Selfweight: 30kg
Total weight: 40kg



Bolt frame to trolley
10 M8 bolts

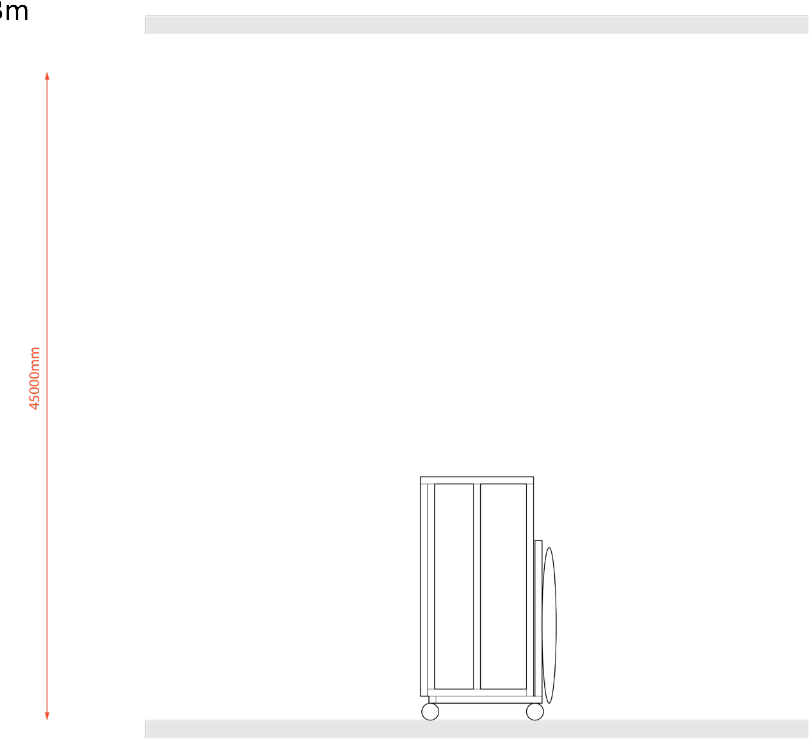


Frame & trolley
Dimensions: 0.7m*0.85m*1.5m
Total weight: 40kg



Required vertical reach

Vertical reach: 4.5m - 1.5m = 3m

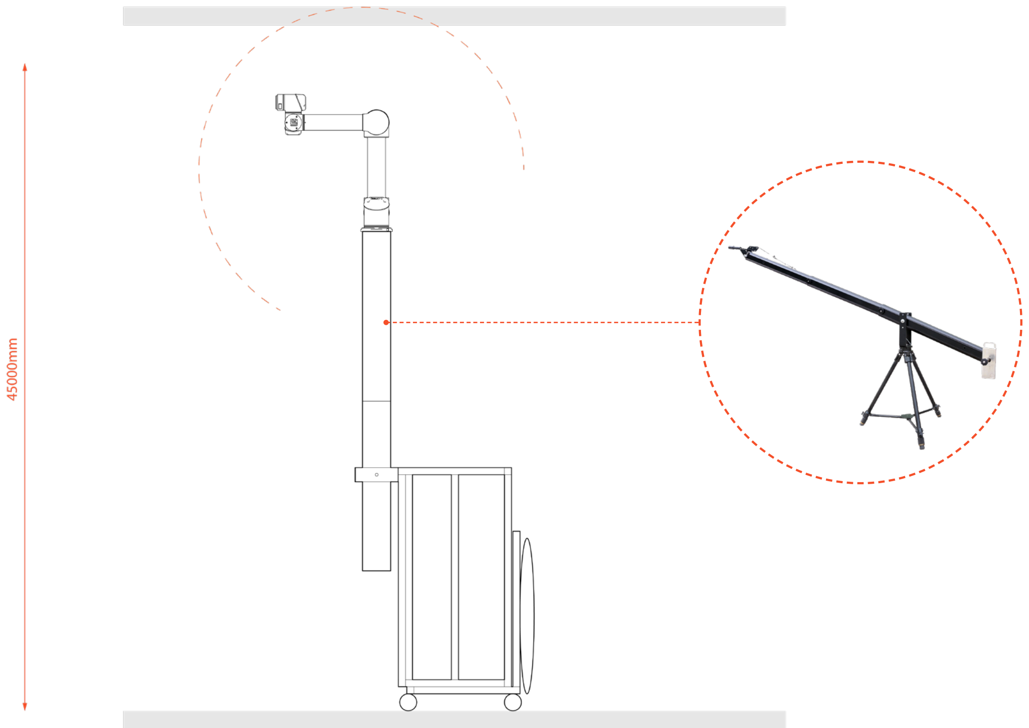


Camera crane

Payload: 25kg

Selfweight: 24kg

Total weight: 64kg

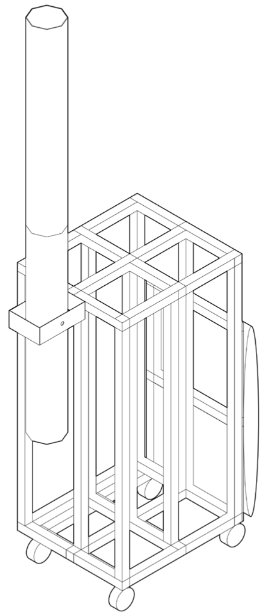


Crane attached to frame

With steel plate & M8 bolts

Self weight: 1kg

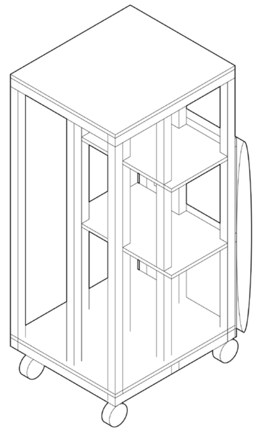
Total weight: 65kg



Shelves & top

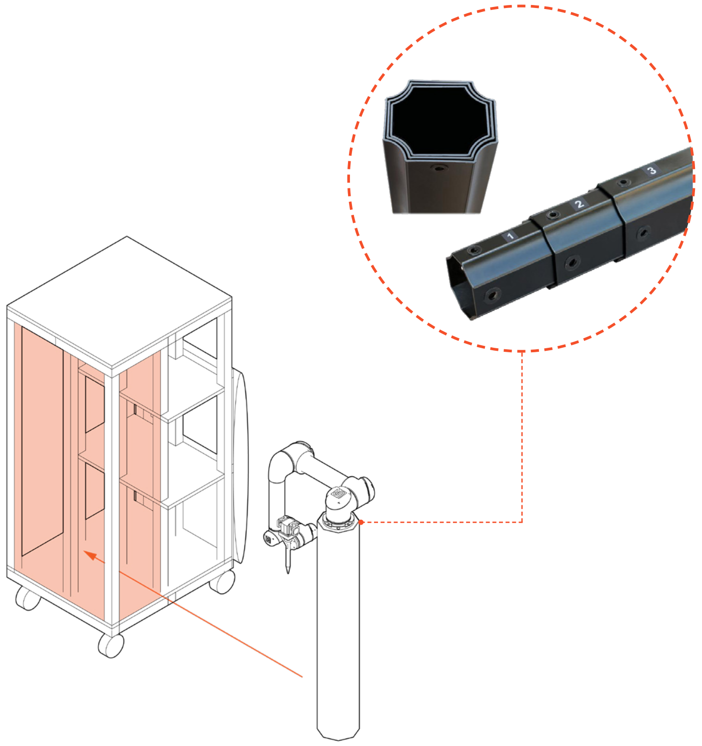
Self weight: 1kg

Total weight: 66kg



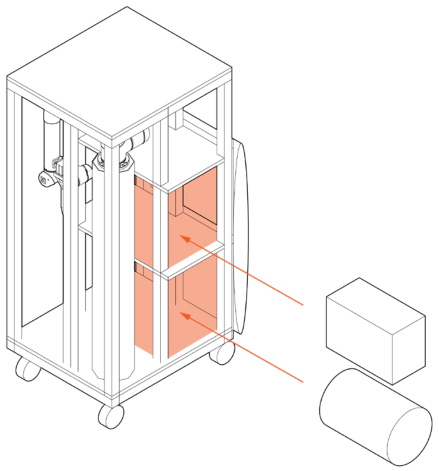
Crane + robot storage

Crane folded in for storage
UR5 robot weight: 20kg
Extruder weight: 1kg
Total weight: 87kg



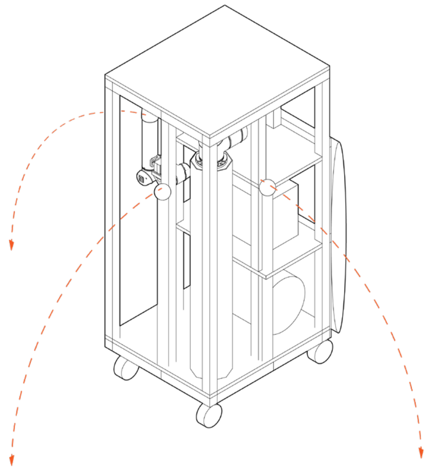
Compressor & robot controller

Storage space in back shelves
Compressor weight: 5kg
Robot controller weight: 15kg
Total weight: 107kg



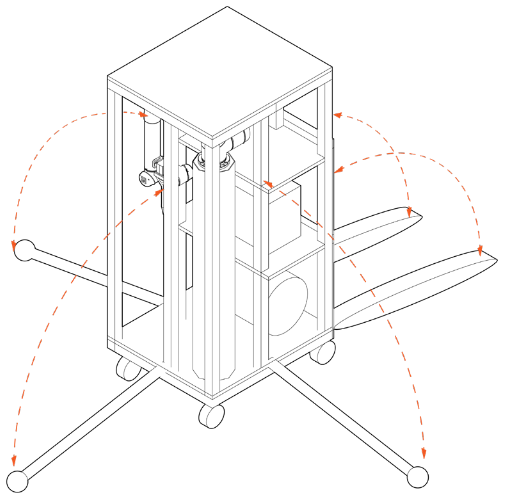
Stabilizing legs

3 retractable
Self weight: 2kg
Total weight: 113kg

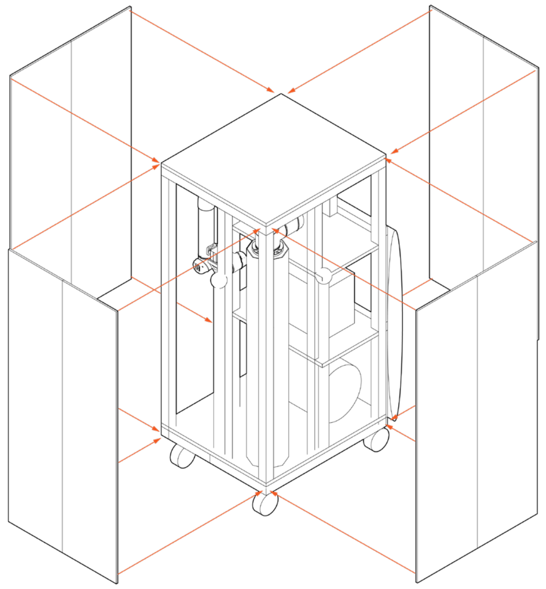


Stabilizing legs + trolley tracks

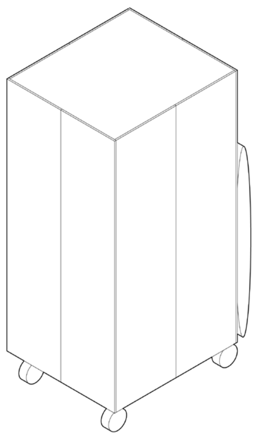
For stability during printing
Total weight: 113kg



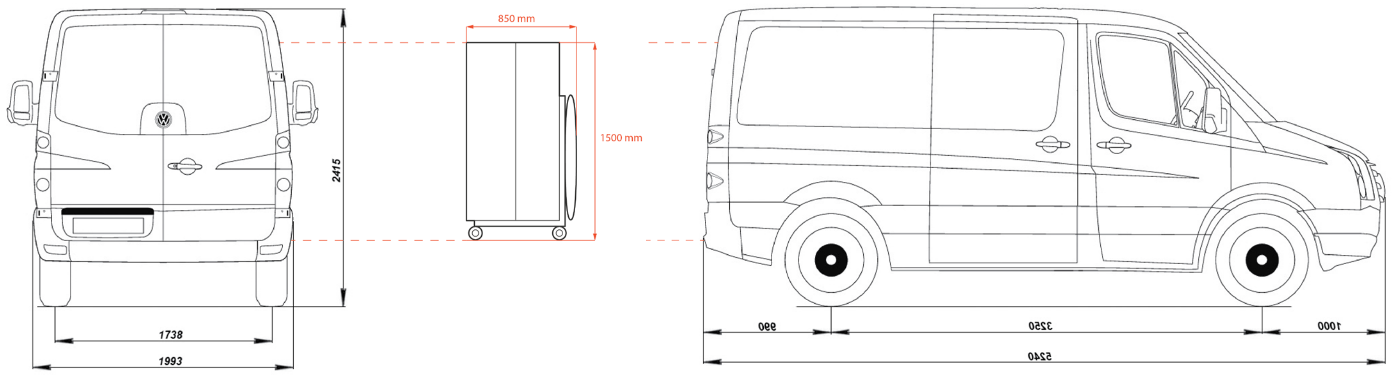
Protective doors
Polycarbonate doors
Self weight: 8kg
Total weight: 121kg



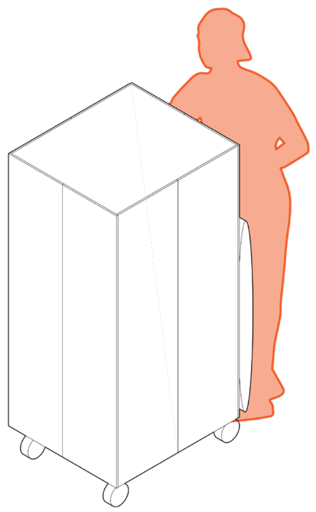
Final design: transportation mode
Total weight: 121kg



Transportation to site
Fits in standard transport vans

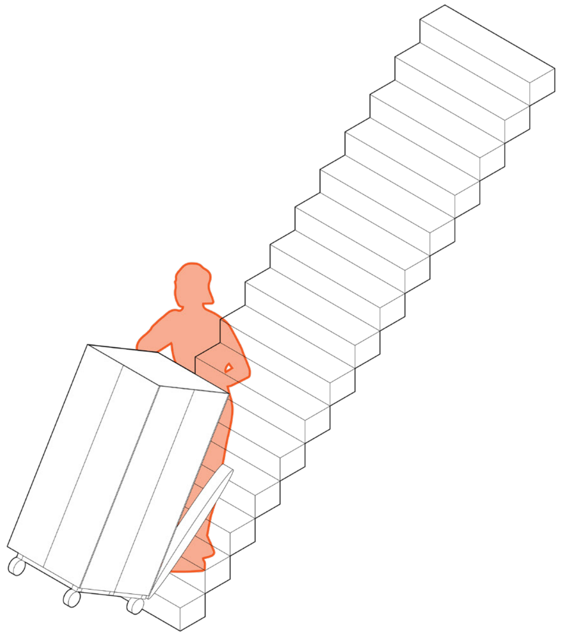


Movable by 1 person
Due to electric powered trolley

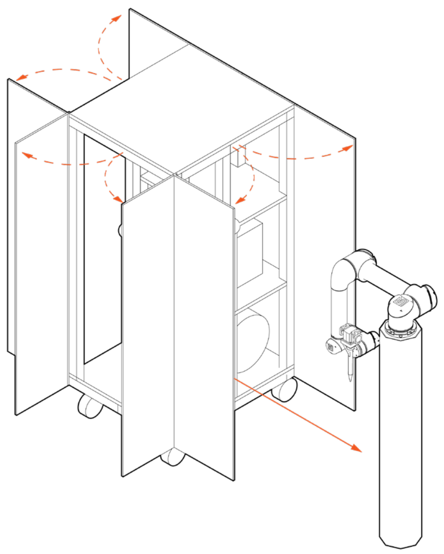


Movable up stairs by 1 person

Electric powered stair-climbingtrolley

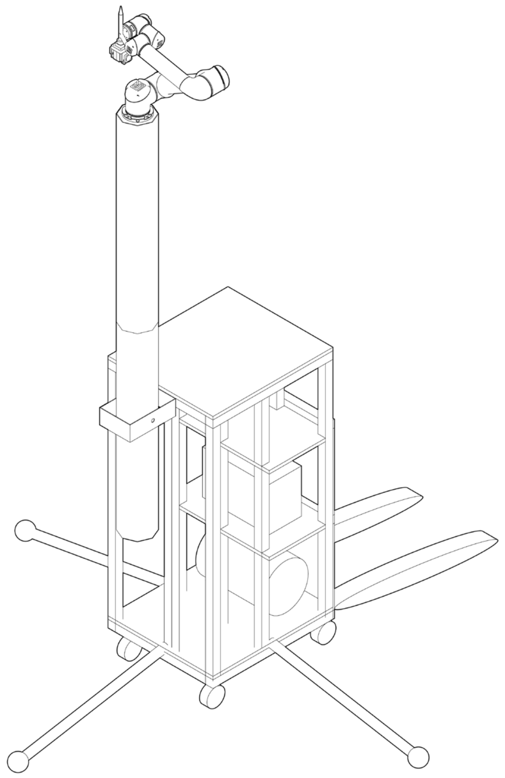


Openable doors to remove componants



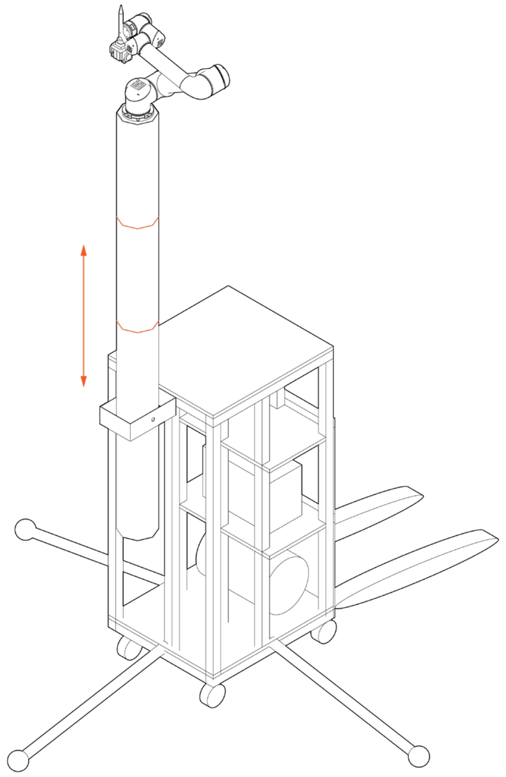
Quick mounting on site

Crane & robot mountable by 1 person

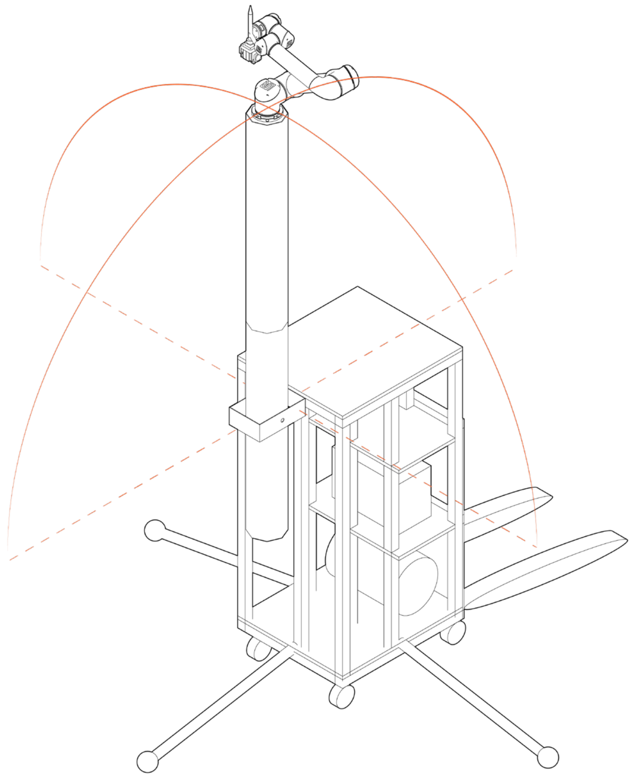


Adjustable crane height

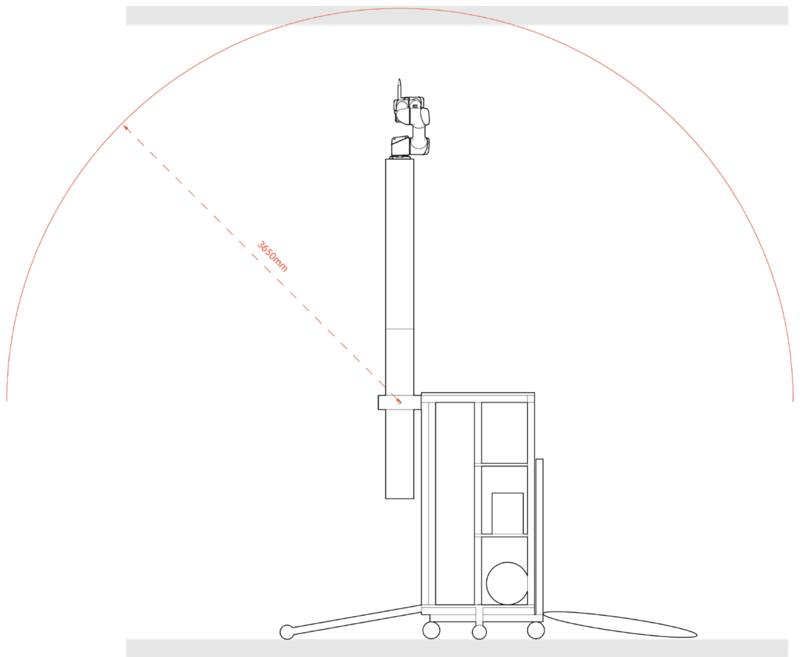
2m - 4.5m adjustable height



Crane orientation adjustable
Creating larger working area



Adjustable crane height
+-3.65m working radius
(External support may be
required for large inclinations)



8.9. Limitations

The concept design of the prototype Restoration Robot Platform has some limitations which must be considered and could be solved after building and testing a first prototype.

The first limitation is concerning the stability of the platform during printing. When the robot is moving at the end of a long crane arm, it will generate a large moment and the crane may not be able to keep the robot properly stable during printing in such a case. Experiments could show if the active gyroscopic stabilizing mechanism of the camera crane will suffice to keep the robot stable during printing. If not, a variety of different methods of stabilizing the robot are suggested in the subchapter “Stability”. The ideal situation would be if the robot could be attached to the ceiling itself, possibly to the physical calibration markers, with a non-intrusive attachment method. In such a case, the crane would provide support to keep the robot at the right elevation, while the robot would be supported from lateral movements by its attachment to the ceiling. This could be further investigated.

Another limitation is the working range of the robot. When the robot is calibrated at a stationary position of the caddy, the robot itself as well as the crane could be moved in different orientations without needing to recalibrate the robot. Since the crane is not motorized and not driven by software, the crane arm needs to be manually moved around when the robot must access another part of the ceiling. With the current method of mounting the crane, the crane can only move in two directions. This is sufficient for application in which the caddy is directly underneath the area which is to be restored on the ceiling. However, if the area is larger than the working range of the robot, then having a crane with more freedom of mobility would be better. Additionally, if the crane could be turned with a stepper motor too and integrated into the RobotDK software, it could function as a large first joint of the robot. This may make the platform significantly heavier but could nevertheless be an interesting path to investigate further.

Autonomous mobility is briefly discussed in the previous chapters as a desirable feature to overcome limitations in working range. However, applying such a technique would require the driving feature to become an additional “axis of movement” for the robot and would require navigation sensors etc. for the robotic platform, which makes the RRP heavier (think of on board batteries) and more complicated. For most stucco ornament restoration tasks, such features would likely not be required, however, to design a truly autonomous RRP, these features could be explored in further studies.

8.10 Cost of proposed restoration methodology

The total cost of the proposed platform is around 35000 euro. The annual salary of a plasterer in the Netherlands is around 35700 euro (Nationaleberoepengids, n.d.). This means that if a restoration plasterer's company has a shortage in labour of one plasterer, the company could invest in such a system for roughly the same cost as the annual salary of one employee. By reconstructing the complex geometry of the ornaments digitally and translating this geometry into instruction for the robot, a lot of on-site time could be potentially saved since the robot will, if everything goes according to plan, print the exact complex geometry which is modelled directly in-situ with a precision high precision of 0.5mm. Redo's of parts could be avoided and plasterers could avoid doing strenuous work. Furthermore, instead of four plasterers working simultaneously on one ceiling for long periods of time, the robot could be used with one employee who checks if everything is going properly once the robot has been set up, which can also save cost for a company.

Element	Price (euro)	Percentage of total cost	Sources
UR5 robot	32000	91,87	blog.robotiq.com
Kite-11 crane	1250	3,59	proaim.com
Extruder	100	0,29	Estimate
Electric stair climbing trolley	800	2,30	alibaba.com
Full chassis	500	1,44	Estimate
Compressor	110	0,32	hbm-machines.com
Material delivery tube	20	0,06	Estimate
Material reservoir	50	0,14	Estimate
Total	**34830**	**100**	

Figure 204 *Table showing cost of equipment for Restoration Robot Platform. Source: see table.*

Of course, employees of such a company would be required to obtain new skills in digital craft, such as transforming point clouds to a mesh, interpolation of geometry and transforming a geometry to instructions for the robot. This would be an investment in knowledge that a company would be required to make. A more sustainable solution would be to incorporate these skills as part of the 3-year part-time course to become a "Meester stucadoor".

Since the proposed restoration methodology requires not only the above mentioned elements but requires other tools and software for the 3D scanning and digital repair phase, the table below is created provide a more complete overview of tools, software and costs associated with Digital Fabrication methodology for in-situ restoration of stucco ornaments.

Element	Price (euro)	Percentage of total cost	Sources
UR5 robot	32000	60,81	blog.robotiq.com
Kite-11 crane	1250	2,37	proaim.com
Extruder	100	0,19	Estimate
Electric stair climbing trolley	800	1,52	alibaba.com
Full chassis	500	0,95	Estimate
Compressor	110	0,21	hbm-machines.com
Material delivery tube	20	0,04	Estimate
Material reservoir	50	0,1	Estimate
RoboDK software licence	3495	6,64	robodk.com
3D scanner	6299	11,97	3dshopnl.com
VR mesh software	7000	13,30	vrmesh.com
Rhinoceros CAD software	995	1,89	rhino3d.com
Total	**52619**	**100**	

Figure 205 *Table showing cost of all equipment & software for proposed restoration methodology. Source: see table.*

Adding a 3D scanner and required CAD, meshing and robot programming software, increases the total cost 1,5 times. The robot remains by far the most expensive component, taking up more than half of the expense, while the next most expensive elements are the software tools required. Still, considering the time and additional manual labour that can be saved, such an investment can be earned back within a few years. Again, cost of operation with additional scanning work, CAD reconstruction, robot programming and supervision would also need to be taken into account for a fair comparison of cost. The most benefit in the Digital Fabrication methodology is however in the fact that this method can be used to fill in gaps left by a rising shortage in skilled labour and is in the long run more sustainable as it eliminates the need for labour intensive and physically demanding work.

09.

CONCLUSIONS & OUTLOOK

9.1. Overview of proposed restoration methodology

The research conducted in this thesis on investigating and developing a Digital Fabrication method for in-situ stucco ornament restoration has been summarized in a comprehensive overview in Appendix A “Final proposed Digital Fabrication restoration methodology“.

9.2. Final conclusions & discussion of results

To conclude the work, the sup questions are answered after which the main research question can be answered. The results are discussed and further research paths are suggested to bring the development of the proposed restoration method further.

9.2.1. Sub questions

To what extent can a gypsum-based mixture be developed for Additive Manufacturing?

Based on the results of the experiments conducted, it can be concluded that a gypsum-based mixture can be developed which is to a large extent suitable for the purpose of in-situ Additive Manufacturing. Key criteria to consider when developing printable mixtures are identified as Pumpability, Extrudability, Buildability, Open Time, Shrinkage & Cracking and Adhesion. The developed printing mixture (G5, with Knauf Rotband gypsum, marble powder and water in a 1,5:0,5:1 ratio) shows good pumpability at around 4 bar pressure. It can be used to achieve a resolution of 1 mm (extrusion width), which is expected to attain a desired “close to smooth” surface texture. When printed vertically down It can be stacked up to 21 layers without noticeable deformations, which seems insufficient for creating larger ornaments. The maximum number of “stackable” layers when printing occurs upside down, could not be tested, as this requires a 3D printer or multi-axis robot to avoid inaccuracies in the geometry stacking due to manual work. Due to closing of the LAMA, the 3D printer could not be used. Therefore, the number of layers found to be stackable in normal orientation by manual extrusion are expected to be lower than the actual number achievable by a highly accurate machine. An Open Time of 78 minutes has been determined, which seems to be sufficient for smaller objects. Due to the unavailability of a 3D printer or robot, experiments could not be conducted on the volume which can be printed with high accuracy within this timeframe, therefore some additional experiments with the 3D printer are recommended for future studies to check this aspect. Furthermore, a solution is proposed to create a continuous coordinated mixing process, which would eliminate the time constraint imposed. No observable shrinkage or cracking was found in the final printed samples, which lead to the conclusion that the selected ratio between gypsum, water and aggregates in the mixture is suitable for this purpose

To what extent can the printing mixture be extruded on inclined substrates?

The manual experiments show the printing mixture has sufficient adhesion strength in fresh state when extruding on angles of 0, 30, 45, 60, 90 and 180 degrees (upside down) for at least 5 layers. Samples printed in different inclinations, all show a very high adhesion strength (73 N – 274 N) in dried state and are therefore suitable for the intended application. The adhesion strength of extruded specimens on a sanded or wet surface is similar to the adhesion strength of manually applied stucco to an untreated substrate. Contact area between printed sample and substrate, as well as viscosity of the printing mixture are identified as important factors influencing adhesion of the printed mixture in fresh state. Furthermore, several strategies are identified for increasing the adhesion strength, including manipulation of the printing mixture, substrate and printing process. However, the effect of these strategies on the adhesion strength is not fully clear. This is in part because the effect of inaccuracies caused in the printed geometry due to manual extrusion is expected to have a significant impact on the printed samples’ adhesion strength. Furthermore, due to the limited time available,

adhesion strength could only be assessed for a small sample size. Further experiments are recommended to be conducted with a multi-axis robot, which can print with a fixed printing speed, extrusion speed, infill density and printing path, to eliminate differences in contact area between the sample and substrate. In this way, effects of various enhancements to the printing mixture, substrate or printer settings on the adhesion strength can be better studied.

How can a Restoration Robot Platform be developed, considering constraints related to the context of operation and 3d printing process of stucco ornament restoration?

A set of guidelines have been formulated for the design of a prototype of a Restoration Robot Platform. The guidelines are based on physical constraints of the type of context in which such a platform would be deployed and on practical and technical requirements of digital fabrication technologies. With the use of these guidelines, a concept design is created for a prototype of such a Restoration Robot Platform with off-the-shelve components. A weight restriction of 155kg and a bounding box of 0.7m *0.85m*1.92m are defined as the main physical constraints for the platform.

The design consists of a lightweight aluminium chassis of 0,7m*0,85m*1500mm, onto which a gyroscopically stabilized camera crane is mounted. The lightweight collaborative UR5 robot, equipped with a protective sleeve, can be mounted on this crane to reach ceilings up to 5,5 meters tall. The crane with mounted UR5 and all supporting equipment such as the robot controller, material delivery system and compressor can be stowed inside the aluminium chassis during transportation. The chassis is mounted onto an electric stairclimbing trolley, which can be used to move the platform up staircases by one person and can be transported in a standard transportation van.

9.2.2. Main research question

To what extent can a Digital Fabrication methodology and 3D printable gypsum-based mixtures be developed for restoration of stucco ornaments by means of in-situ additive manufacturing?

By answering the sub questions, the main research question can be answered. The research shows that the designed gypsum-based mixture is suitable for in-situ Additive Manufacturing application. The developed Digital Fabrication methodology for in-situ restoration is for a large part based on a combination of existing proven technologies used in practise and is therefore likely to meet the demands for this application. Unfortunately, due to the lack of access to a multi-axis robot, the final setup of the Additive Manufacturing process could not be tested. The manually performed experiments, however, show Additive Manufacturing can be done with the designed gypsum-based mixture on any inclination, and samples extruded with the final mixture recipe show sufficiently good values for the various pre-defined 3D printing criteria. Therefore, stucco ornament restoration by means of in-situ Additive Manufacturing with gypsum-based mixtures appears to be feasible and shows enough potential to be able to be developed further for application in practise in the future.

9.3. Future perspectives

9.3.1.Robotics & craftmanship

In a future scenario, where Restoration Robots would be adopted for restoration of stucco ornaments, restoration plasterers will not be fully replaced by these robots. The robots will simply be an additional tool to the arsenal of the restoration plasterers, architects and engineers working in the conservation and restoration field. The work of the restoration plasterer and restoration architects could be focussed more on preliminary testing with different materials and using their knowledge to supervise robots who take over the physically demanding work. In cases where the restoration work is not very labour intensive and does not involve complex geometries, the restoration plasterers could still perform manual restoration tasks. By doing preliminary testing on the material involved, the ingredients for the printing material could be chosen, and the various printing parameters will be determined. Then, instead of climbing up on that tall ladder to work for hours on end above their head, the ornament fabrication would be done by a Restoration Robot.

Figure 206 *3D printed ceramic objects, by EL studio. Adopted from: https://www.elstudio.nl/?p=1784*

The in-situ AM technique may not be limited to only restoration of damaged ornaments. Using AM for creating gypsum-based ornaments can lead to creating new kind of ornaments altogether. AM can create new type of geometries which traditional techniques would not be able to create. High level of detail and complex interconnected curved surfaces are not a problem for AM. The thesis points out that given the right aggregate size, fine resolutions are achievable, so a high level of detail can be reached by choosing suitable aggregates. 3D printing with ceramics (clay) for example, has kickstarted a new type of pottery where the beauty of the stacked layers of a ceramic pot are highlighted and much appreciated features. Currently, some researchers, pottery artists and 3D printing enthusiasts are exploring ceramic 3D printing to create intricate geometries, only possible with this novel technique (see Figure 206). Even geometries which combine manual work, with AM, could be a new way of creating new type of ornaments.

By setting AM free from its “traditional” way of building up objects by stacking layers on top of each other on a flat surfaces, opens quit literally a new dimension for the potential and applications of AM. Printing on uneven surface in any orientation, combined with a solid autonomous orienting-and-navigation system could lead to the development of Restoration Robots that could work in hazardous or difficult to reach locations or could simply be adopted where skilled labour is missing. Filling in the foreseen shortages in skilled labour and labour intensive jobs, could lead to more affordable and sustainable methods of restoration. According to Mathias Kohler, Professor at ETH Zurich, “Robots can do more labour intensive, heavy work, so this would not be needed to be done by humans. Humans can do more fulfilling jobs.” With the help of the restoration plasterers

of today, their knowledge and craft itself could be conserved, by embedding it into such digital tools. In the future, restoration plasterer’s job would not be to work above their head for hours on end, but to analyse, judge and give the right instructions to their robot co-worker, who could then do the physically demanding and heavy work.

9.3.2. The construction site of the future

Assuming that restoration and construction fields do start to adopt robots on site, it is interesting to think about what a restoration or construction site would look like in the future. Throughout history, an observation can be made about the decreasing number of workers on the construction site. The Great Pyramid of Giza was built by thousands of workers, doing harsh, physically demanding work, thousands of years ago (see Figure 207). Today, modern constructions sites have on average 25 construction workers (Change, 2017), who can use motorized heavy duty machines to do much of the heavy lifting work (see Figure 208). Yet the construction (and restoration) profession remains physically demanding and is therefore unquestionably unsuitable to be in until the age of retirement, as pension ages are rising as well.

Figure 207 *Artist impression of the construction of The Great Pyramid of Giza. Adopted From: https://www.ancient-origins.net/history/demystifying-egyptian-pyramids-hard-facts-009730*

Figure 208 *Construction site in 2020. Adopted From: http://www.themorning.lk/construction-sector-says-distancing-impractical-on-site/*

Today’s construction machines are used to replace muscle and manpower to a certain extent but cannot perform complex or precise movements or autonomously work together with other machines or workers. Not yet. Introducing robots which, can perform highly complex tasks with great power, high accuracy and speed, do not need lunch or toilet brakes and could potentially work nonstop in cooperation with each other, would revolutionize the construction site like never before. BIM (Building Information Modelling), a digital tool used to coordinate design and construction in a 3D environment, is capable of creating highly detailed 3D drawings of a building and building component. This high level of detail and the 3-dimentionsal nature of the information is however lost on the construction site, as 2D drawings are made to use as reference on site for workers from this 3D model. Robots could make full use of the 3D nature of BIM tools to precisely plan and build our buildings in a way humans cannot. The physically demanding construction work could be taken over by robots, as human workers, with knowledge of construction, may fulfil less strenuous supervisory roles on site. This may sound like science fiction, however there are already research projects which explore the idea of deploying partially or fully autonomous robots to build or repair the built environment (see Figure 209), which will be explored in the next subchapter.

Figure 209 Rendering of digitally fabricated earth & timber housing by IAAC. Adopted from: https://iaac.net/educational-programmes/applied-research-programmes/otf-3d-printing-architecture/

9.3.3. Impact on Architecture and the built environment

Not being able to conserve, preserve and restore our buildings would lead to a deteriorating state of the built environment. This could mean we would lose some of our most valuable cultural assets in the built environment due to our inability to meet the demand for preservation of these assets with traditional means. The thesis presents a feasible and affordable alternative to restoration of stucco ornaments, which has the potential to fill in gaps in the absence of skilled labour in this specialized field.

The introduction of robots in architecture, can change the architectural and construction landscape and challenge current design and construction methods. For example, bricks are made in their distinct size and shape because this makes it easy for a mason to lift and place them with one hand. Architects knows this, so they design their buildings with “brick sized bricks” and therefore the aesthetics and construction process of a brick building is directly related to this traditional construction method of a brick building. Robots offer different possibilities than a construction worker. A brick building built by a construction robots, may have much larger bricks, as the robot may be much stronger than a construction worker. Or perhaps the building will no longer consist of clay in the form of discrete brick elements, but instead of continuously 3D printed clay walls (see figure 3). This can change the aesthetics of future architecture, while the possibility of using sustainable materials for digital fabrication with construction robots could also contribute to the sustainable development of the built environment and human health.

9.3.4. Robotic architecture

This subchapter will give an impression of some innovative and novel construction and restoration methods which envision the application of robotics in architecture and restoration.

Aerial Construction - ETH Zurich

The Aerial Construction research project investigates how multiple drones can work together to build a bridge with ropes in a coordinated way (D’Andrea, 2012) (see Figure 210). By using multiple, smaller and manoeuvrable robots, it could be possible to construct or restore buildings or building components in areas which are difficult to access for humans.

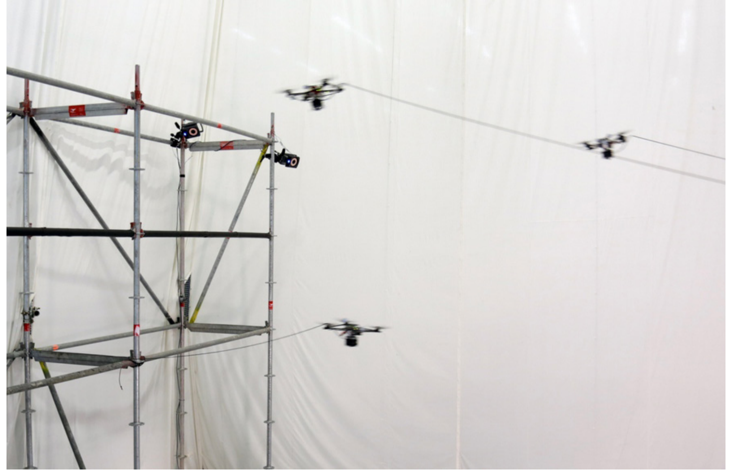


Figure 210 Rope bridge assembly with cooperating drones by ETH Zurich. Photo source: https://idsc.ethz.ch/research-dandrea/research-projects/aerial-construction.html

Spatial Timber Assembly - ETH Zurich

The Spatial Timber Assembly project, again from ETH Zurich, is a good example of combining benefits of digital fabrication and robotics such as high accuracy and the ability to do heavy lifting; with the flexibility of human workers. Robotic arms cut and drill timber beams and hold them in place so a human worker can bolt them together (Block, 2018). In this way, the construction is ensured of high precision, speed and no additional supports are needed for structures.

Figure 211 Spatial Timber Assemblies project by ETH Zurich. Photo source: https://www.dezeen.com/2018/04/16/robotic-construction-architecture-technology-eth-zurich-switzerland-spatial-timber-assemblies/

BREAK THE GRID - Danis AM hub, GXN

“Break the grid” is a research project conducted by various Danish research institutes. In Break the grid, researchers envision a future where 3D-printers are broken free from their desktop confinement to meet challenges of an explosively growing population and climate change (Danish AM Hub, GXN, 2019). By marrying advanced 3D printing technologies with autonomous robotics, they environ a world where autonomous 3D-printing robots roam around to detect and then repair damage to our environment. The researchers propose: land-based crawling robots that detect damage to infrastructure and repair this damage by 3D printing self-healing-concrete to damaged areas; aquatic robots that use wet-setting bio-based binders from oysters to build artificial reefs to protect coastal areas from flooding; and drones that detect and 3D print with functionally graded materials to seal thermal leaks in high rise buildings (Danish AM Hub, GXN, 2019).

Figure 212 3D printing robots, autonomously crawling around the world to repair damages infrastructure. Source: Break the Grid

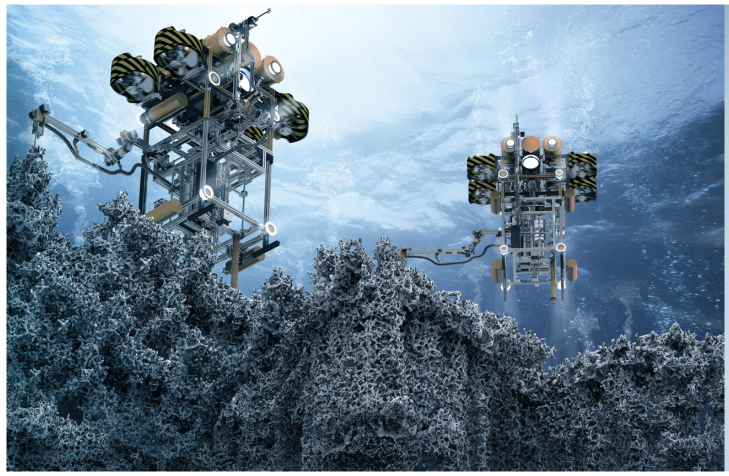


Figure 213 Autonomous aquatic 3D printing robots, repairing damaged corals. Source: Break the Grid

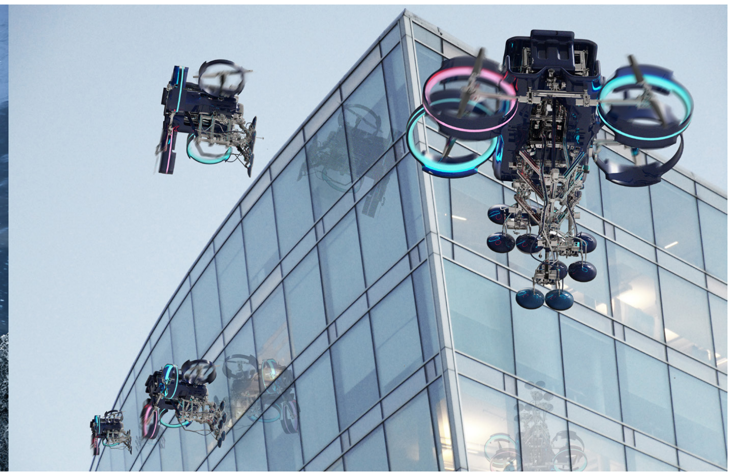


Figure 214 Autonomous 3D printing drones, repairing thermal bridges in high rise buildings. Source: Break the Grid

Research projects such as these show the potential impact advancements in Digital Fabrication and Robotics can have for the built environment. Some of these ideas seem utopian, but the boundaries between what is fictional and what is reality will slowly start dissolving, as we as a society start learning about them and adopting them for the betterment of our world.

9.4. Reflection

There is a growing shortage of capable hands in construction and restoration, while an explosively growing world population and growing pressure on the environment, urges us to create sustainable, affordable architecture and to preserve our existing building stock. To meet these global challenges, an innovative approach in architecture and construction field is required. Architecture and the construction industry have proven to be slow to adopt innovations and have been using traditional methods for a long time. According to a study by McKinsey (2015) construction is one of the least digitized industries in the world (see figure X) (Rajat Agarwal, Shankar Chandrasekaran, 2016). Although architectural drawings are made on a computer nowadays instead of by hand since the introduction of CAD and BIM, buildings are still built largely on site by human hands, which leads to many mistakes on site which delays construction time, wastes materials and money, which leads to inefficiency in a time where efficiency is crucial. Since the 70’s construction has seen a decline in gross value-added per hour worked, which points to a decrease in productivity in this field, while all other fields seem to have increased their productivity greatly after the Second World War (see figure X) (Medium, 2017). The lack of digitization and the inability to increase productivity seem to be related in my opinion. By developing, adopting and integrating digital design and manufacturing technologies in architecture and construction, the design-to-construction and maintenance process of buildings could be made much faster, cheaper, less wasteful and more sustainable.

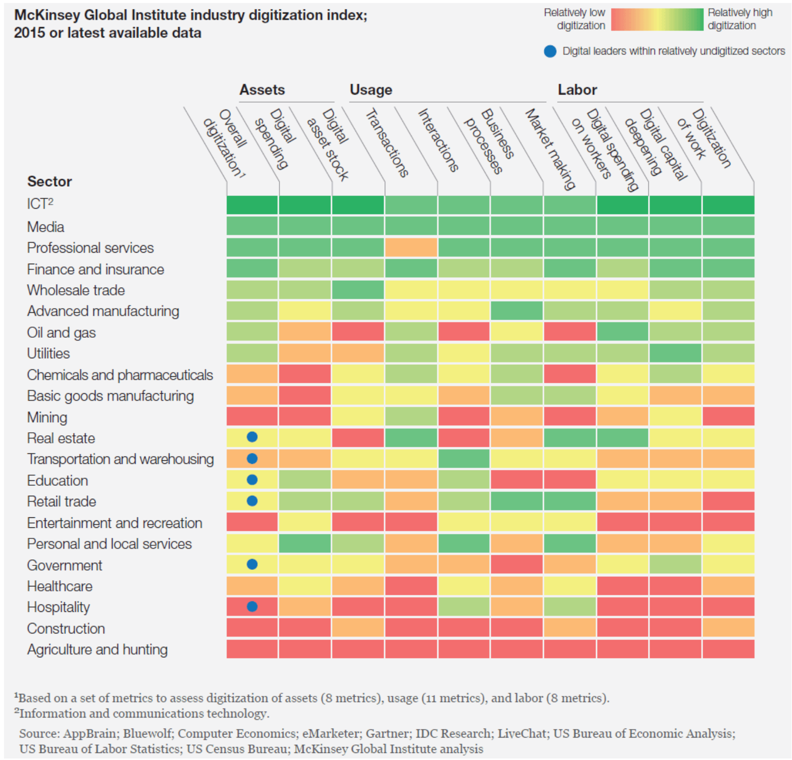
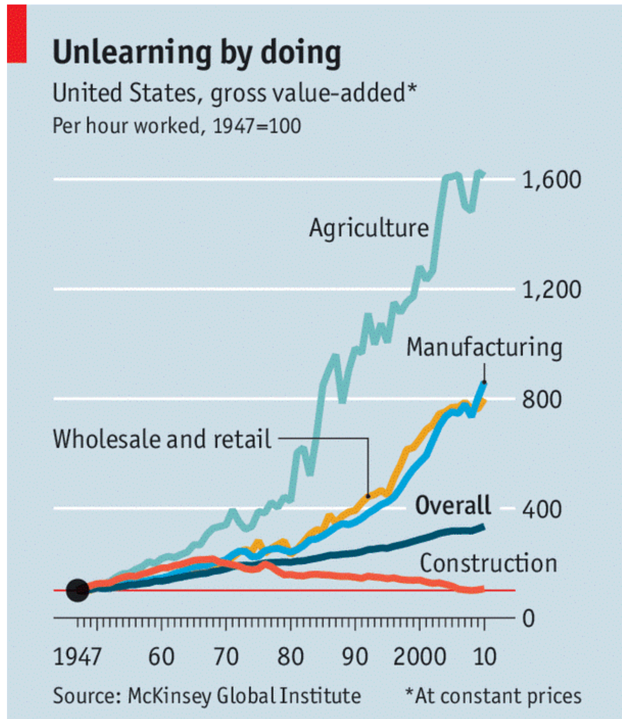


Figure 215 Industry digitization index 2015. Adopted from: https://digital.hbs.edu/platform-rctom/submission/trillions-in-wasted-productivity-digitalization-in-the-construction-industry/



Economist.com

Figure 216 Productivity accross various industries. Adopted from: https://medium.com/@leanstation_/reality-in-improving-efficiency-in-the-construction-industry-a1f318fbbe1

But why has construction been slow to adopt innovations? The fact that so many different parties are involved in a single large construction project (architects, contractors, MEP engineers, façade engineers, building physics consultants, fire safety consultants, structural engineers, foundation contractors, etc.) may have to do with this. For example, if the architect wants to do something new and innovative, this may lead to the contractor to take more risk in building such architecture with his traditional methods, which is why he may resist such innovative designs. New and innovative architecture may require new construction methods and new construction machines. Due to fragmentation of parties involved in construction, the question of "who has to develop such methods and machines?" arises. Is it the architects who make the design? But the architects are not responsible for building the buildings they design. Is it the contractors? But why would they invest in such new techniques and machines if they can just keep building the way they know and still earn enough money. Additionally, architects must know the new construction methods and tools in order to design architecture that can be built with such machines and methods. Or is it the other way around and should new methods and machines be developed to suite new types of architecture?

Such questions lead me to thinking about a new type of profession, "the Maker". The Maker is a designer and an engineer. The Maker has knowledge about architectural design, engineering, construction, has skills in using digital tools and how these disciplines are connected to each other. The Maker doesn't have to be one person but can also be a company which has people who together have this multidisciplinary knowledge, and who are capable of designing, engineering and producing buildings themselves. Making designers also responsible for fabricating the buildings they design, could lead to them making better designs, developing innovative construction methods & machines and add much more efficiency to the overall design-to-fabrication process of a construction project. This may sound like an utopian idea; however, we can already see companies that have adopted this idea. Octatube, who specialize in special glass structure, design, engineer, build and install all their projects themselves with their in-house team. The New Makers, a TU Delft start-up, design, engineer and build their CNC milled timber construction elements themselves on a customized CNC machine they developed to create their ideal architecture. To innovate in architecture and construction requires the development of your own customized tools and equipment for your specific task. This is the role of the Maker of the future.

Glossary

1. Digital Fabrication method: Fabrication method which may include digital scanning, design and fabrication tools.
2. Additive Manufacturing (AM): Layer-by-layer digital fabrication method.
3. 3D printing = Additive Manufacturing (AM).
4. Setting time = Open time: Timeframe within which a certain mixture material is in a workable (specifically in context of this thesis, a printable) state.
5. Printing material: A material (mixture) which is used to 3D print by means of extrusion based additive manufacturing.
6. Additive manufacturing/AM: In the context of this thesis this refers to extrusion based additive manufacturing.
7. Stucco: Mixture of binder (like gypsum) and aggregates (like stone powder).
8. Lime plaster: plaster containing lime, sand and water.
9. Gypsum: Gypsum product from manufacturer, containing gypsum powder and additives.
10. Ornament: decorative element on ceiling, wall or as standalone object.
11. Sample: one part of a larger whole/batch of a mixture.
12. Specimen: extruded or otherwise created discrete object from a particular mixture.
13. Mixture: mixture of gypsum with aggregates and water in certain ratios unique to that particular mixture.
14. Robotic platform: Supporing machinenary which allows for a robot to be used for specific tasks in specific environments.

10.

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Section tab image references

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2. Photo, "Stukadoor bezig met het dichten van naden tussen de gipsplaten" (Spaarnestad Fotoarchief 1980). Adopted from Geerken, H., & Freling, W. (2010). Reconstructie en Herstel. In Stuc: Kunst en Techniek.
3. Flowchart, made by author.
4. Photo, "Function 3D printed Ceramics", 2012-2020, Olivier van Herpt. Adopted from: http://oliviervanherpt.com/functional-3d-printed-ceramics/
5. Photo, "Robot Extruder", 2020, Author.
6. Photo, "Gypsum mixture", 2020, Author.
7. Photo, "Extruding on inclined surfaces", 2020, Author.
8. Image, made by author.

11.

APPENDIX

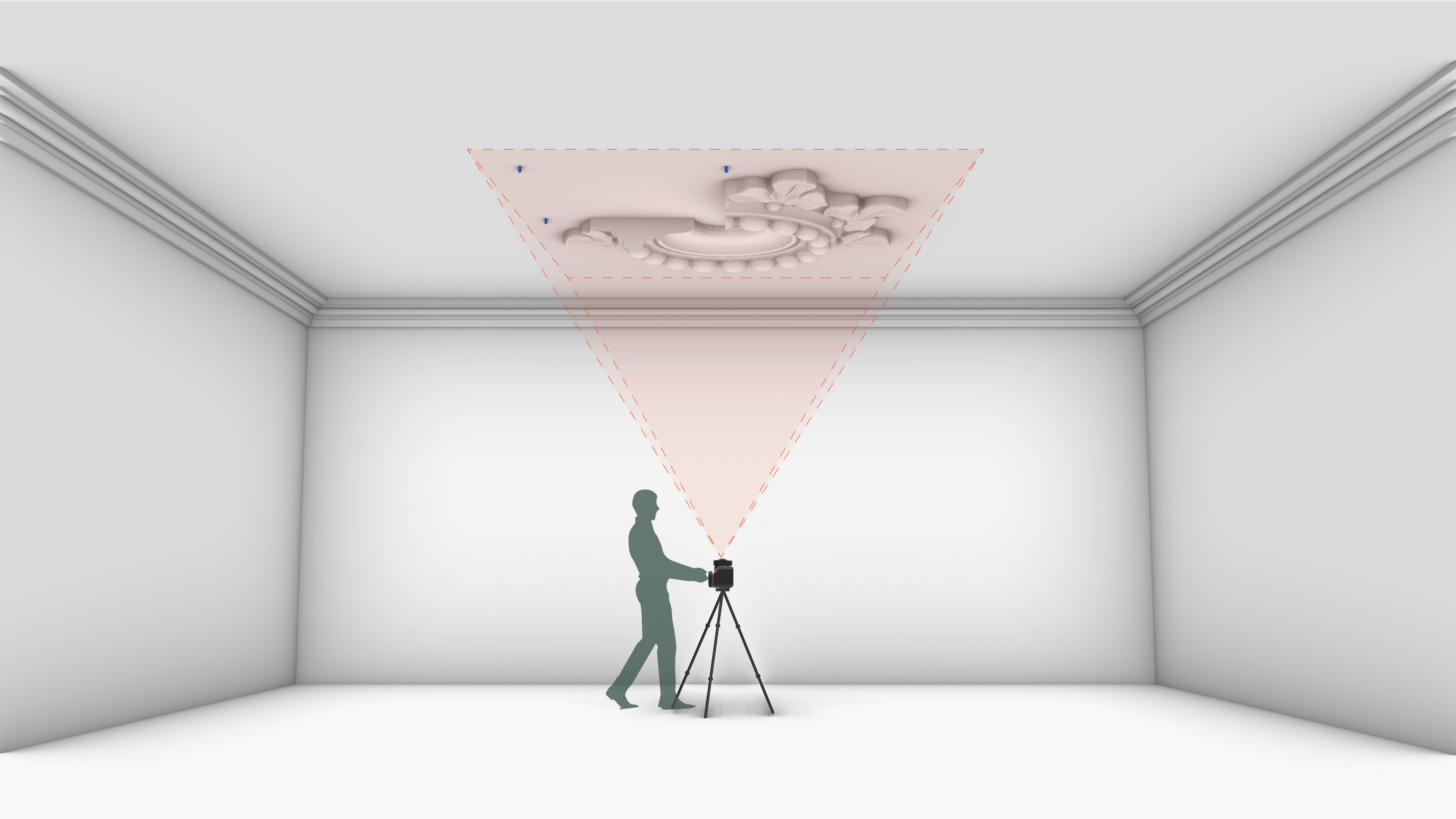
APPENDIX A

Final proposed Digital Fabrication restoration methodology

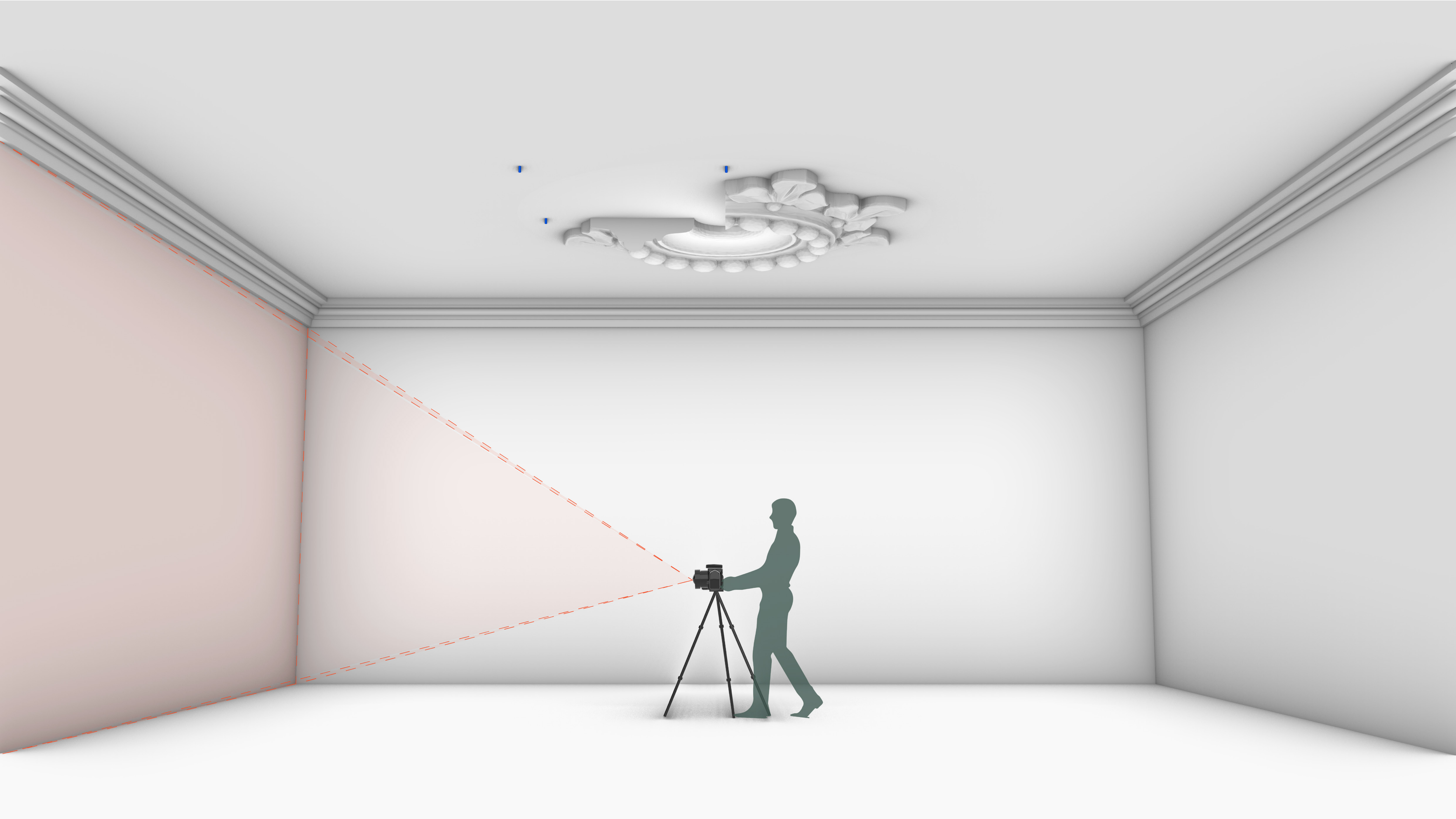
Step 1. Damaged ornament

Step 2. Inspect damaged area

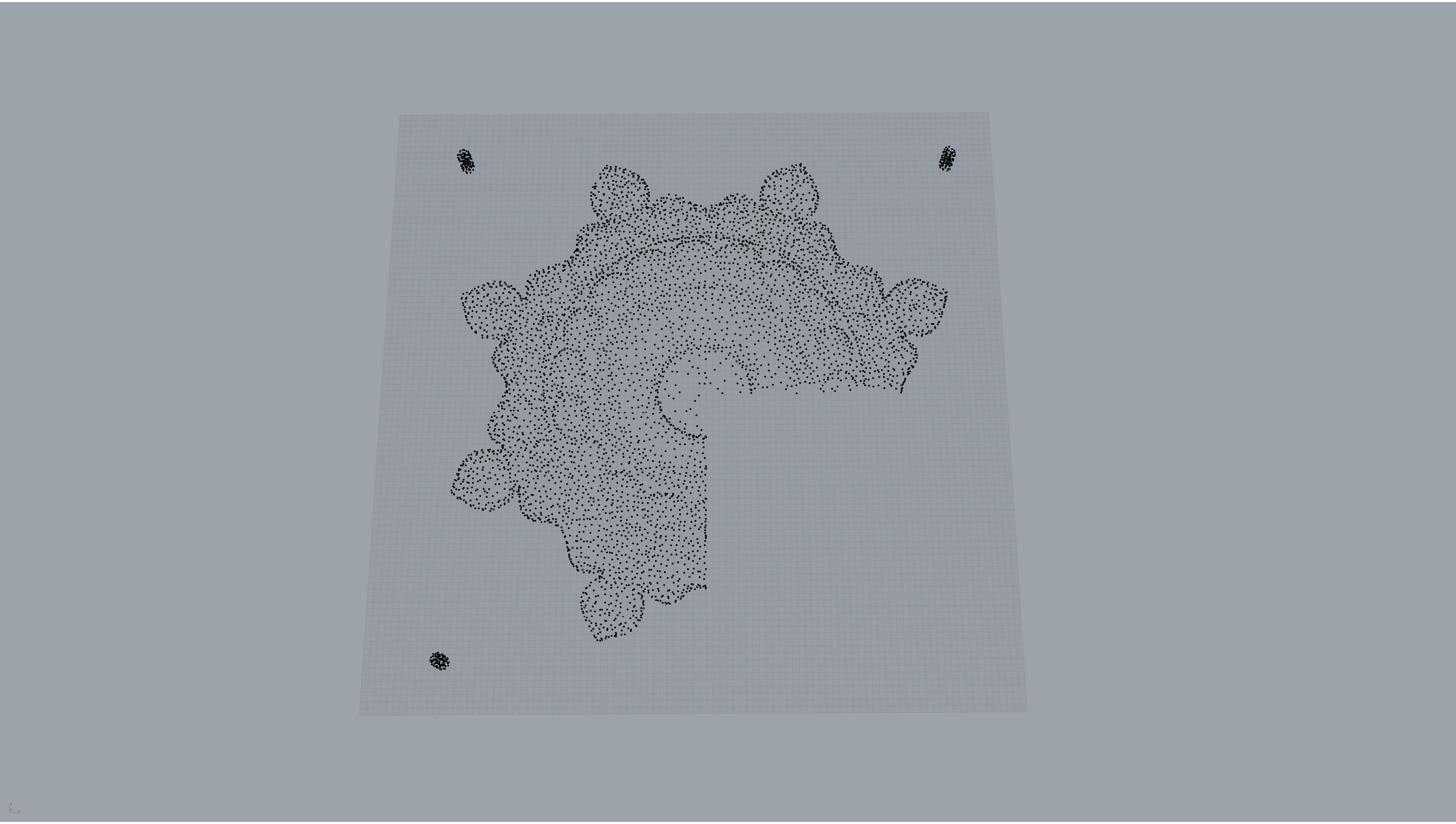
Step 3. Place reference markers



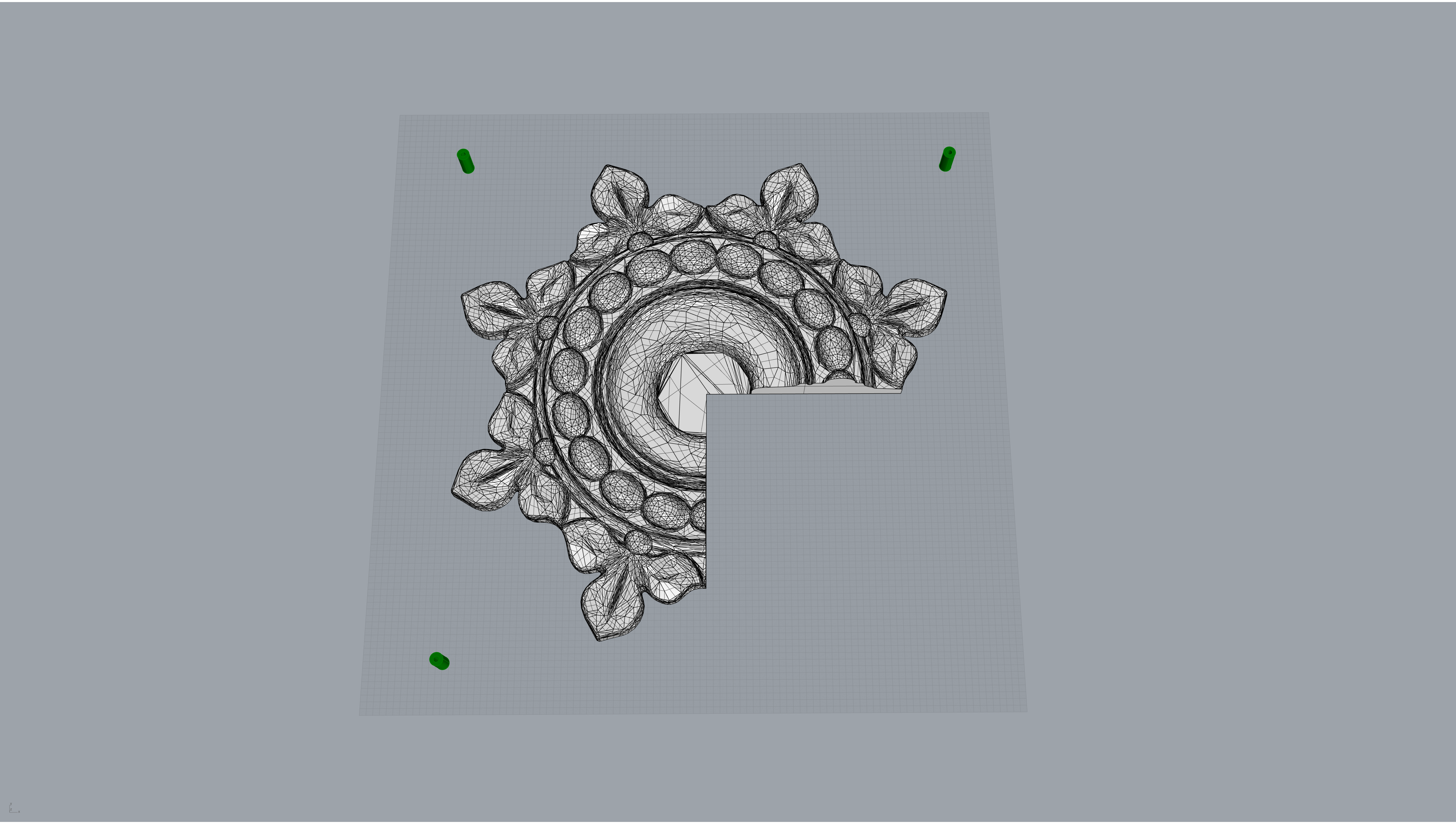
Step 4. Make high resolution 3D scan of damaged ornament



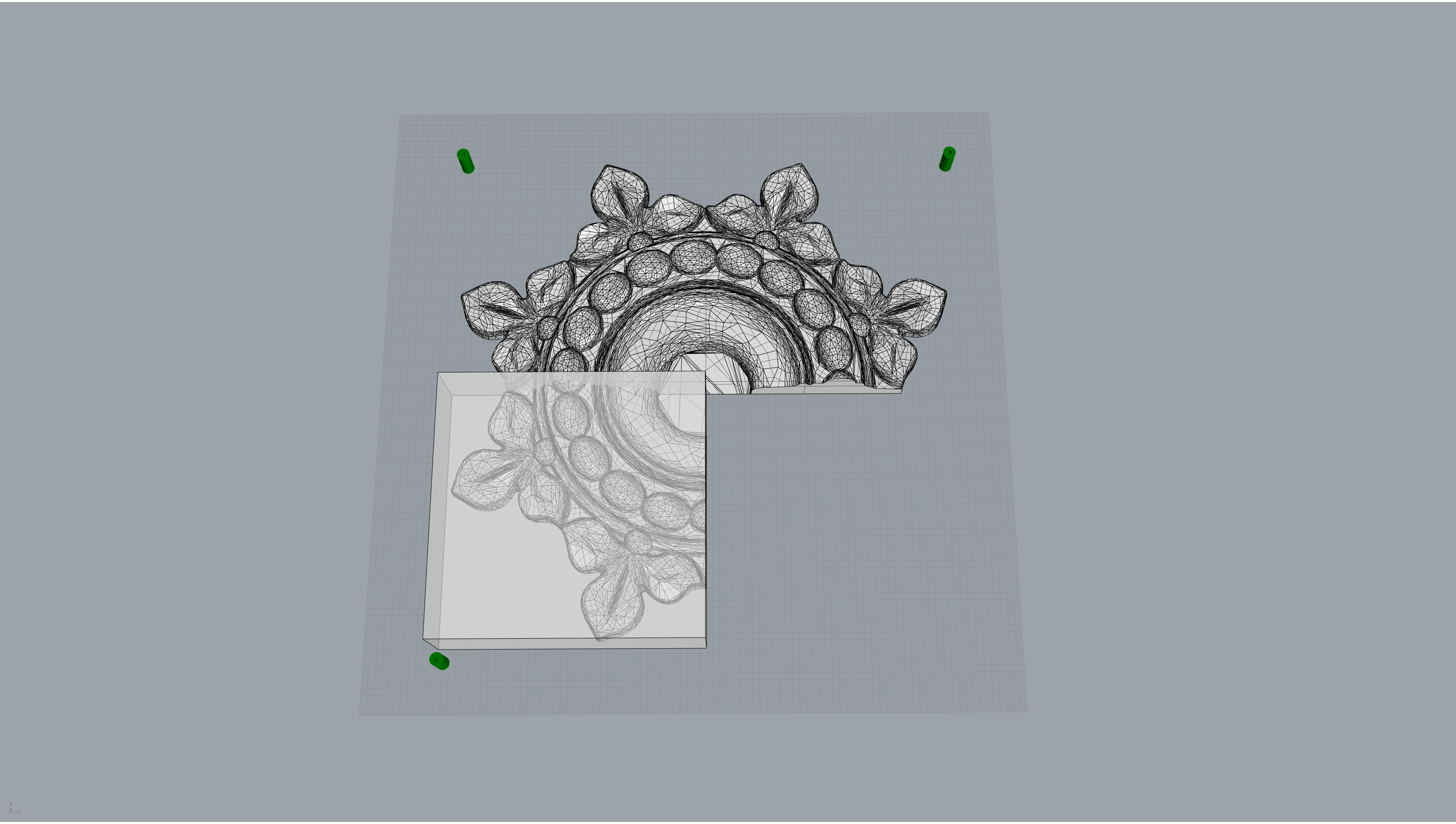
Step 5. Make low resolution 3D scan of room



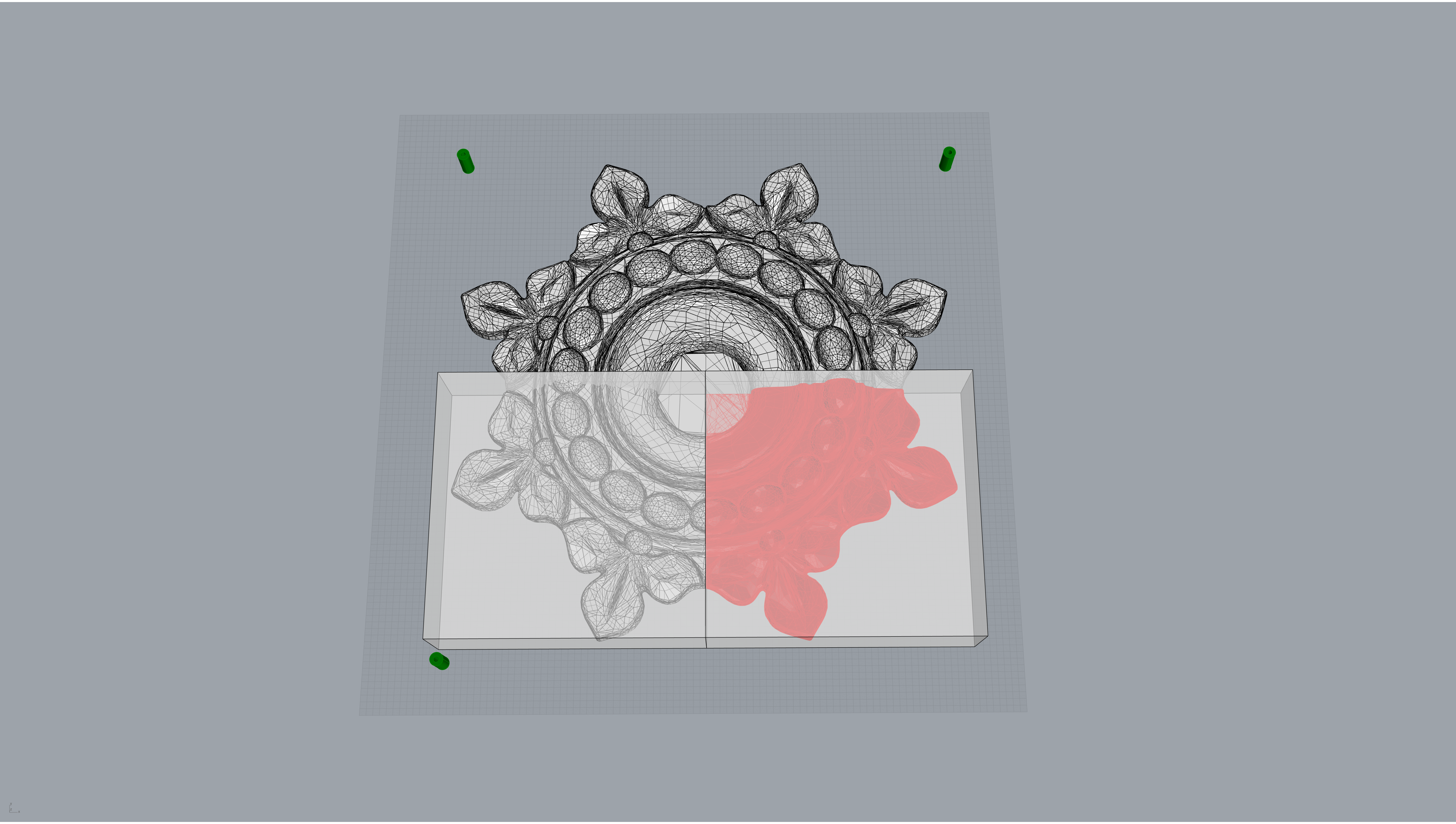
Step 6. Point cloud of damaged ornament + reference markers obtained from 3D scan



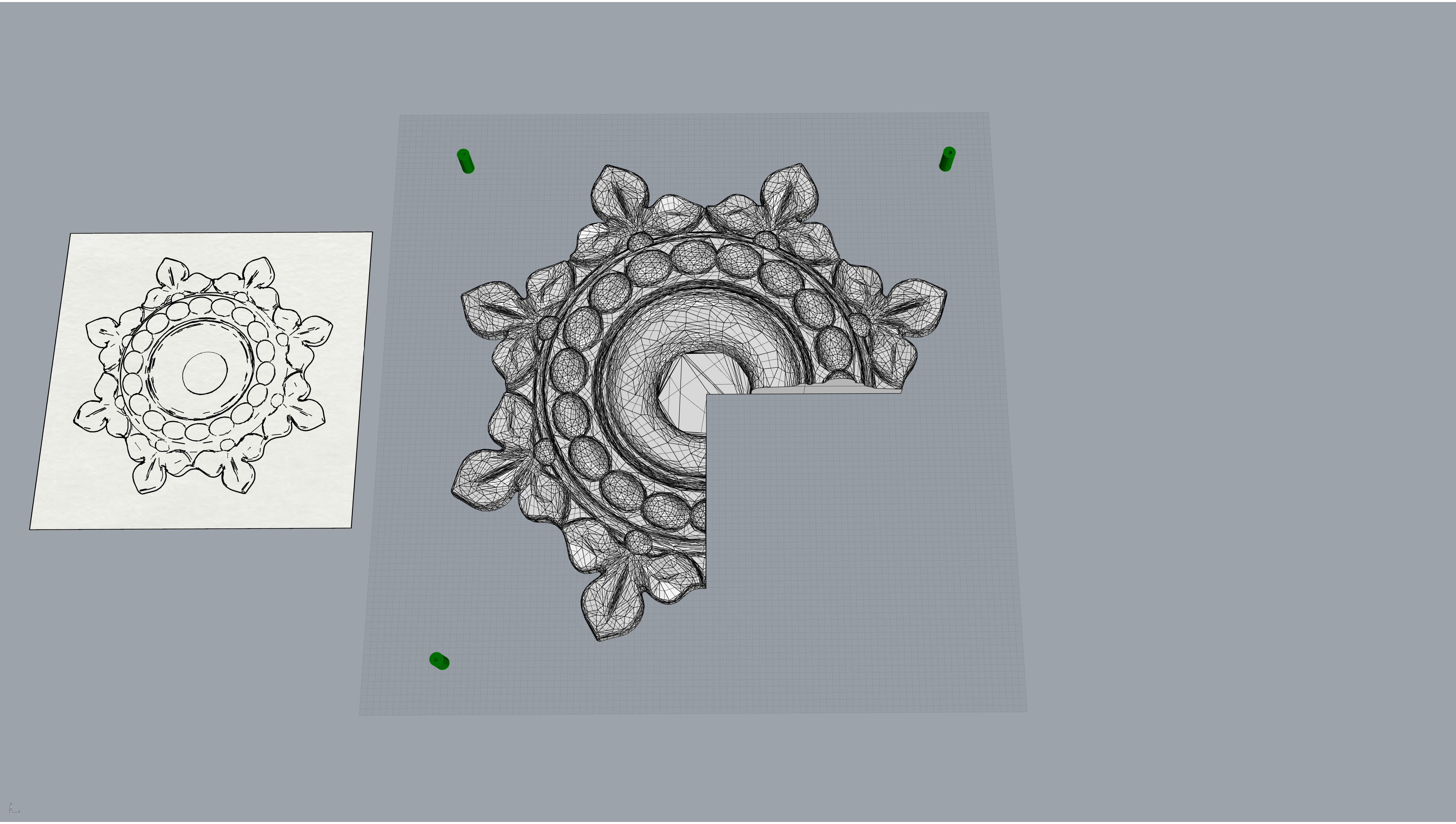
Step 7. Convert point cloud to mesh



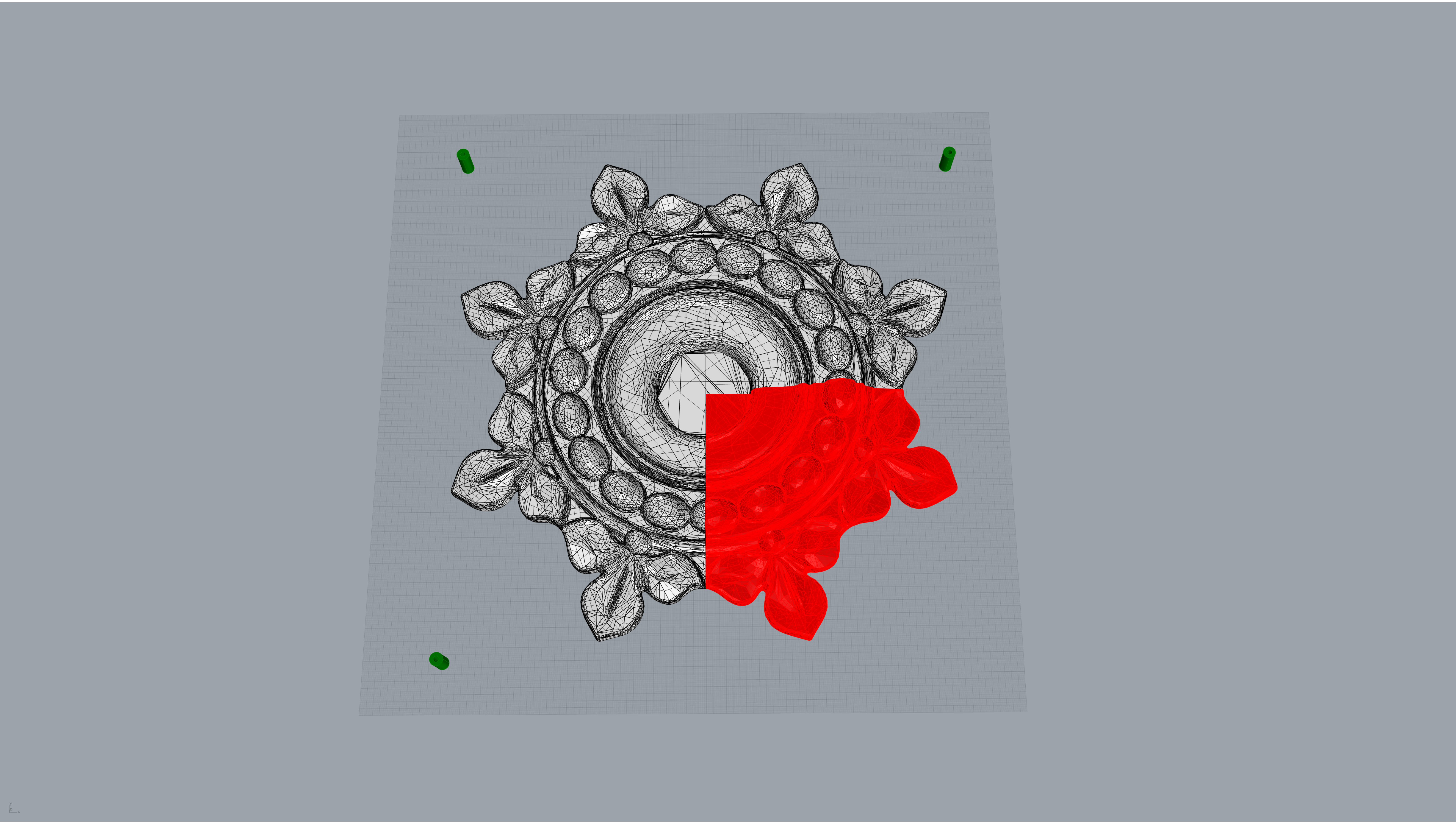
Step 8. Identify repeating elements for interpolation



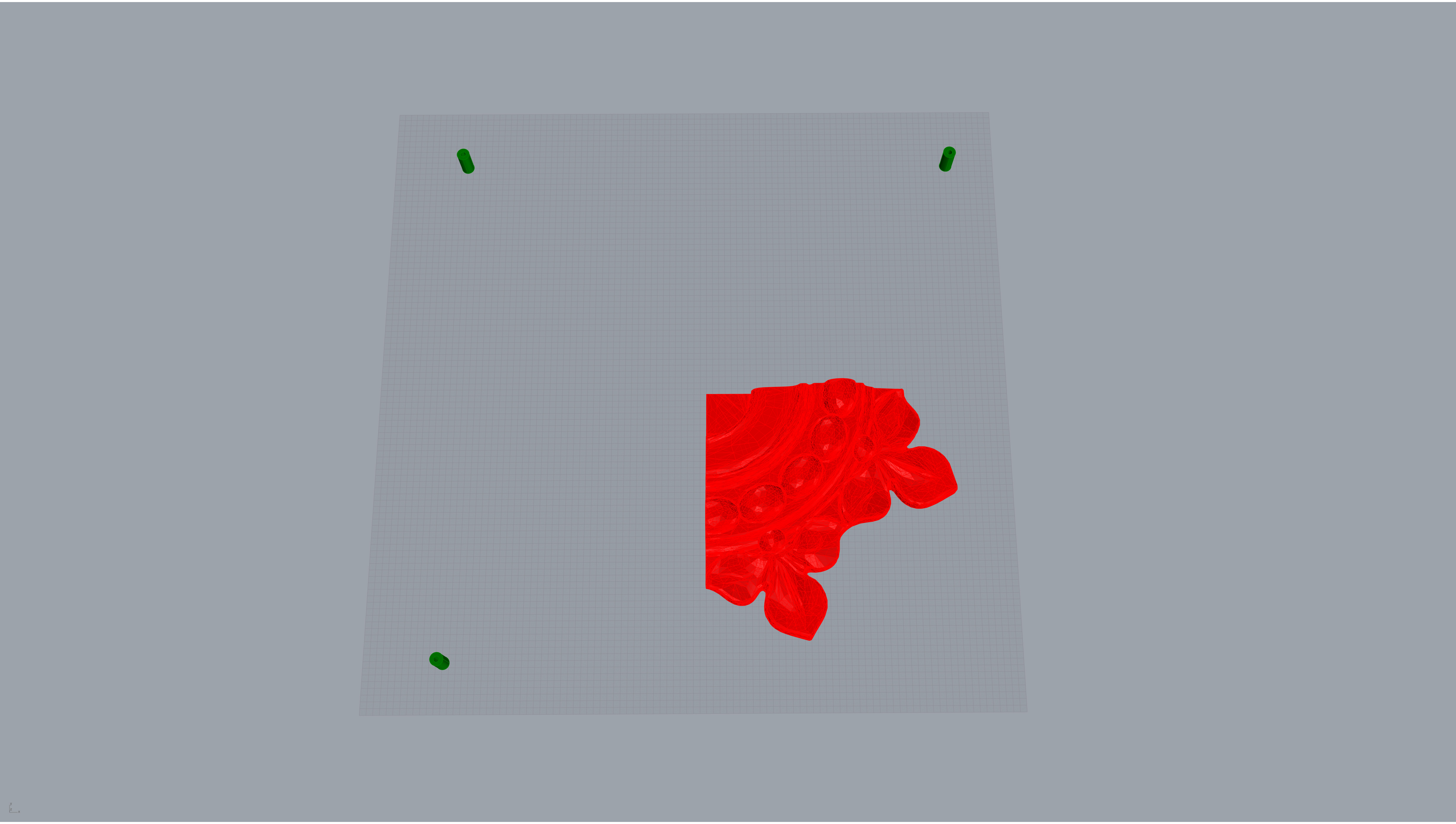
Step 9. Copy/Mirror for geometry interpolation



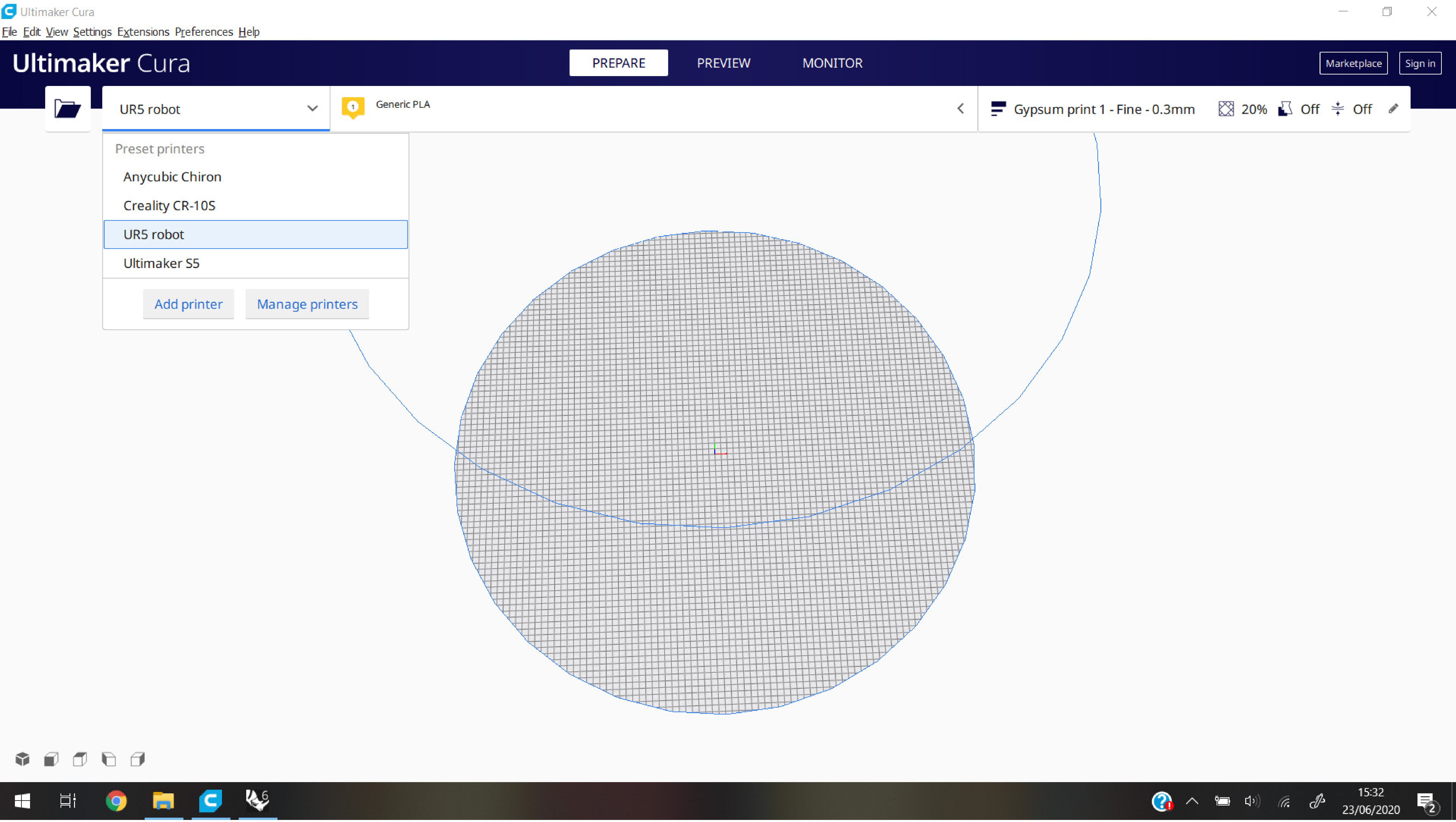
Step 10. Alternative: Model from scratch with historic documentation as reference



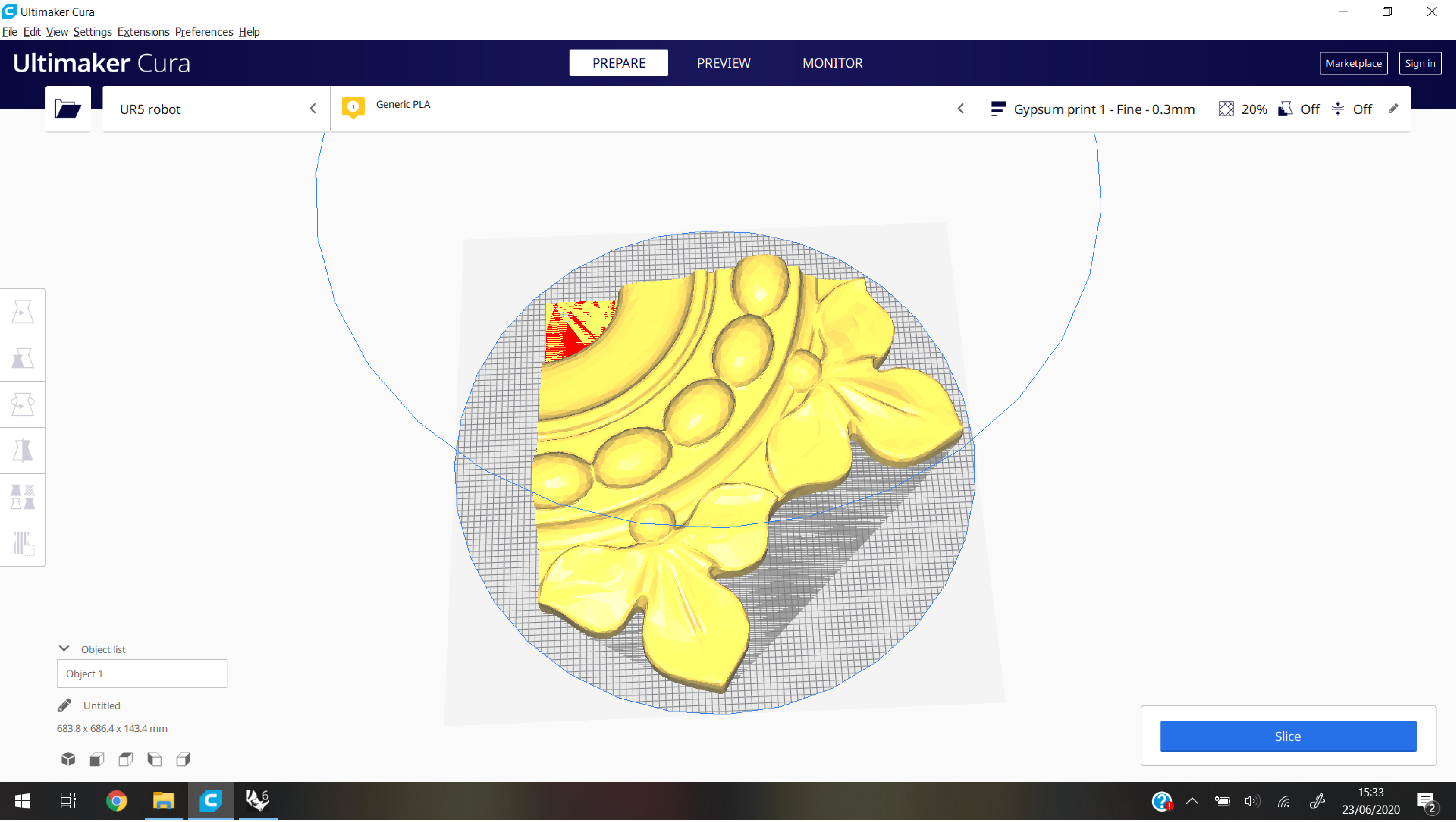
Step 11. Acquired missing geometry



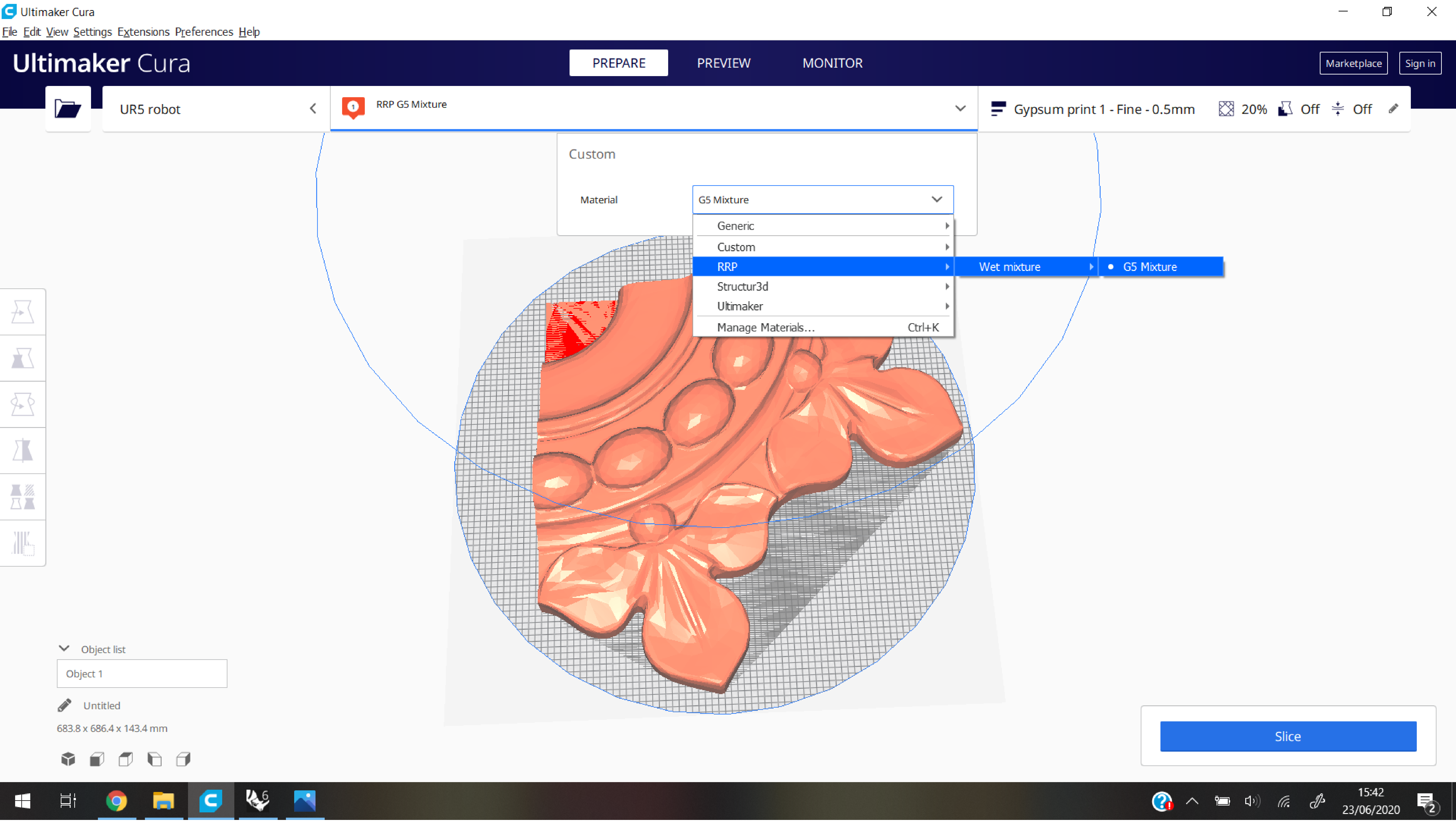
Step 12. Export missing geometry in “STL-format” from Rhino to Cura



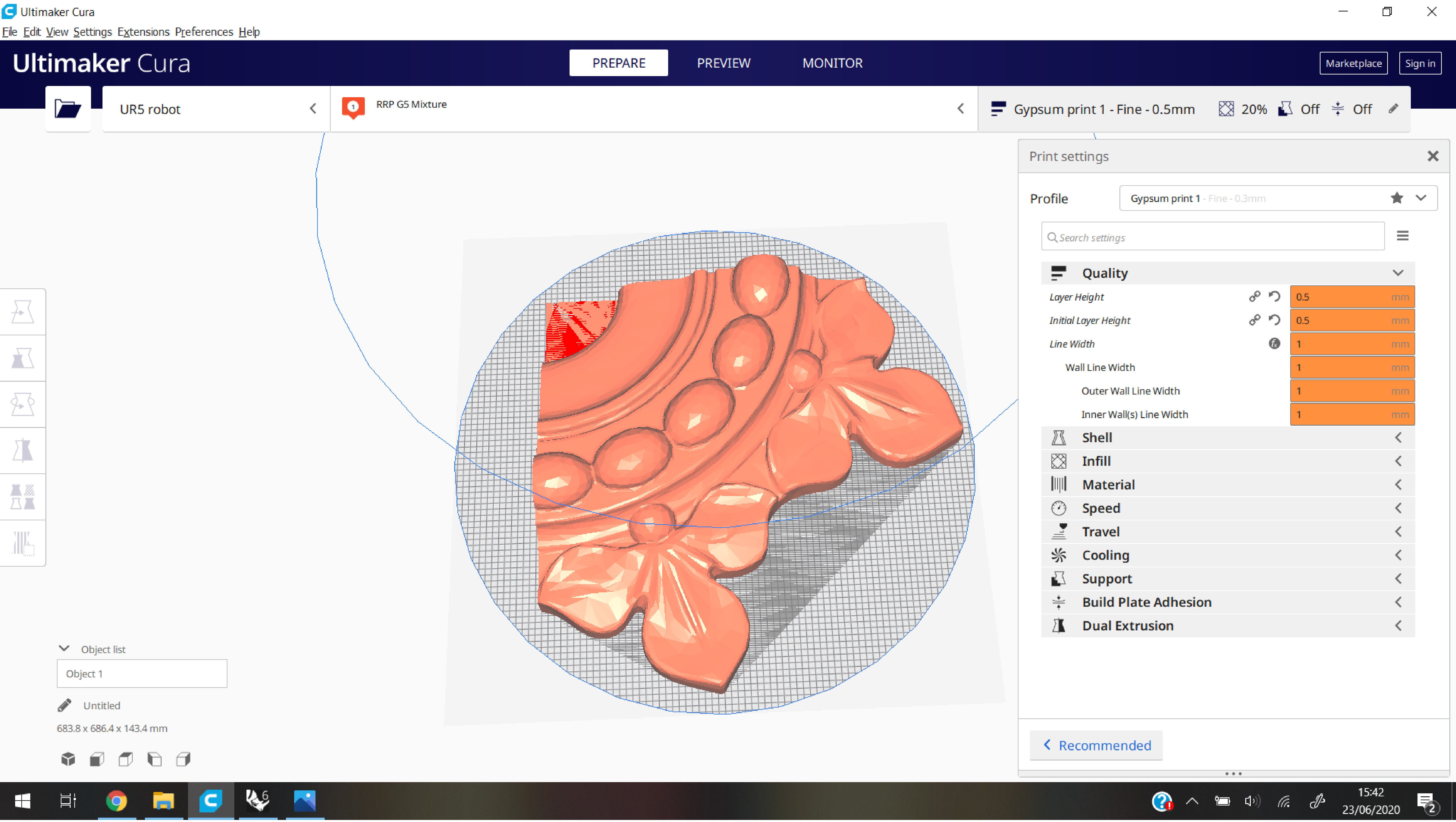
Step 13. Cura 3D printing software: Select UR5 robot + extruder in “printer selection”.



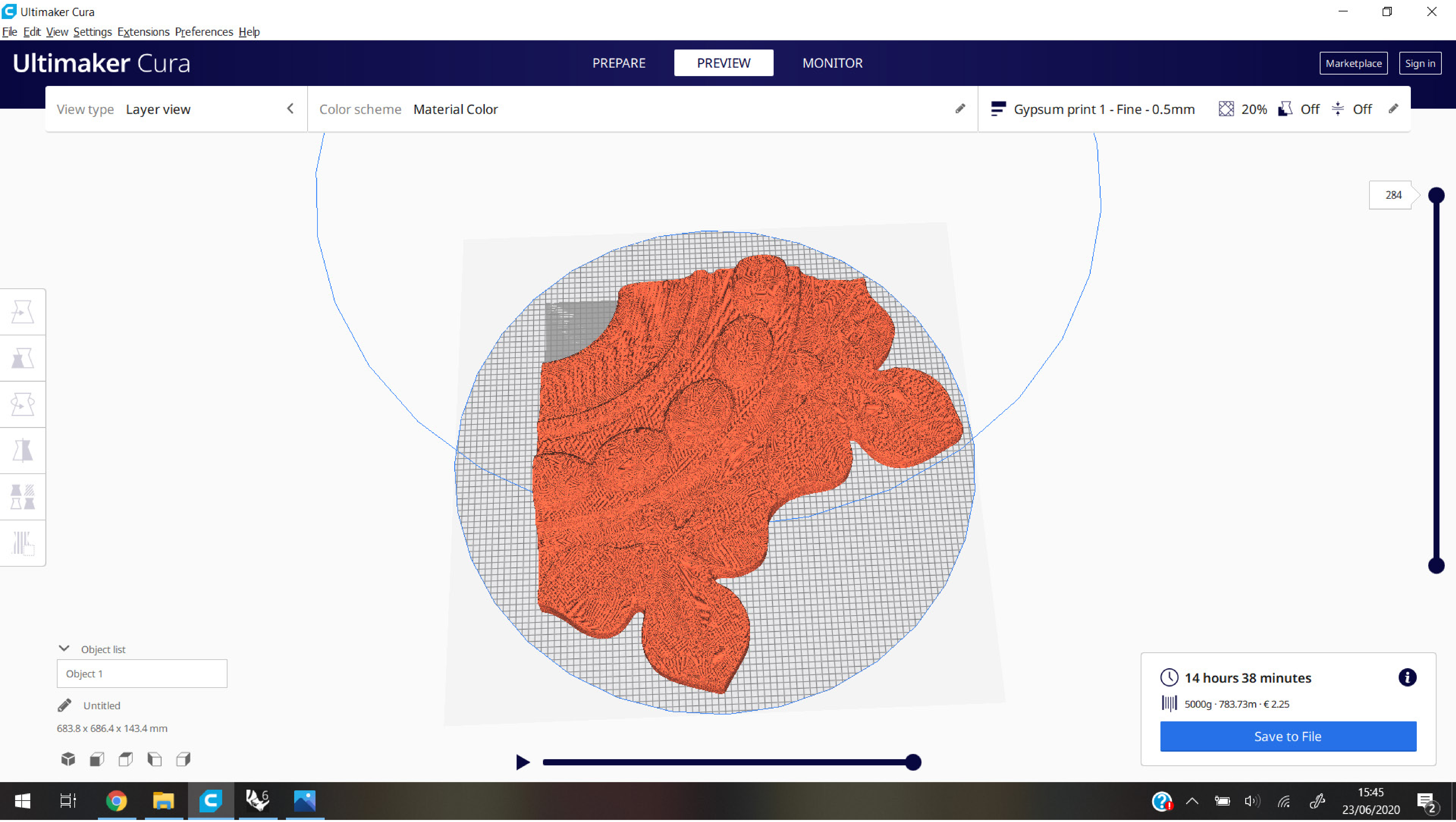
Step 14. Import STL file of ornament



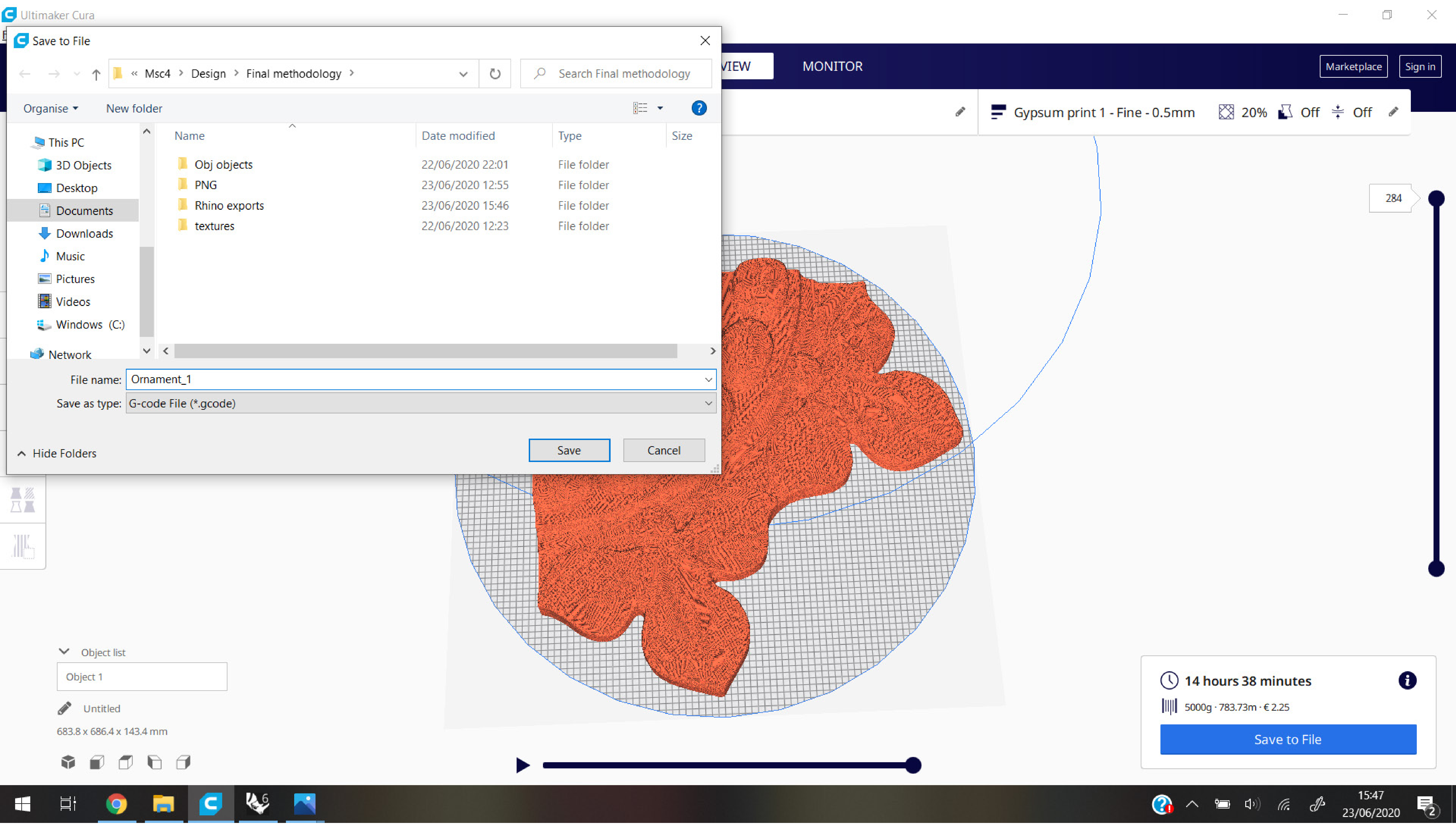
Step 15. Choose printing material profile



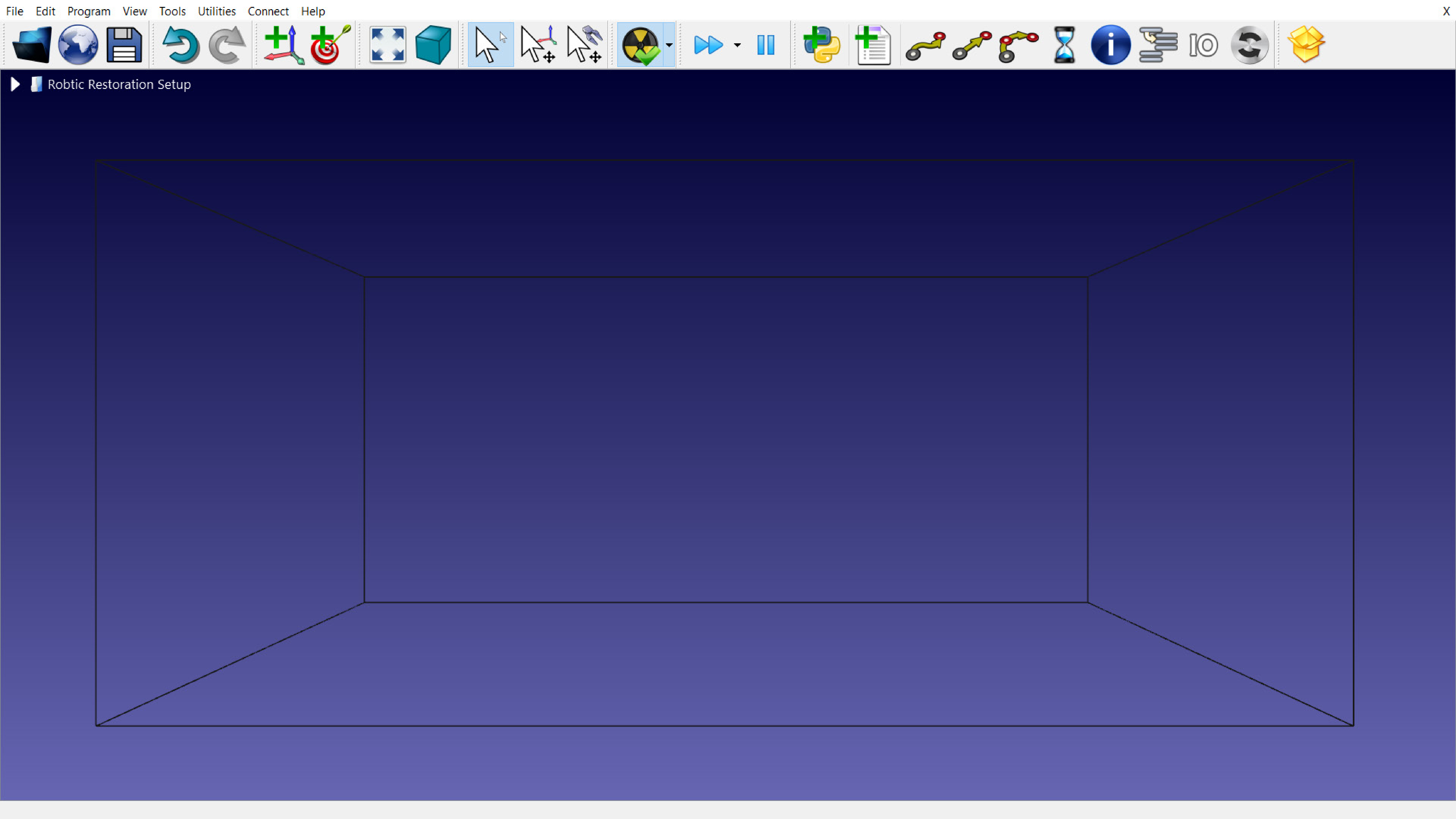
Step 16. Use default printing profile, or customize 3D printing settings



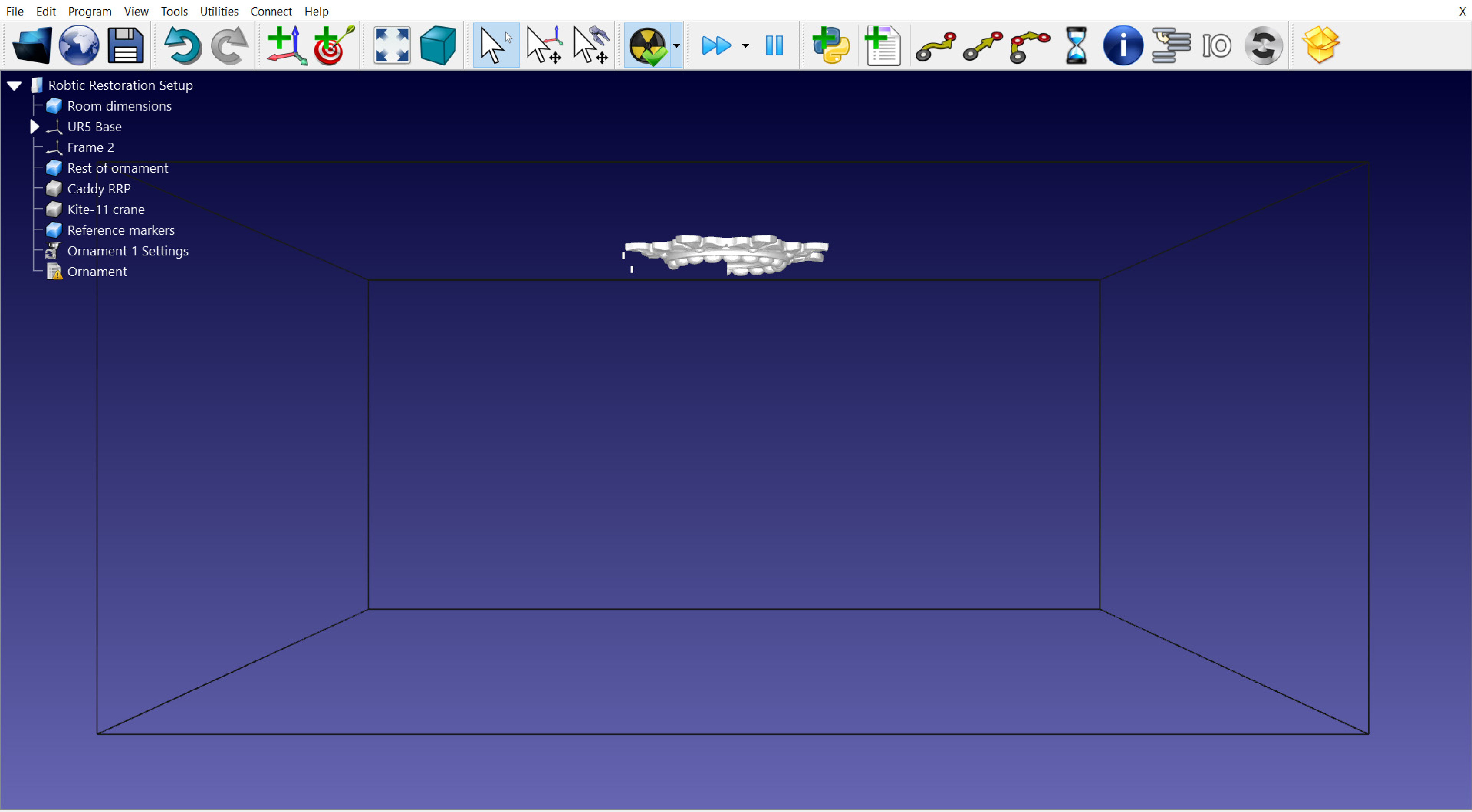
Step 17. Slice geometry with selected settings



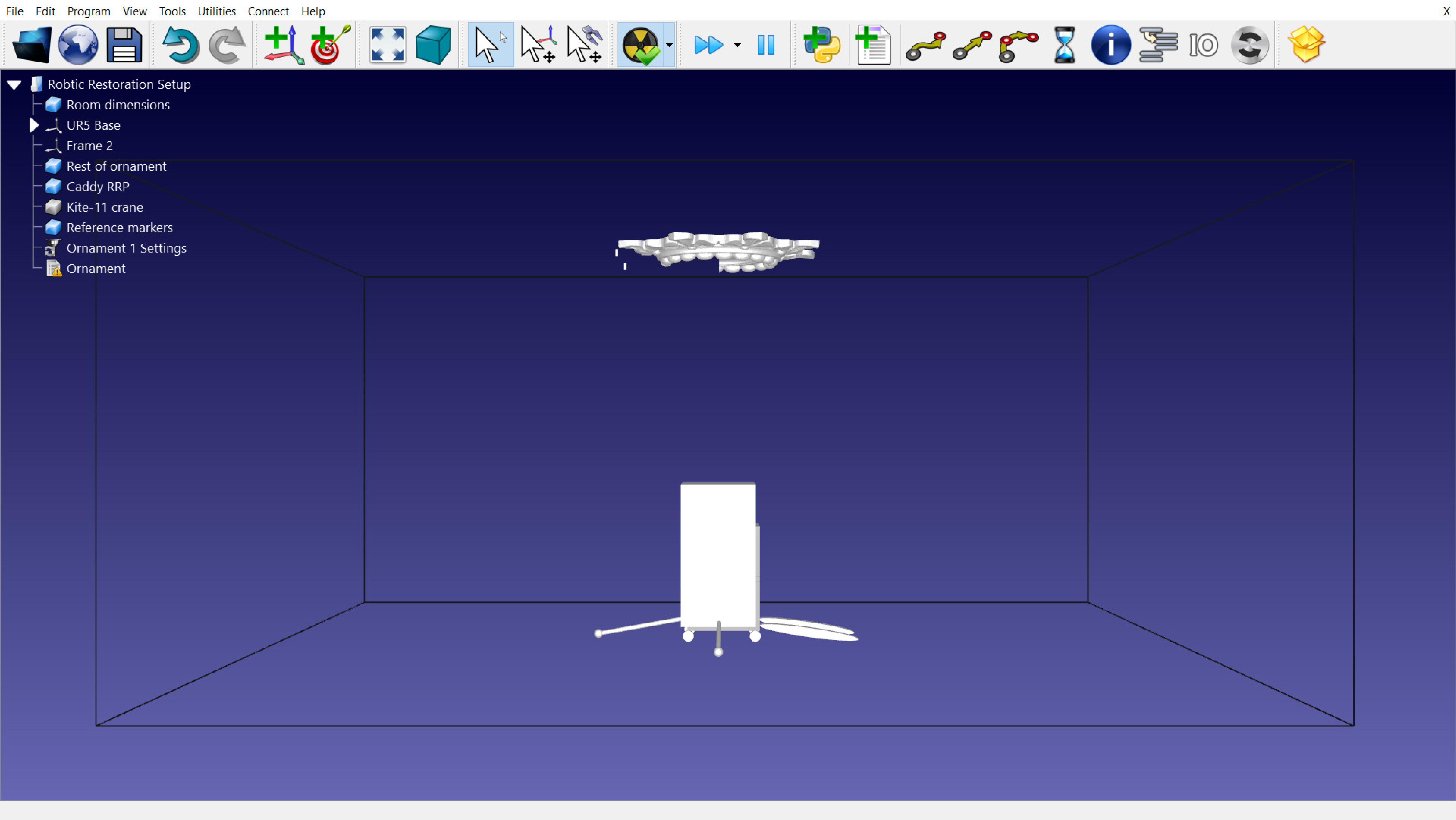
Step 18. Save file as G-code



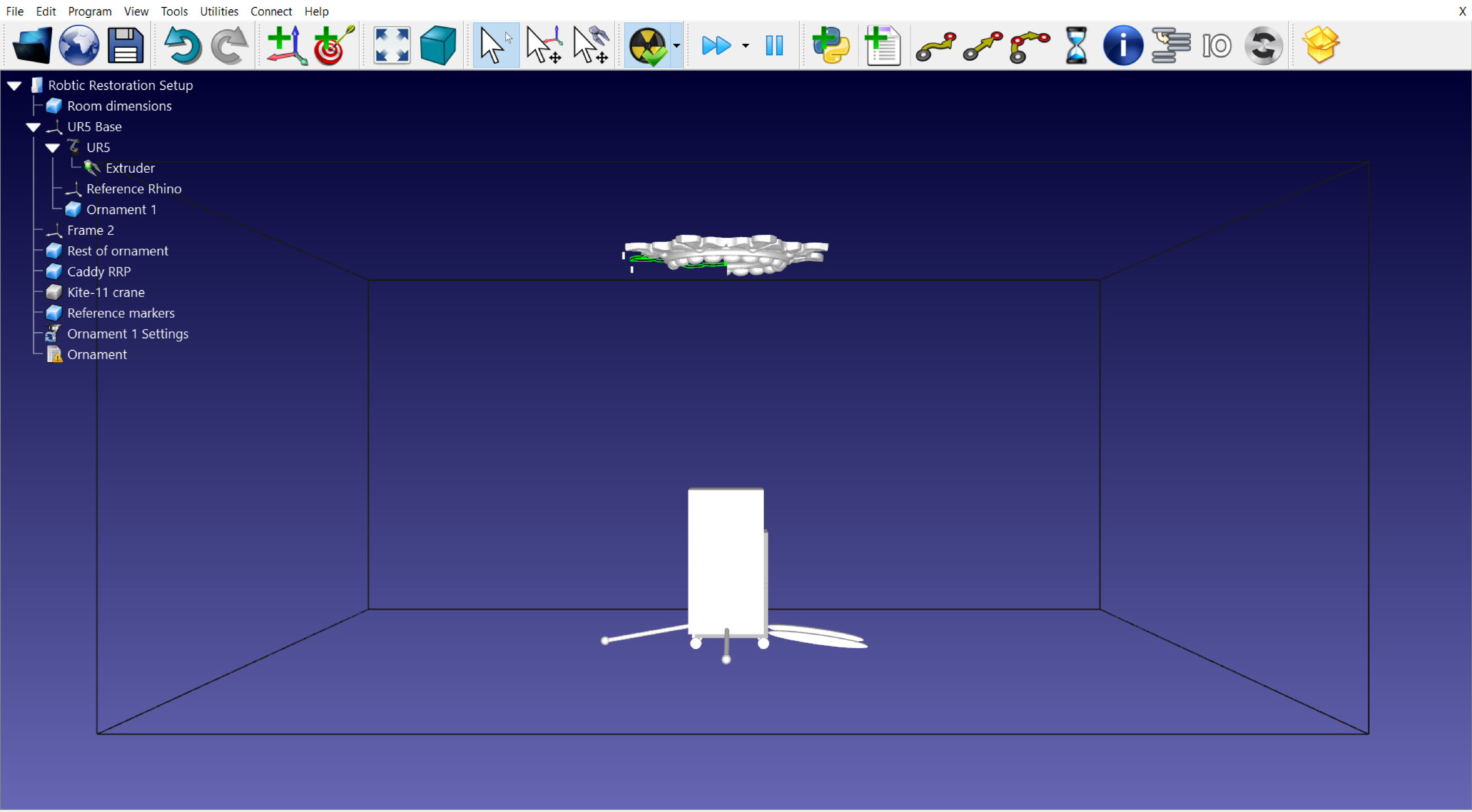
Step 19. Load room into RoboDK from room 3D scan



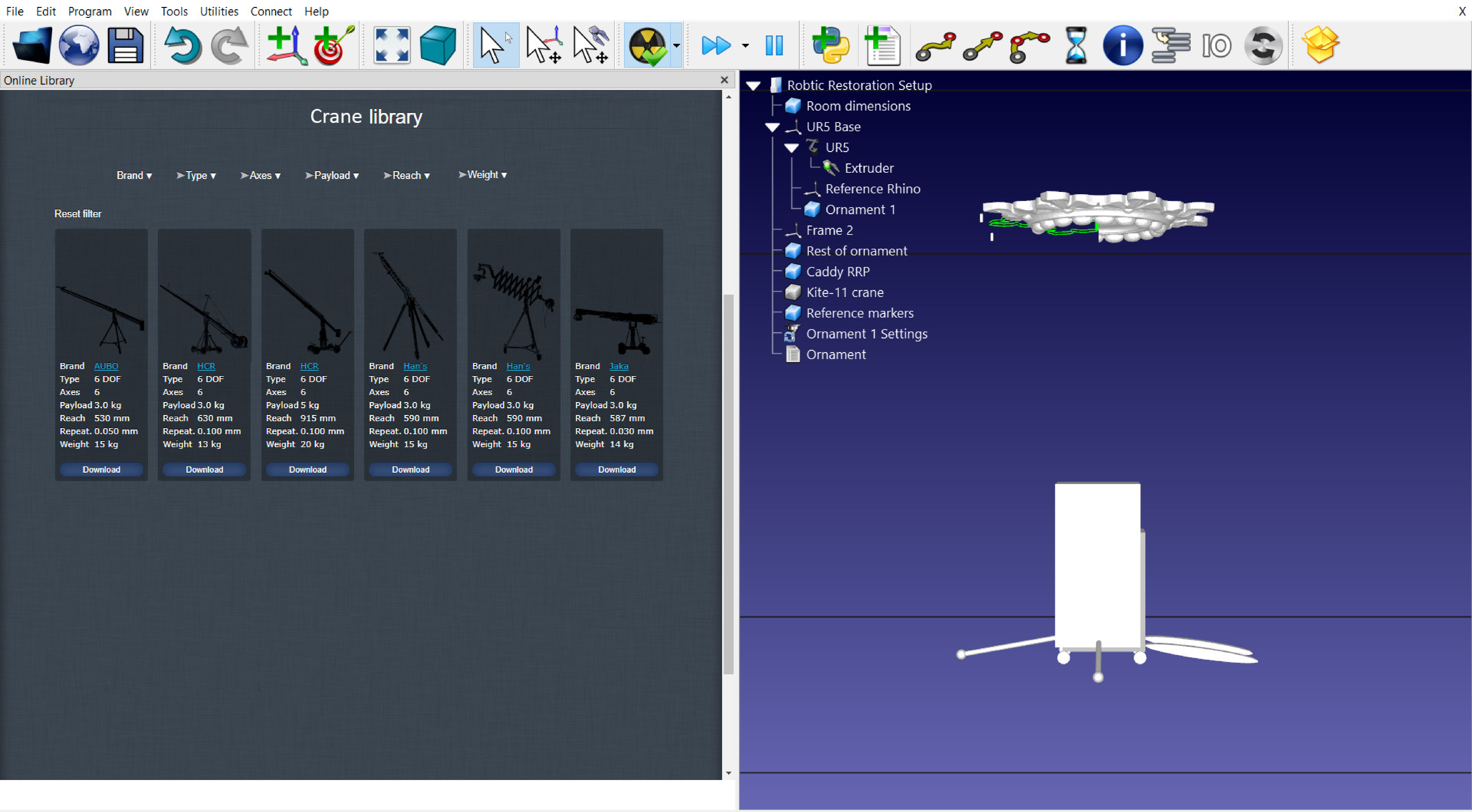
Step 20. Load remaining ornament + reference markers from 3D scan into RoboDK



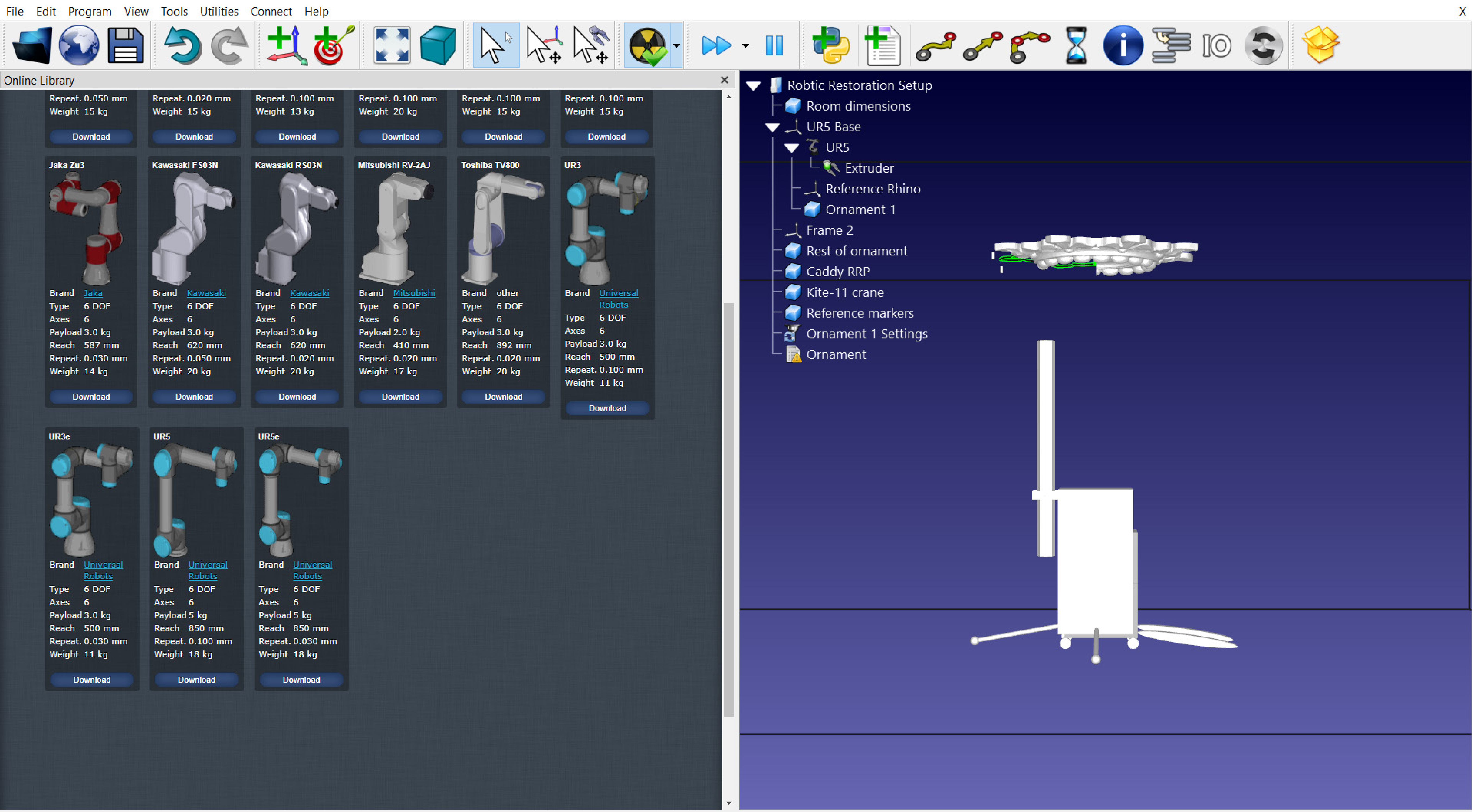
Step 21. Load RRP Caddy



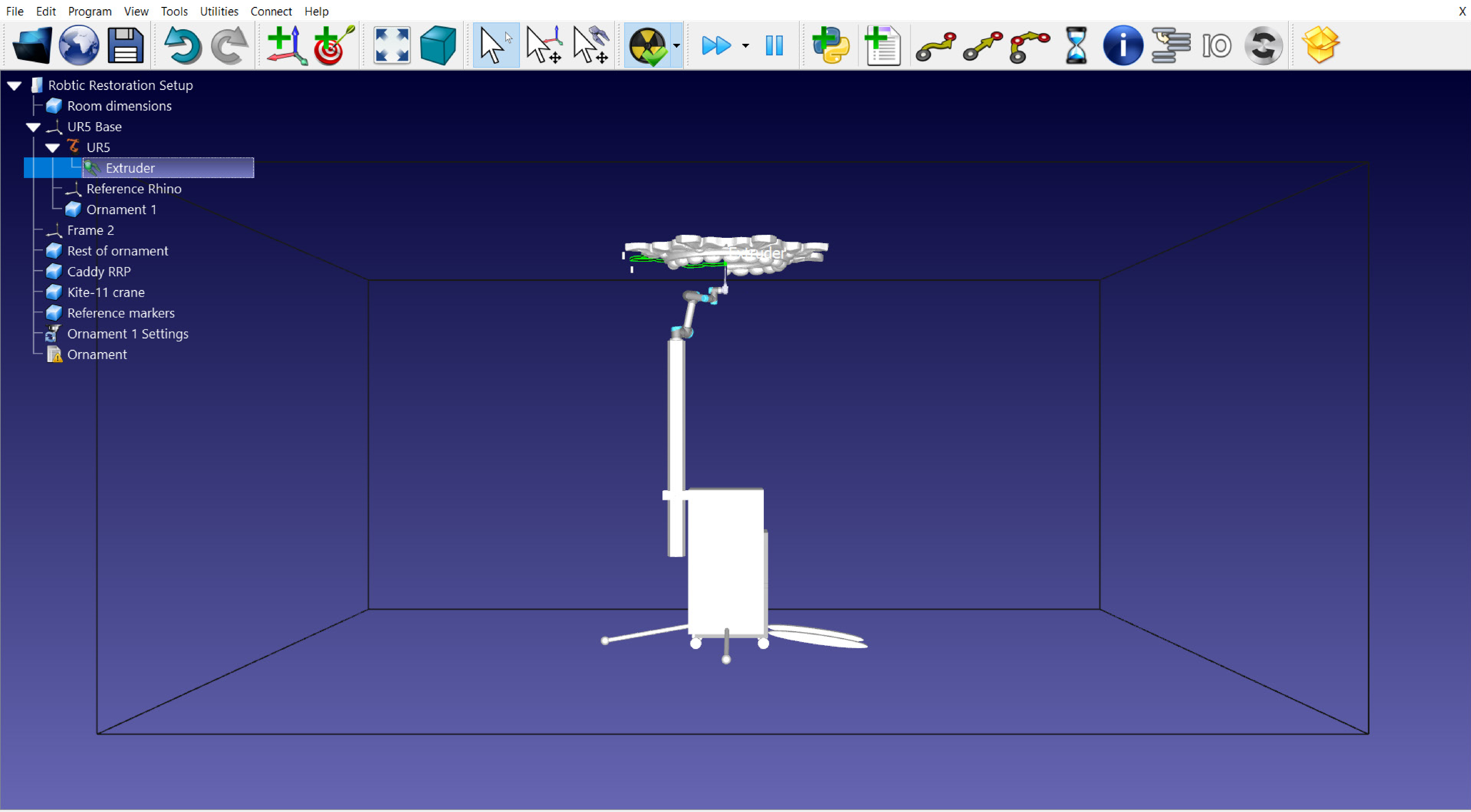
Step 22. Load in 3D printing file



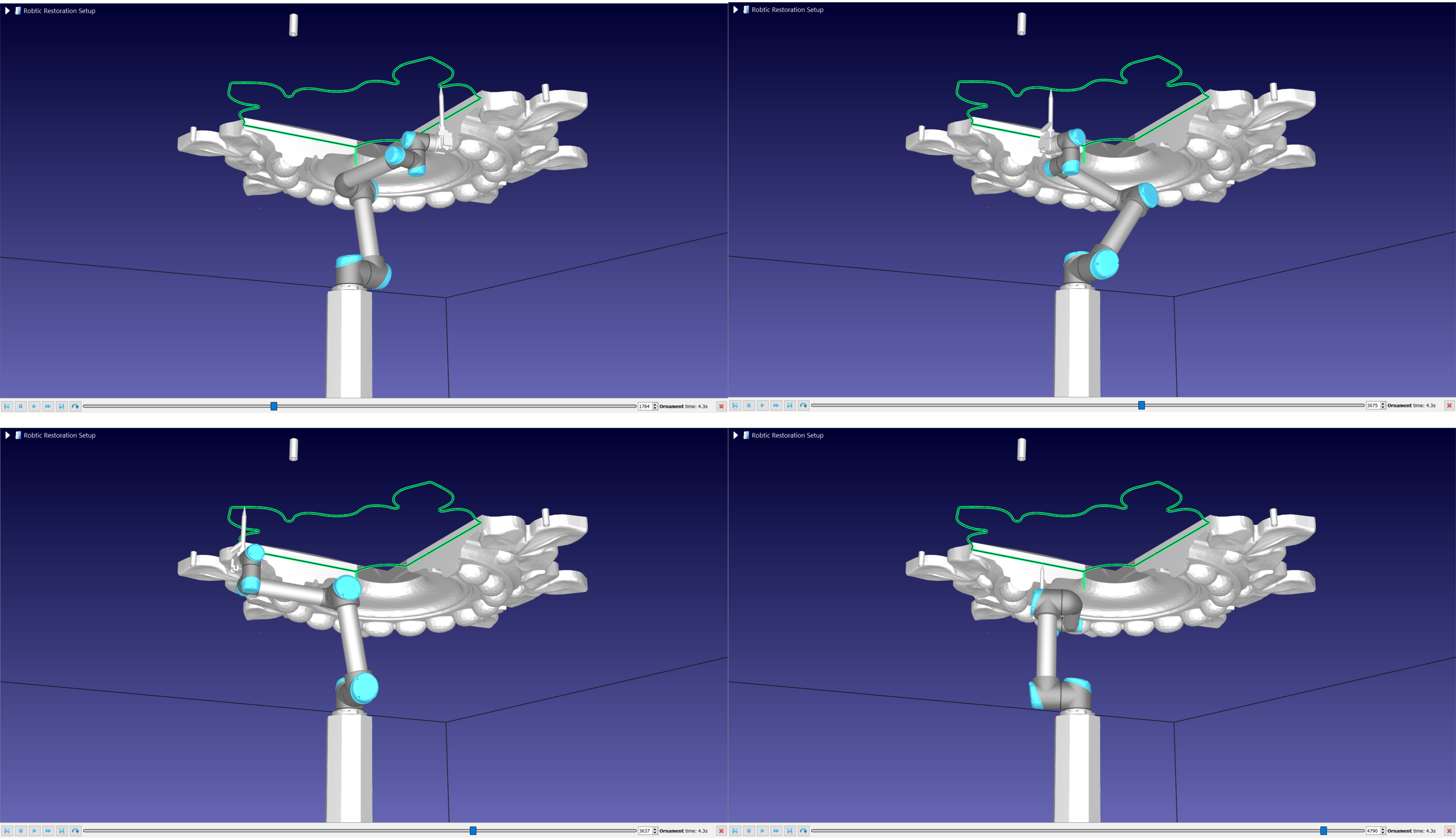
Step 23. Select crane from online crane library



Step 24. Select robot (Filter on robots with sufficient reach and weight for chosen crane)

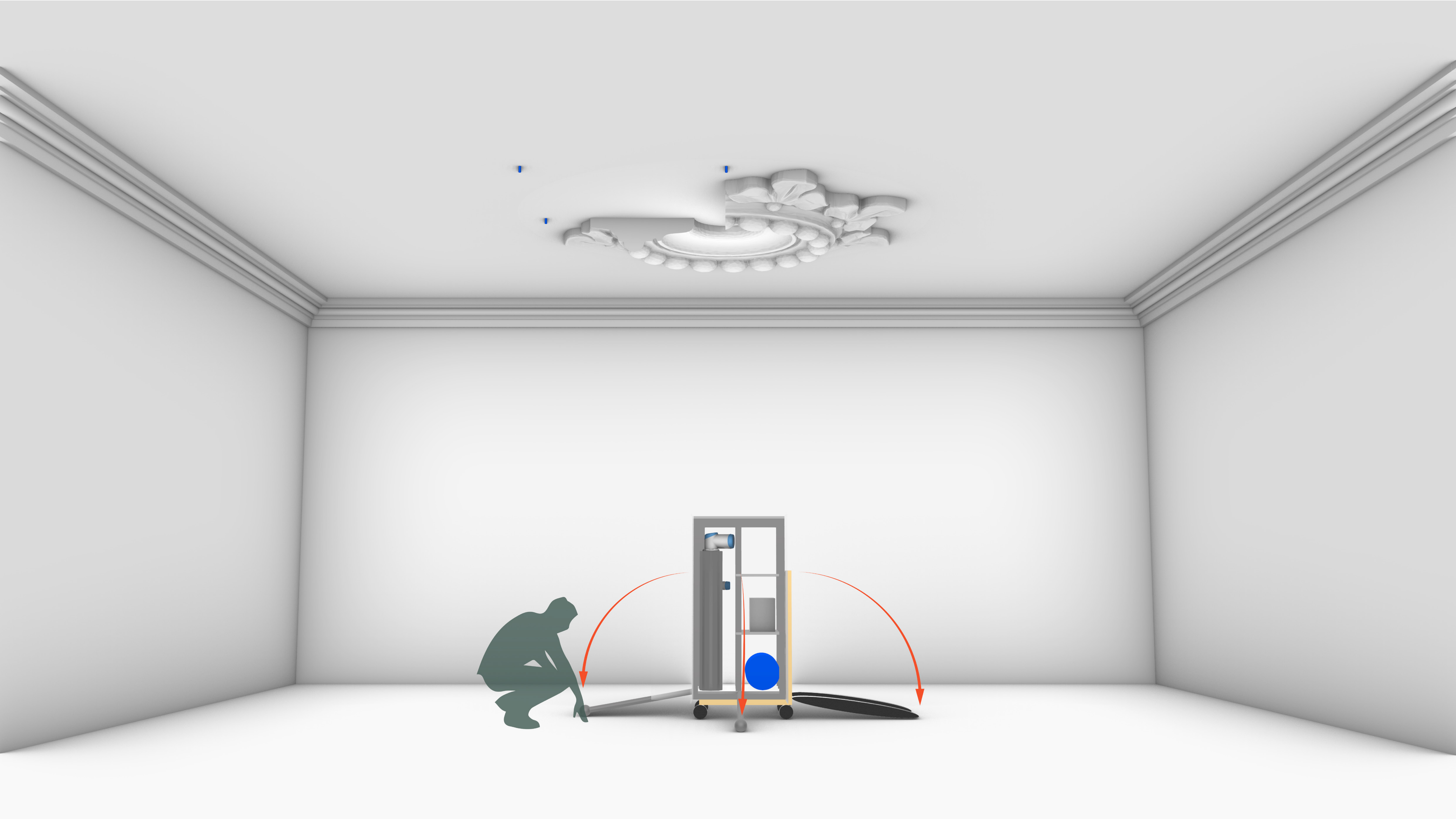


Step 25. Load in extruder and attach to robot wrist as Tool



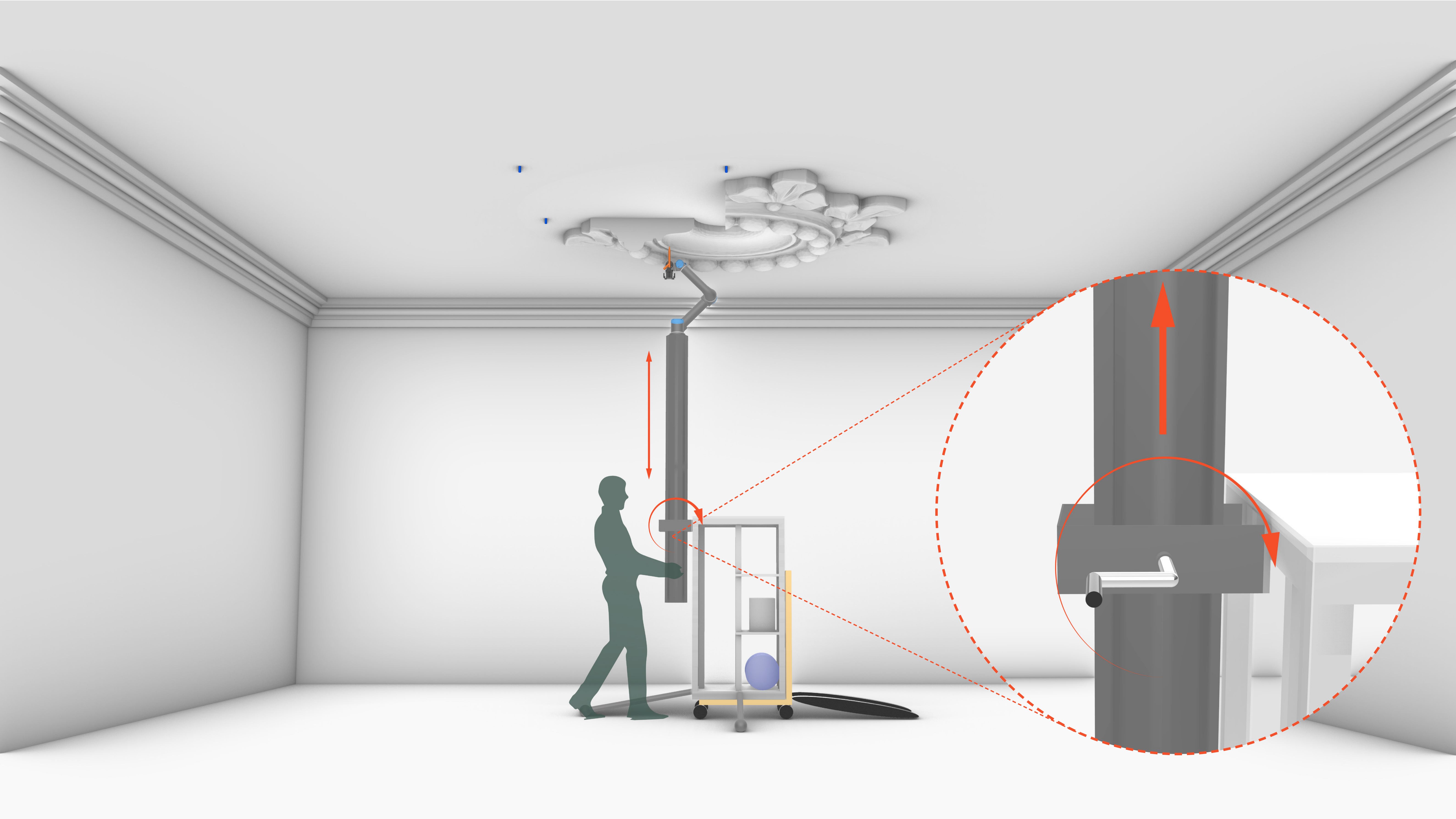
Step 26. Simulate printing process & save final G-code (Evaluate if robot can reach every point and create collision-free toolpath)

Step 27. Bring RRP to site

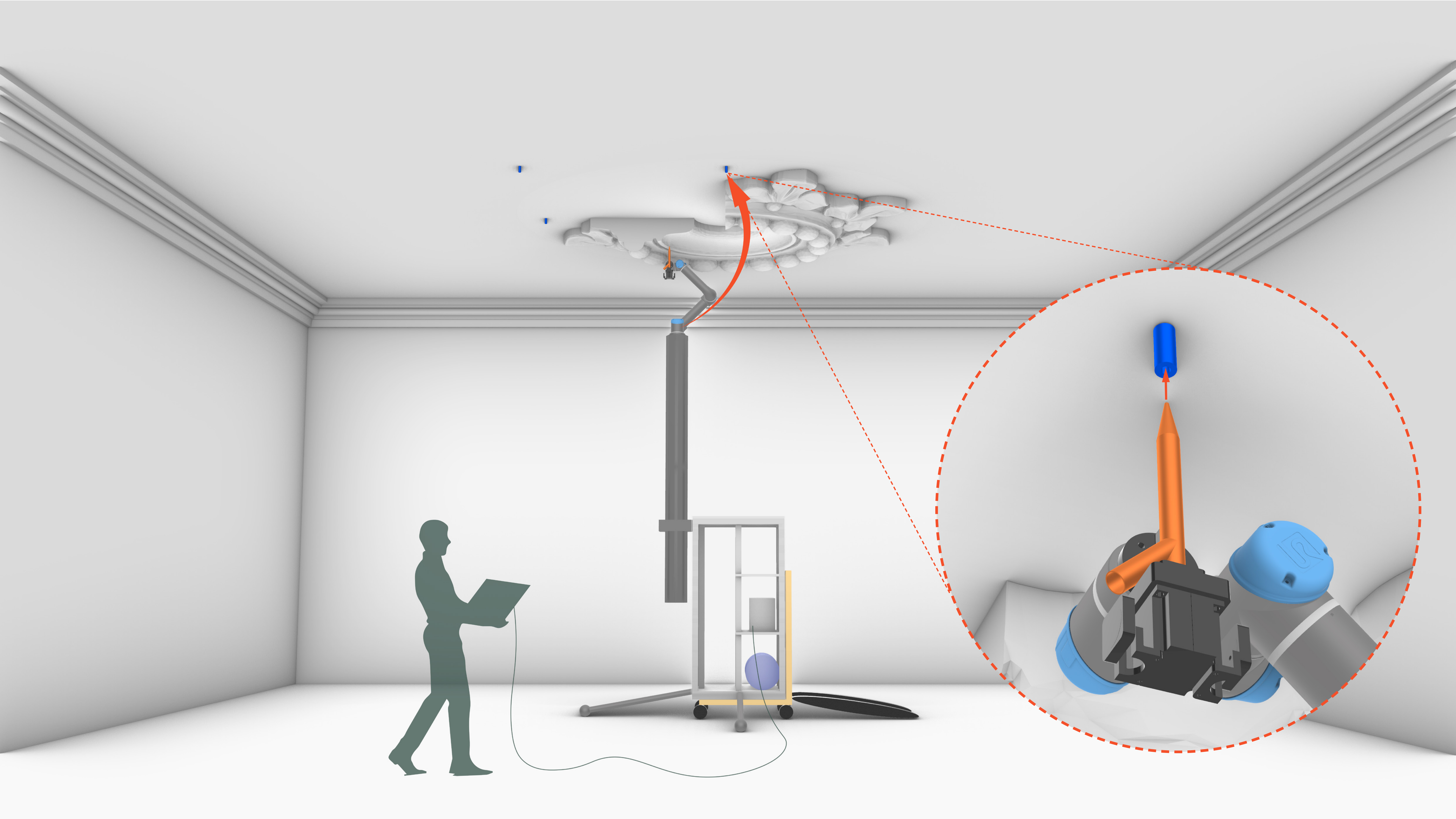


Step 28. Stabilize platform with stabilizing legs & tracks

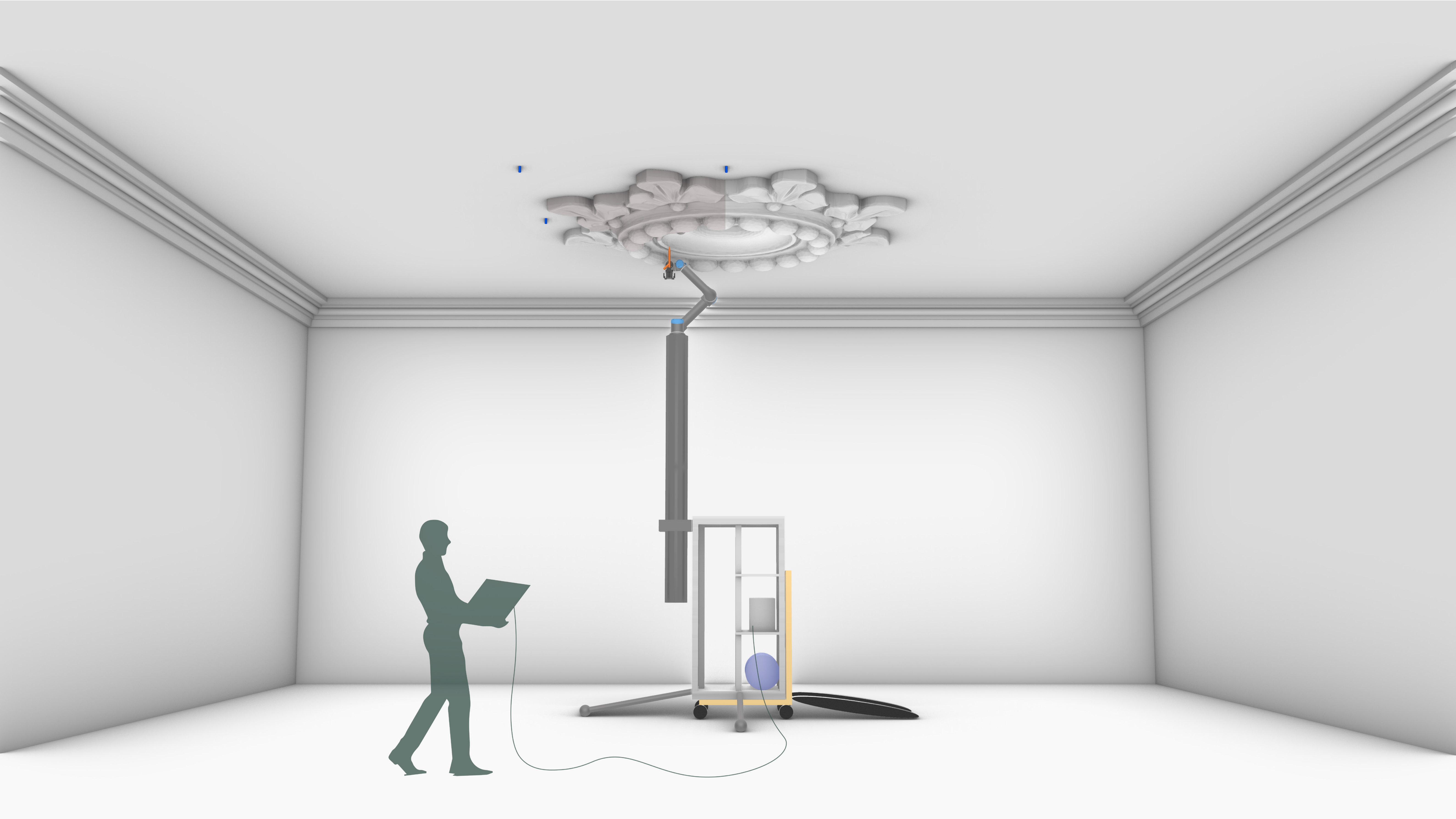
Step 29. Mount crane with robot onto caddy frame



Step 30. Ajust crane height with handle

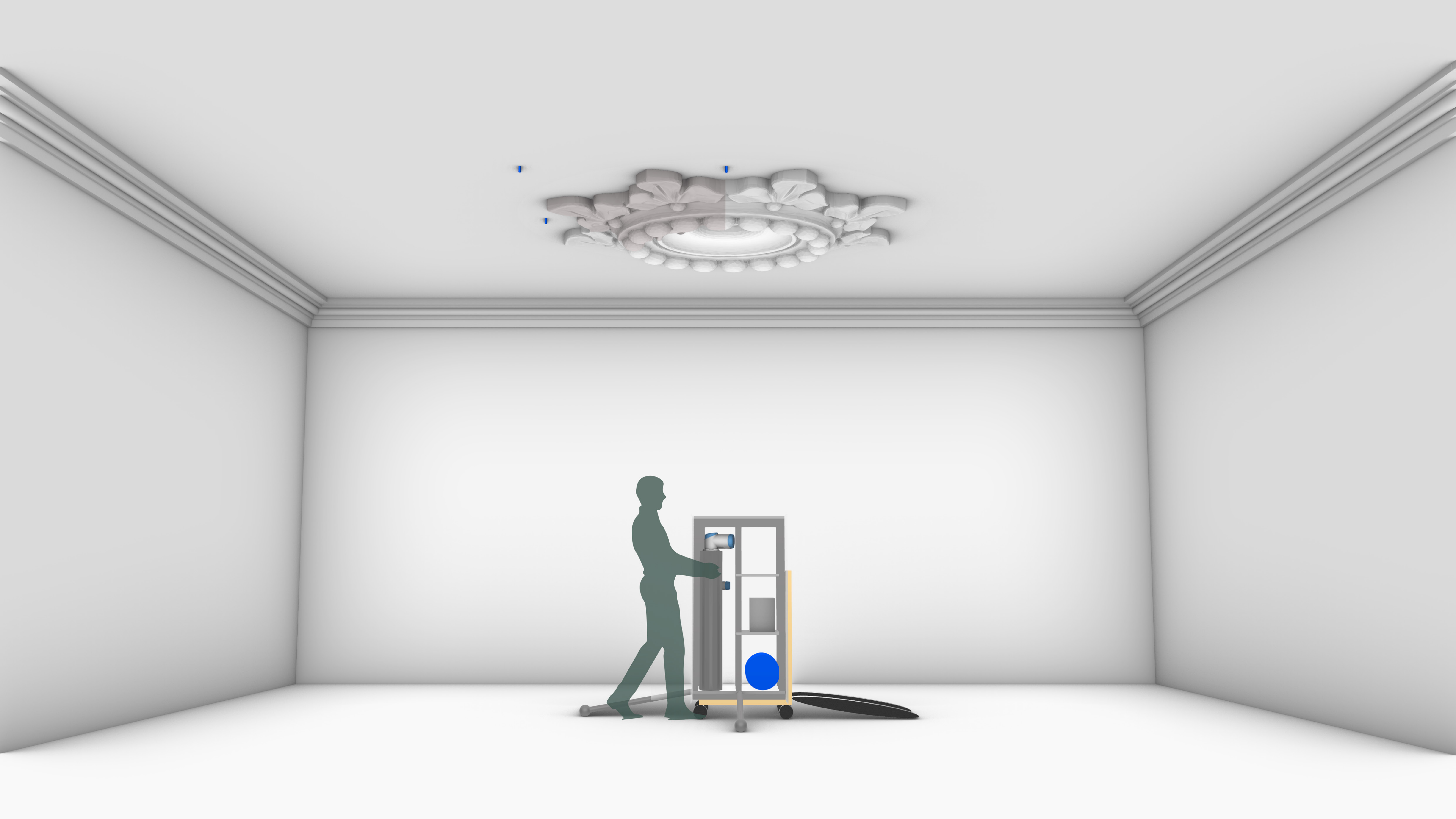


Step 31. Calibrate robot manually to reference markers

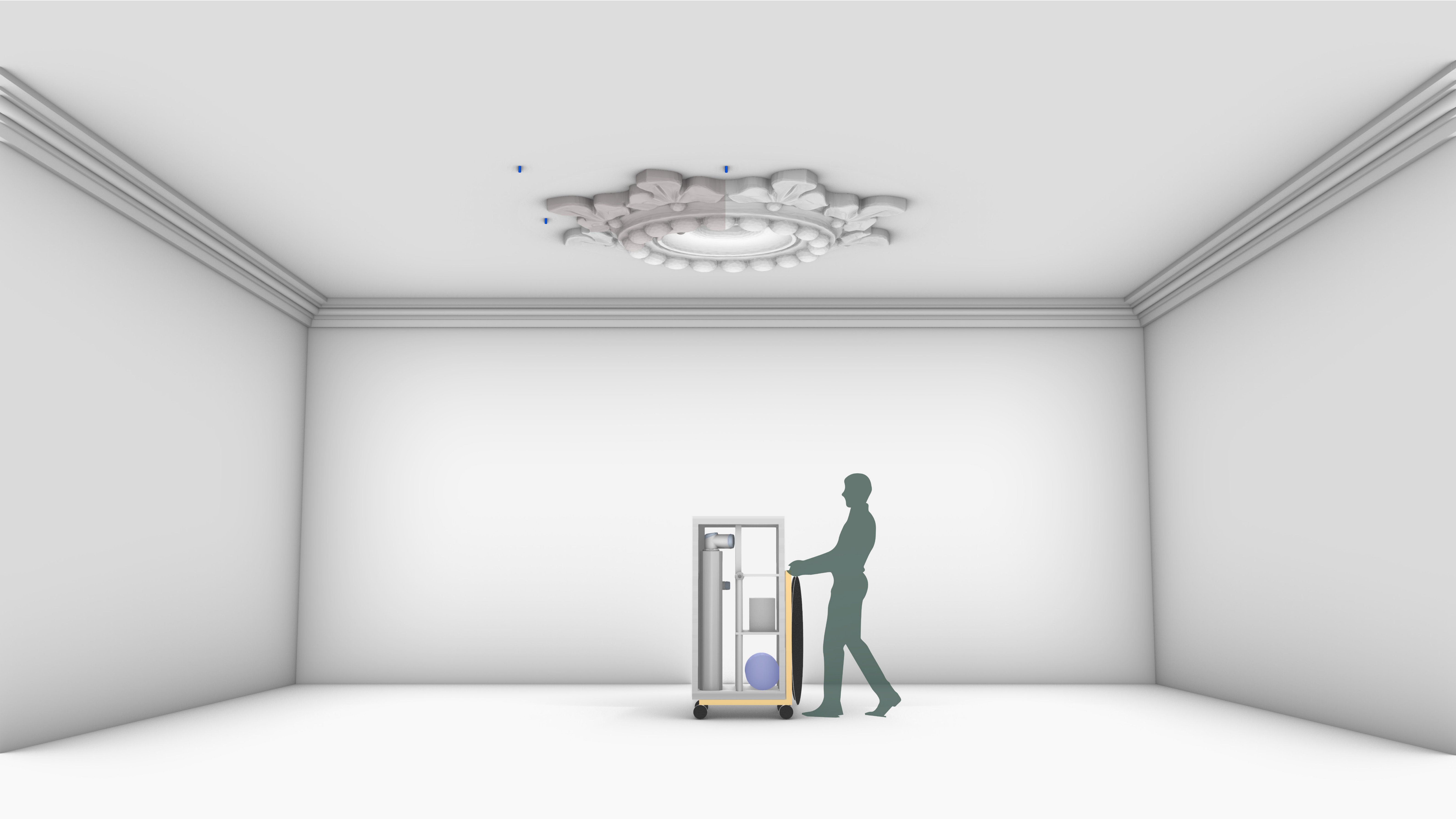


Step 32. Run G-code. Robot 3D prints ornament in situ.

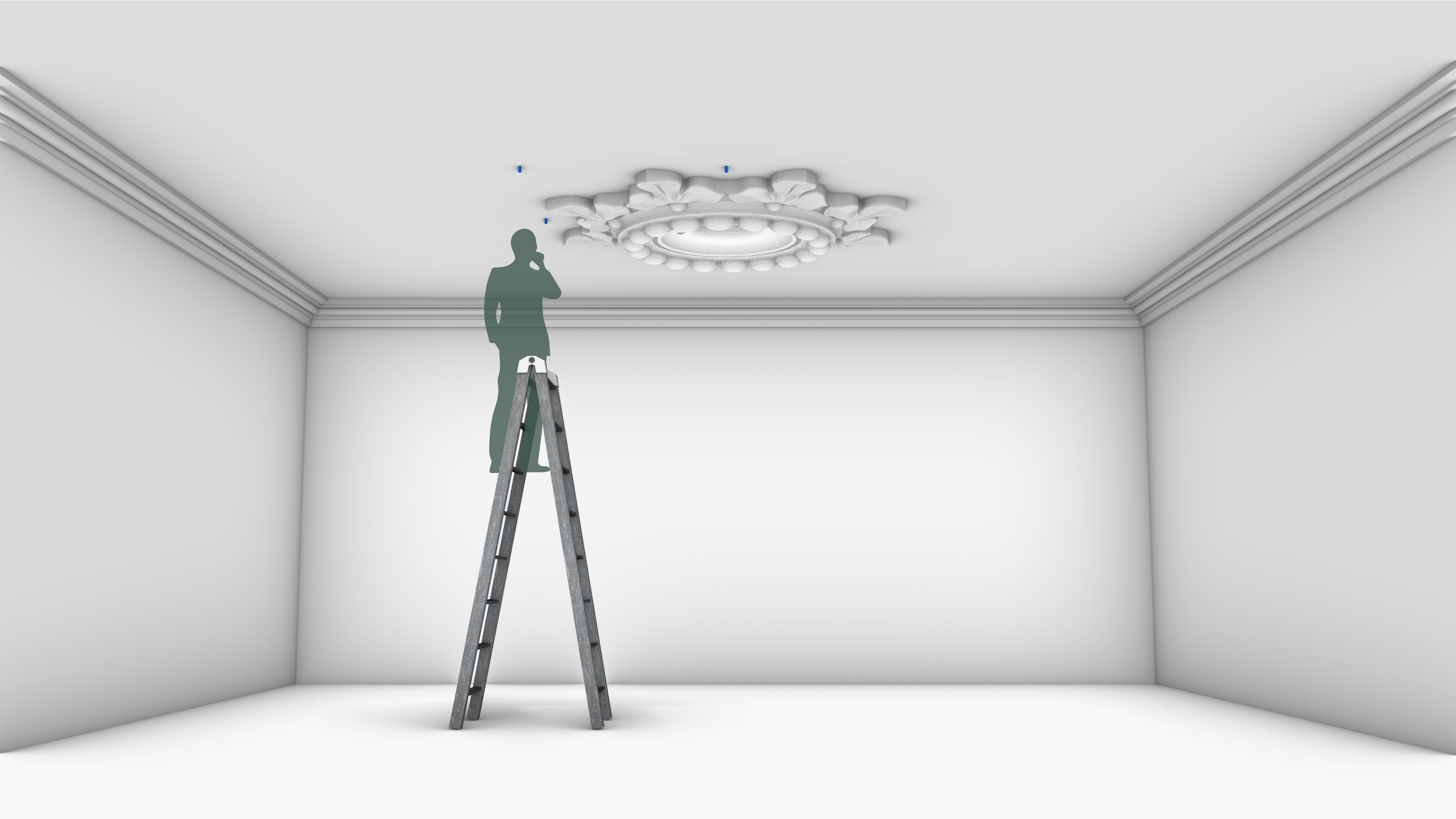
Step 33. Inspect work



Step 34. Dismount crane & robot for storage



Step 35. Close doors and remove caddy from site



Step 36. Final inspection 48+ hours after drying

Step 37. Remove reference markers

Step 38. Final result

APPENDIX B

Printer settings data

Input values for Cura & RoboDK

Printer settings input

Quality		Note
Nozzle width (mm)	2,25	
Layer height (mm)	1	Extr. Speed
Initial layer height (mm)	1	
Outer wall line width (mm)		
Inner line width (mm)		
Top line width (mm)		Top of a sub-part
Bottom line width (mm)		Bottom of a sub-part
Infill line width (mm)	1	First layers
Initial layer line width (mm)		First layers
Finish layer line width (mm)		Visible layer

Shell		Note
Wall thickness (mm)	2	>1,3
Wall line count	1	
Top thickness (mm)	2	>1,3
Top layers	1	
Bottom thickness (mm)	2	>1,3
Bottom layers	1	

Infill		Note
Initial fill density (%)	100	Better adhesion
Infill density (%)	30	
Infill pattern...	Zig-zag	
Infill layer height (mm)	2	
Infill line width (mm)	2	

Travel		Note
Avoid collision with print	TRUE	RoboDK setting
Avoid collision with substrate	TRUE	RoboDK setting
Collision avoidance margin (mm)	50	
Z Hop	TRUE	Slicer setting
Z Hop height (mm)	350	Bounding box Z + 50

Speed		Note
Perimeter wall speed (mm/s)		Lower
Infill wall speed (mm/s)		Higher
Initial layer speed (mm/s)		Lower
Final layer speed(mm/s)		Lower
Average printing speed (mm/s)	40	
Extrusion speed (mm/s)		Motor speed (NEMA23)
Compressor pressure (bar)	4	

Printer settings output

Settings output		Note
Printing time (min)	41,66666667	TRUE
Layer count	300	FALSE
Print sections required	14,28571429	
Bounding box X	TRUE	
Bounding box Y	TRUE	
Bounding box Z	TRUE	
Robot stationing coordinates	(x,y,z)	Middle
Length of toolpath (mm)	100000	

CAD file

Print geometry		Note
Volume (m^3)	0,006	
Mass (kg)	6	TRUE
Bounding box X (mm)	500	TRUE
Bounding box Y (mm)	400	TRUE
Bounding box Z (mm)	300	TRUE
XY plane area (m^2)	0,2	

Robot specification

Robot specs		Note
UR5		
Max payload (kg)	5	
Reach X (mm)	750	
Reach Y (mm)	750	
Reach Z (mm)	750	

Nozzles

Name	Width (mm)	Note
N1	3,25	
N2	4,7	
N3	5,5	
N4	2,95	
N5	1,75	
N6	1	

Material specifications

Material specs		Note
Bulk density (kg/m^3)	1000	
Shrinkage (%)		
Buildable layers	21	
Min extrusion width (mm)	1	
Pumping pressure (bar)	4	
Open time (min)	78	
Adhesion fresh (1-5)	5	Excellent
Adhesion dry (kg)	27	TRUE

APPENDIX C

Printing tools specifications data

Printing material experiment results

Printing material			Open time	Extrudability				Buildability	Aesthetic	Aesthetic	Adhesion dry state	Adhesion fresh state
Sample	Gypsum/marble powder	Gypsum/water	Printable time (min)	Line continuity (1-5)	Nozzle width (mm)	Extrusion width (mm)	Extrusion/nozzle width (-)	Nr. Of layers without collapse	Shrinkage (%)	Cracking (1-5)	Pull-out force (N/cm^2)	Displacement (mm)
G0		1,55/1	4	1	5	.		1		1		.
G1		1,75/1	2	2	5	.		1		1		
G2	02:01	1,55/1	1	3	5	.		1		3		
G3		1,55/1	35	4	2,25	2,5	1,111111111	5		2	3,546099291	
G4	01:01	1,02/1	84	4	4,55		0	5		.		
G5	03:01	1,50/1	78	5	2,25	2,5	1,111111111	21		1	9,574468085	
G6	06:01	1,50/1	85	4	4,55	5,5	1,208791209	11		2		
G7	02:01	1,50/1	40	4	4,55	4,6	1,010989011	15		2		
G8	2,5:01	1,50/1	45	4	4,55	4,8	1,054945055	9		3		
G9	04:01	1,50/1	45	4	4,55	4,5	0,989010989	14		2		
G10		1,22			1,75	1	0,571428571					
G11		1,55/1	85	5	1	1	1			2		
G12												
G13												
G14												
G15												

Hardware specifications

Crane

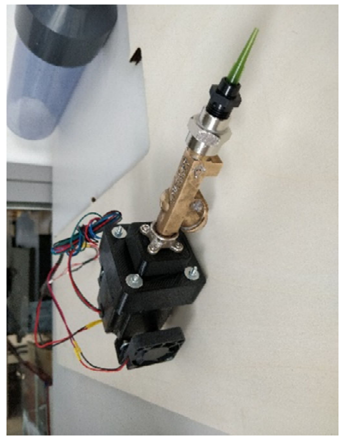
Kite-11 sp	Value
Reach (mm	3320
Weight (kg	24
Payload (k	25
PWR (-)	1,041666667
DOF (-)	3

Robot specification

UR5 spec	Value	Note
Brand	Universal Robots	
Type	6 DOF	
Axes	6	
Weight	20	
Payload (k	5	
PWR (-)	0,25	
Reach Z (m	750	
Repeatabil	0,1	

Extruder

Printer spe	Value
Motor	NEMA23
Power (A)	4
AC/DC	DC
Torque (kg	12,85
DEG	1,85



Compressor

Compressor specs	Value
Air output (L/min)	45
Power (PK)	0,75
Max pressure	8
Voltage (V)	230
Capacity (L)	20
Weight (kg)	23

Nozzles

Nozzle nar	N1	N2	N3	N4	N5
Diameter (	1,4	2,3	5,4	7	10
Length (m	45	82	36	37	85

APPENDIX D

Arduino sketch

Arduino sketch

stepper_FINAL | Arduino 1.8.11

File Edit Sketch Tools Help

stepper_FINAL

```
#include <Stepper.h>

const int stepsPerRevolution = 3000;  // change this to fit the number of steps per revolution
// for your motor


// initialize the stepper library on pins 6 through 7:
Stepper myStepper(stepsPerRevolution, 6, 7);
int driverDIR = 6;  //DIR- pin

int reverseSwitch = 2;  //Push button for reverse , could be limit switch, or two in paraller between 2 extremes, electronic switch better
boolean setdir = LOW;  //Set Direction , toggle to reverse motor

int stepCount = 0;  // number of steps the motor has taken

//Interrupt Handler

void revmotor (){
  setdir = !setdir;
}

void setup() {
   attachInterrupt(digitalPinToInterrupt(reverseSwitch), revmotor, FALLING);
   Serial.begin(9600);
   delay(25);  //millisecond delay between pulses
}

void loop() {
  // read the sensor value:
  int sensorReading = analogRead(A0);

  Serial.println(sensorReading);
  digitalWrite(driverDIR,setdir);
```

Save Canceled.

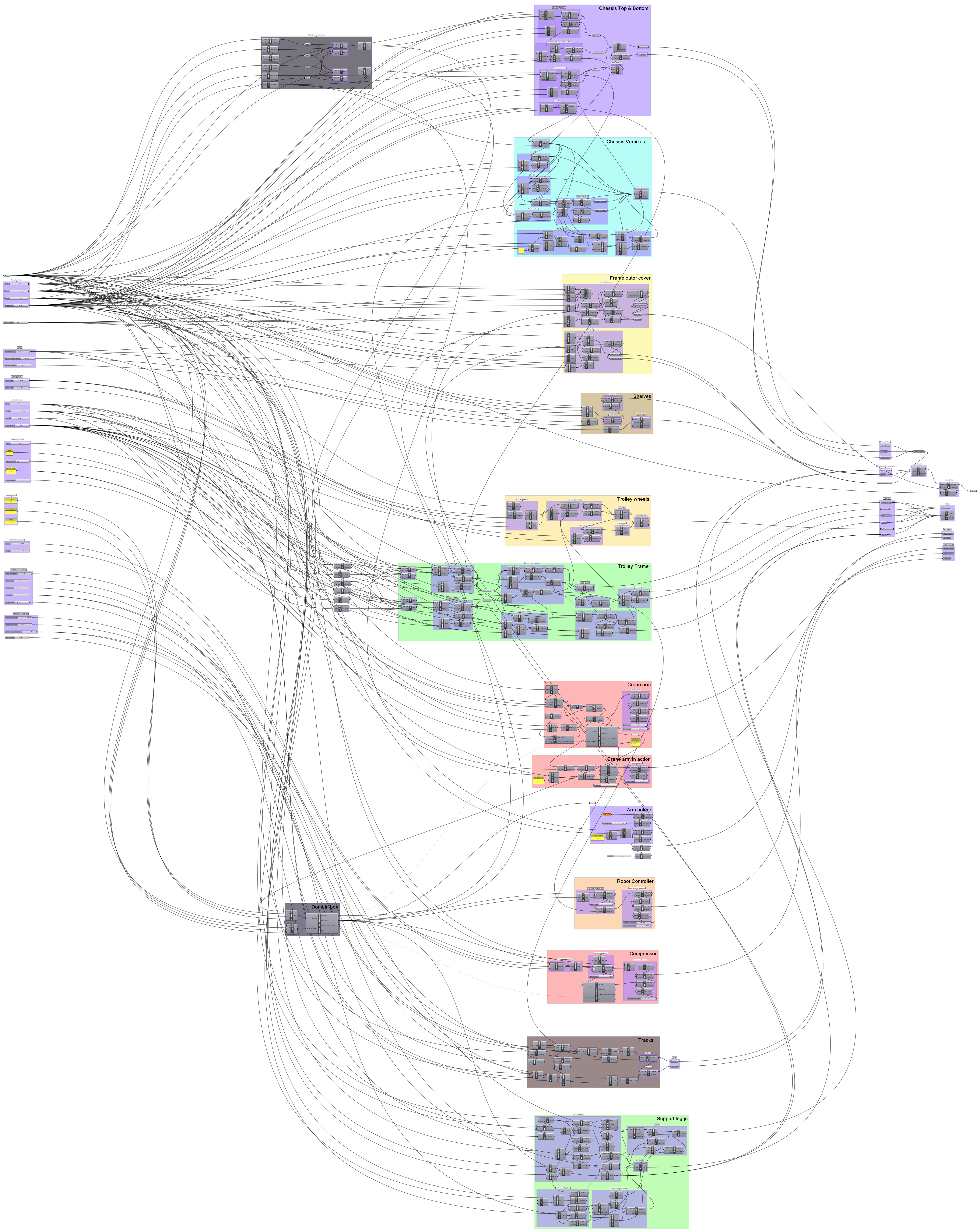
1

Arduino Uno on COM4

APPENDIX E

Caddy design grasshopper script

Grasshopper script of parametric Caddy model



APPENDIX F

Overall research flowchart

Overval Digital Fabrication methodology & design strategies

APPENDIX G

Printing process flowchart

Digital Fabrication process flowchart

APPENDIX H

Materials & robot information

	Gevaar componenten voor etikettering	:	Niet van toepassing
	Gevarenaanduiding	:	Niet van toepassing
	Gevarenklassen/-categorieën	:	Niet van toepassing
	Voorzorgsmaatregelen/ preventie	:	P102 - Buiten het bereik van kinderen houden P280 - Beschermende handschoenen/beschermende kleding/oogbescherming/gelaatsbescherming dragen P305+P351+P338 - BIJ CONTACT MET DE OGEN: Voorzichtig afspoelen met water gedurende een aantal minuten. Contactlenzen verwijderen, indien mogelijk. Blijven spoelen P310 - Onmiddellijk een ANTIGIFCENTRUM/arts raadplegen P302+P352 - BIJ CONTACT MET DE HUID: Met veel water en zeep wassen P501 - Inhoud/verpakking afvoeren als bouwafval volgens relevante reglementering
2.3	Andere gevaren	:	Het product ontwikkelt door toevoeging van water een alkalische pH-waarde en kan dan irriterend werken
	PBT/vPvB criteria	:	Niet van toepassing

Rubriek 3: Samenstelling en Informatie over de bestanddelen:

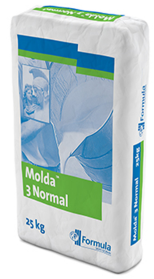
3.1	**Stoffen**		
	Chemische karakterisering	:	Mengsel
	Algemene beschrijving	:	Calciumsulfaat op diverse graden van hydratie met additieven (gehydrateerd kalk, lichte mineralische toeslagstof, tenside, cellulose ether, natuurlijke oxycarbonaat-zuren)
	Gevaarlijke bestanddelen:	:	Niet van toepassing
	Verdere bestandsdelen	:	
	CAS nummer	:	7778-18-9 Calciumsulfaat
	EINECS nummer	:	231-900-3
	REACH nummer	:	01-2119444918-26-XXXX
	Aanvullende informatie	:	De volledige tekst van de genoemde gevarenaanduidingen en H-zinnen vindt u terug in rubriek 16. Stoffen met een grenswaarde voor blootstelling op de werkplek vindt u terug in rubriek 8

Rubriek 4: Eerste hulpmaatregelen:

4.1	**Beschrijving van de eerste hulpmaatregelen**		
	Algemeen	:	Verwijder onmiddellijk alle verontreinigde kleding
	Inslikken	:	Reinig de mond. Geef veel water te drinken. Raadpleeg een arts
	Contact met de ogen	:	Reinig de ogen met veel water. Oogleden moeten van de oogbal afgehouden worden om een zorgvuldige reiniging te verkrijgen. Contactlenzen verwijderen, indien mogelijk. Raadpleeg een arts wanneer klachten aanhouden

MOLDA 3 NORMAL

Fibrous and Decorative Plaster



PRODUCT DESCRIPTION

Molda 3 Normal Plaster is an unformulated hemihydrate plaster ($CaSO_4.1/2H_2O$) produced from naturally occurring high purity gypsum mineral It is off-white in colour. It is used for the production of decorative fibrous plasterwork and in general casting applications. This product can also be used as a filler or additive within proprietary formulations

PRODUCT BENEFITS

- **Typical set time and working properties suitable for production of fibrous plasterwork**
- **Good reproduction of fine detail**
- **Unformulated high purity plaster also suitable for use within proprietary formulations**

OTHER MARKETS

Ceramics, Construction Materials, Food, Agriculture and Environment

APPLICATIONS

Sanitaryware, Fibrous plaster, Tableware, Floor, Wall

TECHNICAL INFORMATION

Plaster to Water Ratio	
Plaster to Water Ratio (by weight)	1.55:1
Water to plaster ratio (by weight)	65%
Plaster to water mix ratio (by weight)	100/65
Chemical Properties	
Chemical Name	Calcium sulphate hemihydrate
Chemical Composition	$CaSO_4.1/2H_2O$
Minimum gypsum purity %	91
Colour	white
Setting Parameters	
Vicat Ring Fluidity (cm)	18
Initial setting time (minutes)	17
Final setting time (minutes)	39
Linear Expansion (%)	0,19
Mechanical Properties	
Flexural Strength (MPa)	5
Brinell Hardness (MPa)	24
Hardness Shore D	50
Dry compressive strength (Mpa)	14
Physical Properties	
Particle Size (% weight retained)	0.1% at 200 µm 3% at 100 µm
Loose bulk density (kg/m³)	600

UR5e technical details

Performance

Power consumption	Approx. 200 W using a typical program	
Safety System	All 17 advanced adjustable safety functions incl. elbow monitoring certified to Cat.3, PL d. Remote Control according to ISO 10218	
Certifications by TUV Nord	EN ISO 13849-1, Cat.3, PL d, and **full** EN ISO 10218-1	
F/T Sensor - Force, x-y-z		
Range	50 N	
Resolution	2.5 N	
Accuracy	4.0 N	
F/T Sensor - Torque, x-y-z		
Range	10 Nm	
Resolution	0.04 Nm	
Accuracy	0.30 Nm	

Specification

Payload	5 kg / 11 lbs
Reach	850 mm / 33.5 in
Degrees of freedom	6 rotating joints DOF
Programming	Polyscope graphical user interface on 12 inch touchscreen with mounting

Movement

Pose Repeatability	+/- 0.03 mm, with payload, per ISO 9283	
Axis movement robot arm	Working range	Maximum speed
Base	± 360°	± 180°/s
Shoulder	± 360°	± 180°/s
Elbow	± 360°	± 180°/s
Wrist 1	± 360°	± 180°/s
Wrist 2	± 360°	± 180°/s
Wrist 3	± 360°	± 180°/s
Typical TCP speed		1 m/s / 39.4 in/s

Features

IP classification	IP54
ISO Class Cleanroom	6
Noise	Less than 65 dB(A)
Robot mounting	Any Orientation
I/O ports	Digital in 2 Digital out 2 Analog in 2 Tool communication RS-485
I/O power supply in tool	12V/24V 600mA continuous, 2A peak
Ambient temperature range	0-50°C*
Humidity	90%RH (non-condensing)

Physical

Footprint	Ø 149 mm
Materials	Aluminium, Plastic, Steel
Tool (end-effector) connector type	M8 | M8 8-pin
Cable length robot arm	6 m / 236 in
Weight including cable	20.6 kg / 45.4 lbs

* The robot can work in a temperature range of 0-50°C. At high continuous joint speeds the maximum allowed ambient temperature is reduced.

Control box

Features

IP classification	IP44
ISO Class Cleanroom	6
Ambient temperature range	0-50°
I/O ports	Digital in 16 Digital out 16 Analog in 2 Analog out 2 500 Hz control, 4 separated high speed quadrature digital inputs
I/O power supply	24V 2A
Communication	Control frequency: 500 Hz ModbusTCP: 500 Hz signal frequency ProfiNet and EthernetIP: 500 Hz signal frequency USB ports: 1 USB 2.0, 1 USB 3.0
Power source	100-240VAC, 47-440Hz
Humidity	90%RH (non-condensing)

Physical

Control box size (WxHxD)	475 mm x 423 mm x 268 mm 18.7 in x 16.7 in x 10.6 in
Weight	Max 13.6 kg / 30.0 lbs
Materials	Steel

Teach pendant

Features

IP classification	IP54
Humidity	90%RH (non-condensing)
Display resolution	1280 x 800 pixels

Physical

Materials	Plastic
Weight including 1 m of TP cable	1.6 kg / 3.5 lbs
Cable length	4.5 m / 177.17 in

UNIVERSAL ROBOTS

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