The Patching of Built Ornamental Heritage using Digital Fabrication

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24-06-2016

Abstract

The purpose of this research is to explore the role of LIDAR Technology and Digital Fabrication techniques in the field of architectural conservation, particularly for the patching of ornamental heritage. The information is compiled in the form of a guide. Information gathered via the aid of experiments and subsequent observations is also recorded. These experiments were performed using various professional 3D scanning, digital fabrication, and traditional mold making techniques for the transference of geometry. The case recorded in detail is the patching of a mechanically damaged Belgian Blue Limestone column fragment. Another aspect of the research is to explore the use of various mesh generation and manipulation methods. This information can then be used by conservationists to aid in conservation efforts when traditional methods are either not sufficient or not feasible, thereby exploring the role of the 'Neo-craftsperson' in the digital age. To gather subjective insight on the topic, professional conservationists were also interviewed and all opinions are recorded.

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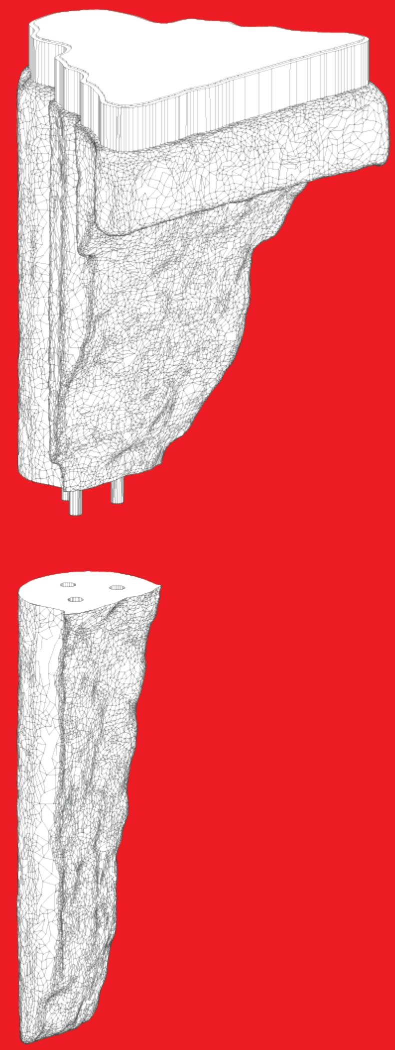

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Acknowledgements

This graduation project would not have been possible without the support of my family, the constant ear and help of my friends Chris and Robert. My mentors, Frank, Marcel and Rob ensured that I remained grounded during the course of my research and helped me explore avenues I would have otherwise ignored. I would also like to thank Boreas and Wido, who laid the foundations of my project. The Greek duo, Telesilla and Faidra helped me when I had no one else to turn to, this is their project as much as mine. Finally, I would like to thank Bilbo for keeping me sane through the course of the last year.

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1. INTRODUCTION

Built Heritage, Palmyra, Craftsmen & The Digital Revolution

Figure 1. Temple of Bel, Palmyra. *Source: James Gordon*

One of the pressing epidemics of our time is the continual degradation of humanity's built heritage, especially in inaccessible regions often affected by conflict (Hanna, Tawfeeq, & Mackay, 2015). Built heritage is an extension of humanity's collective cultural heritage (Tweed & Sutherland, 2007) and therefore has an inherent value that cannot be recreated irrespective of technological progress. Its value is derived from either historical context, chronological significance or the sheer quality of the craftsmanship. The ongoing conflict in Syria and the consequential destruction of Palmyra - a Neolithic city in the district of Tadmor - are an example of how built heritage is being systematically destroyed, often irreversibly (Hanna et al., 2015). The city developed its heritage over a period of centuries, and of course none of the original craftsmen survive, but there is yet some hope.

A number of factors contributed to the initiation of this graduation project. These include a research lacuna in the use of digital fabrication technology in the field of architectural conservation, particularly in the restoration of ornaments by replacing fragments (regeneration is well documented), a dearth of specialised craftsmen (Bourdieu, 2013) and restrictive craftsmanship labour costs, as well as a proliferation and popularization of digital fabrication techniques amongst the professional and general populations.

Another more personal contributing factor is an imminent threat to Chauburji in the author's hometown of Lahore. Chauburji is a 17th Century Mughal monument near the Walled City being threatened by infrastructure projects being carried out in its immediate vicinity by the provincial government against local conservation regulations. Such events confirm how fragile the state of humanity's built heritage is and how quickly it can irreversibly disappear under certain circumstances.

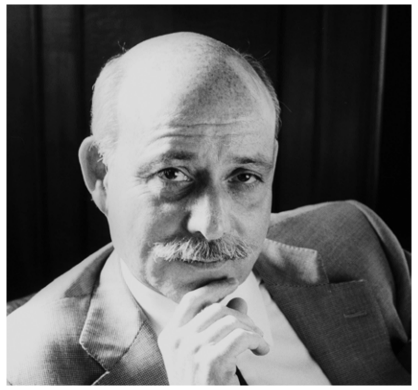
On October 2015, Creative Commons,

Figure 2. Regenerated 3D model of Temple of Bel. *Source: New Palmyra*

Figure 3. Impression of regenerated gate in London *Source: Institute of Digital Archaeology*

a non-profit organization that provides an online repository of license-free creative content, started another repository called 'New Palmyra', which stores the 3D models of Palmyra generated by jailed activist Bassel Khartabil (Busta, 2015). The eventual goal of the repository is to digitally regenerate the entire city of Palmyra with the help of the global community. An example from the repository is the Temple of Baalshamin, pictured in Figure 1, with the regenerated 3D model pictured in Figure 2. This event signifies one of the many ways in which technology is being bridged with the field of architectural conservation, a combination of the new with the old for the preservation of humanity's heritage.

Another example that indicates the proliferation of this idea are the Institute of Digital Archaeology's plans of building replicas of the entrance arch to the temple in Trafalgar Square, London and Times Square, New York City. The project therefore becomes both a venture into the age of the internet of things, as well as an act of resistance. An early representation of the project can be seen in Figure 3. In a similar vein, New York based Rhizome has created an online repository of stl and obj (3D file formats) files for the purposes of disseminating them amongst the public for 3D Printing. The artists describe the goal of the project in the following words, '...we see a call for artists and activists to imagine 3D printing as a radical, political tool for reshaping matter and its digital destiny.' These events coupled with the convenience and personalization that Digital Fabrication technologies promise to provide are pushing it gradually towards mass adoption.



The energy saved at every step of the digital manufacturing process, from reduction in materials used, to less energy expended in making the product, when applied across the global economy, adds up to a qualitative increase in energy efficiency beyond anything imaginable in the First and Second Industrial Revolutions. - Jeremy Rifkin

Figure 4. Digitally Fabricated Restoration of Tympanum Maquette. Source: CIMS Lab

1.1 THE DIGITAL AGE

The aforementioned events are occurring at a time when the world is going through a digital revolution, a 'third industrial revolution' economy is on the brink of emergence. This relates to the fact that physical products are now not only limited to the physical realm but are also available digitally in the form of schematics that can be read by computers, which in turn can provide instructions to machines that can then manufacture the product.

slicing the elements into multiple components. These new 'parts' are often representations of the original form of the design, with the smoothing caused by weather and other stimuli reversed, producing a stark contrast between the old and the new. A domestic iteration of such machines is in the field of additive manufacturing (amongst others), in the form of 3D Printers which are becoming increasingly prevalent, giving the consumer the ability to mass customize their goods. The project aims to not only make use of the digital realm but also

Figure 5. Digitally assisted stone carving. Source: CIMS Lab

A more interventionist approach in which technology is used within the conservation community is through a combination of 3D Scanning and Digital Fabrication. This collection of techniques is gradually gaining popularity within the architectural conservation community, particularly in the use of CNC milling techniques for the recreation of relief elements. The prevalent modus operandi involve replacing entire elements by regenerating the craftsmanship using milling techniques.

Other methods involve 'repairing' the most damaged parts of the elements by

combine it with appropriate technologies to help restore instances of built heritage. The digital realm can thus provide access to the collective expertise of the world's restorers since it removes physical constraints. There is of course, rarely a universal solution for every case but rather specialized or hybridized solutions that are a result of adapting to the specificities and peculiarities of each case. These solutions can range from additive manufacturing to multi-axis milling or a hybridized form of both, depending on the parameters set by the constraints of the case.

1.2 REDEFINING CRAFTSMANSHIP

American curator Richard F. Bach wrote a critique of craftsmanship for the American Magazine of Art in 1922 which is as relevant today as it was at the time.

Written immediately after the aftermath of the Second Industrial Revolution, in the article he argues against the perception that the increasing adoption of tools and machines for production were a threat to craftsmanship and would contribute to a lower quality of products in the long run. He criticizes a popular assumption that a craftsman should work primarily 'by hand' perhaps with the aid of simple hand-held tools. He gives the example of a contemporary potter who would use motorized tools to expedite the job, something that takes nothing away from the quality of the product and the potters are no less craftsmen for trying to improve the craft that they inherited. He declares that craftsmanship, like all other things, improves by competition, so technologies like steam and electricity should not be barred. He suggests that instead of demonizing the machine and regarding it as an enemy of the hand, craftsmen, like modern manufacturers, should 'profit from the resources of science and invention' (which he suggests are part of the ideals of craftsmanship). He goes on to assert that "There *is* a craftsmanship of the machine, there is a craftsman feeling in the factory." (Bach, 1922)

The fundamental point that Bach was trying to make was that if craftsmen have conceded to using tools anyway, why stop there? Why should the scale and type of tool make a difference?

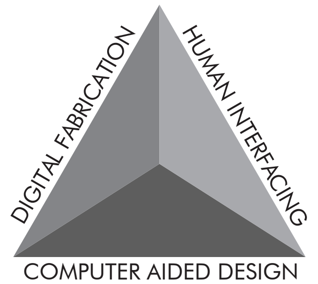
Whilst Bach was talking about craftsmanship in the context of manufacturing and not architectural restoration, the principle remains the same: if the same end result can be achieved with minimal time and effort via the aid of technology, then traditional craftsmanship is reduced to a matter of mere sentiment.

Figure 6. Stonemason using hand tools Source: PolandPoland

Figure 7. An architecture student interfacing with a computer. Source: Author

It can be postulated that in the context of the digital age, a person operating digital fabrication machinery or manipulating digital meshes on their computer could be considered a type of 'neo-craftsman' or 'neo-craftsperson'. The fundamental principal being the same: the use of one's hands to interact with a tool that aids in one's craft.

This redefinition of craftsmanship can be summarized as a triangle. The neo-craftsman's triangle consists of the three technological requirements that enable the physical realisation of digital designs.



In certain cases however, resorting to tradition can be an essential component of the authenticity of a project, depending upon the amount of sensitivity required for the intervention. In the case of architectural restoration, the digital craftsman is only emulating the work of an earlier master, producing new projects directly with the aid of digital fabrication may not result in works with the same sensitivity that the human hand provides, although that is just mere conjecture.

Nevertheless, traditional craftsmanship seems to be in decline, from reasons varying from cost of living to the proliferation of other more lucrative fields. This aspect is further discussed in the Problem Statement section of this chapter.

Taking into account all these aspects with regards to craftsmanship, this project will explore comparing digital fabrication tools with older techniques to determine if the definition of craftsmanship needs to be re-evaluated.

1.3 OBJECTIVE

The paper aims to give insight into the relevance of the project with respect to architectural conservation, to give a general understanding of 3D scanning and scanners, Digital Fabrication techniques, which include additive manufacturing techniques like 3D printing, subtractive manufacturing techniques like Computer Numerical Control Milling as well as laser cutting. Furthermore, the software tools required to 'interpolate' the geometry to be printed will also be covered. In this context, interpolation refers to the prediction of missing geometry using existing evidence, either documented or via evidence on site (if the damaged elements are part of a series of repeating elements).

Ideally, conjecture would be avoided and the interpolation would be kept as accurate as possible. Informed by the literature review, a streamlined work-flow will be created, that consists of the identification of a suitable candidate for the restoration process, the establishment of the criteria for the selection of the most applicable technology, the selection of the technology or technologies, the scanning of the existing geometry, the validation of the digital data, the manufacturing of the geometry and eventually, the on-site installation.

This work-flow will be tested with the help of on-site experiments (a damaged structure will be scanned and repaired) and the conclusion of the experiments will be added to the existing literature, eventually leading to a manual for conservationists.

1.4 PROBLEM STATEMENT

With the increasing prevalence of technology comes a higher standard of living which consequently increases the cost of human labour. It is a fact that skilled craftsmen are rare in the 21st Century, especially specialists in the materials and techniques that might be required for the restoration of built heritage (Bourdieu, 2013). An advantage that technology can also provide however is that the need for skilled craftsmen, essential for certain kinds of conservation efforts, can be negated, bringing down costs. Secondly, conservation efforts are very time intensive, with the ongoing restoration of the Parthenon currently in its 40th year with an estimated end date of 2020 ("Acropolis on course," 2005). During these efforts the monuments are usually covered with scaffolding or kept out of the public domain, disconnecting the population with their history.

With technology, the time spent on site can be reduced, since 3D Scanning is less time intensive than traditional surveying techniques and machines can work day and night without a break.

3D scanning is currently being extensively used in the field of art, notably the digitization of Matisse sculptures in 2002-2007 for virtual comparison, something that would have taken many tools, calipers and surveyors before the advent of 3D scanning technology (Wachowiak & Karas, 2009). With the use of additive manufacturing technology for instance, it is also possible to create hollow or optimized objects with internal lattices, something that is not possible by traditional carving techniques, making the objects lighter while retaining most of their strength.

1.5 GOAL

The goal of this project is to improve upon the tool-sets available to conservationists by making use of the latest technology, thereby combining the old with the new. There is ample research in the fields of 3D scanning and Digital Fabrication, as well as the application of the combination these technologies in the regeneration of art and even bionics.

This project can provide insight into how technology can be introduced into the field of architectural conservation which has traditionally been resistant to new technology. It will also give insight into the role of the craftsman and the relevance of craftsmanship in the digital world.

1.6 RESEARCH QUESTION & SUB-QUESTIONS

'What are the influencing factors in the use and selection of LIDAR and Digital Fabrication for the patching of ornamental heritage? '

The main research question gives rise to certain related sub-questions, such as:

i. Is digital fabrication for patching applications more economical than traditional techniques?

Note: This entails the cost comparison of newer techniques with the techniques used traditionally by craftsmen.

ii. What are the possibilities of hybridization of techniques (combination with traditional methods) for patching with Digital Fabrication?

iii. Is the use of Digital Fabrication for patching advantageous for reversibility?

iv. Can a person without traditional craftsmanship experience achieve usable results with Digital Fabrication?

v. What is the role of the craftsman in Digital Manipulation and Digital Fabrication? (Subjective)

vi. What is the role of the craftsman in Digital Manipulation and Digital Fabrication? (Subjective)

vi. What are the primary limiting factors when patching using LIDAR and Digital Fabrication technologies as they are today?

vii. What kind of role does software play in the patching via digital fabrication process?

The answers to these questions and the conclusions can be found on Page 81 in the conclusions section.

1.7 METHODOLOGY

The crux of the research topic is fragmented into different sections: scanning, interpolation and fabrication. In order to find the optimum methods for the scanning and printing aspects of the restoration, quantitative data has to be derived via experimentation.

The data would then be compared and sorted and finally, deductions would be derived. For the interpolation of the missing geometry however, the nature of the research is partly exploratory as opposed to empirical, due to the highly subjective nature of conservation theory, which comprises a spectrum of varying schools of thought. Conversely, the technical aspects of the interpolation (the use of software, the detection of errors etc.) would be quantitative.

As depicted in the diagram, the Knowledge Base of the project is informed by the subjective aspects of professional opinions (via interviews with architectural conservationists and craftsmen), the literature review and the results of the experiments. The literature review and experimentation both inform each other (the results of the experiments may reinforce or contradict existing literature). The case studies inform both the literature review and vice versa (via discovery of new cases from existing literature. New cases can also be discovered by means of field research, or discovered cases via the literature may lead to other discoveries that reinforce the field research in turn. The field research helps locate ideal candidates (site selection) for documentation and experimentation. Finally, the test candidates (the selected candidates for experimentation) are determined via a combination of the available applicable hardware and the complete list of candidates discovered.

The final products of the research would then be the final report containing the literature review, interviews, the selected candidates, the documentation of the experimentation and the final manufactured products.

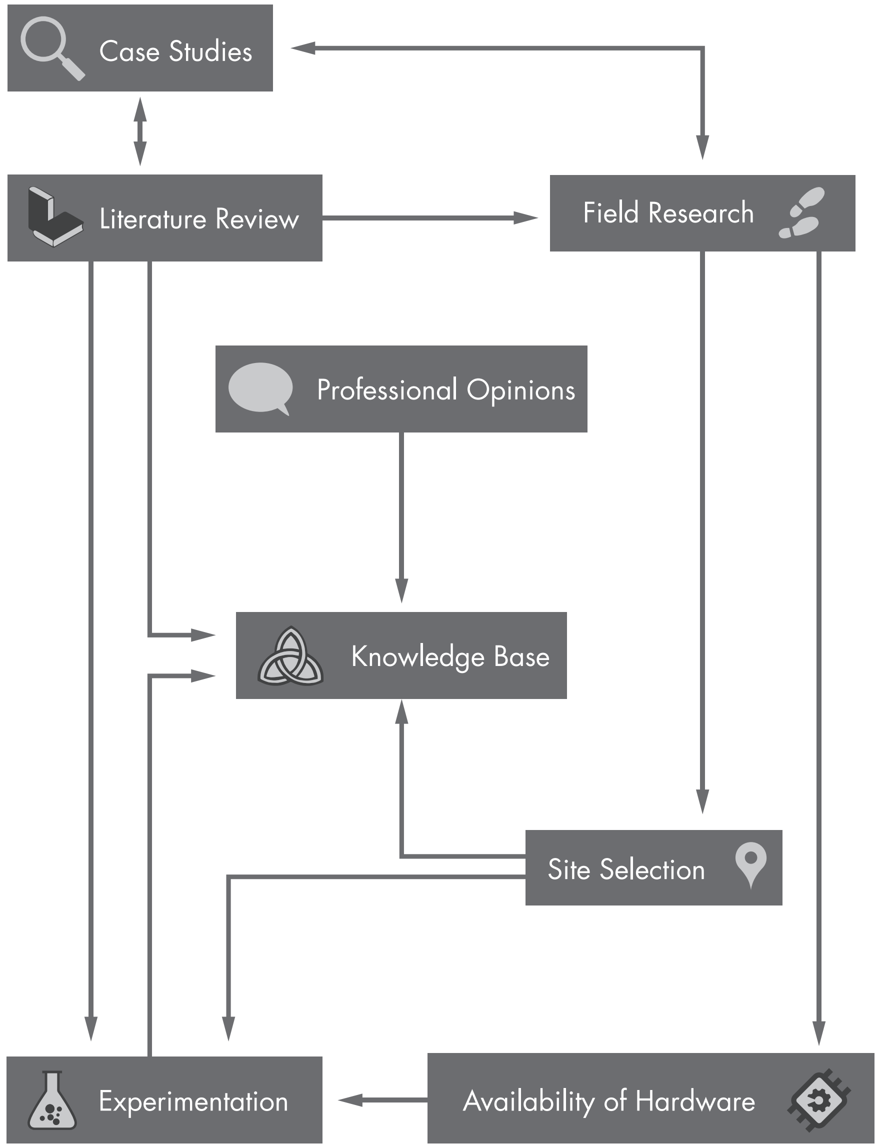


Figure 8. Structure of Research. Source: Author

1.8 SCOPE & CONSTRAINTS

The limitations of the technology and the availability of some equipment will be the most significant constraint. Particularly concrete 3D printing or printing any material that tries to emulate stone, as well as other non-polymer materials. Their resolution and strength in particular, at least in the mainstream, is considerably lower than current polymer printing technologies. The limitations of milling technologies like the size of the component or drill bit may also be a factor.

3D scanning technology whilst still under development, is comparatively advanced and can provide quite usable resolutions.

An issue that may rise however is the portability of the scanning equipment, the laser scanners in particular, which are professional grade and can weigh up to 30 Kg. They also need to be mounted and transported with care and professional supervision is often required. Cameras for photogrammetry however don't face these issues as they are lighter and relatively inexpensive but can produce considerably lower quality results in non-ideal conditions.

2. CONTEXTUALIZING DIGITAL FABRICATION AND CONSERVATION

Bernard Feilden, Authenticity, Degrees of Intervention and Relevance

Restoration is a constituent of architectural conservation, which also encompasses preservation, reconstruction and rehabilitation. All of the aforementioned approaches are dependent upon the charter being followed by the conservationists or their personal reflection on conservation. There is a fundamental difference between approaches to restoration world-wide, the most prominent being the difference between Eastern and Western approaches.

In Japan for example, most of the construction is wood based, making the life cycles of buildings considerably shorter than their Western stone and brick based counterparts. This difference affects the way they approach restoration. More importance is given to restoring a building to its original state as the original craftsman intended, discounting the numerous additions or attempted restorations that have been performed on it over the centuries (Larsen, 1996). This is contradictory to the Western approach, which attaches importance to all the subsequent modifications to the structure and form of a building. Because the Japanese pay homage to the original craftsmen of their built heritage, they retain the techniques and materials originally used, making the use of technology incompatible with their restoration philosophy and perhaps also incompatible with this graduation project.

Nonetheless, the definition of authenticity in restoration remains subjective, with there being no equivalent word in the Japanese language (Larsen, 1996).

There is however an aspect of restoration in Japan that is compatible with this project, the idea of *Kintsugi* (repairing with gold), primarily followed for the restoration of broken ceramic pottery. The idea being to emphasize the breakage as a stage in the life of the vessel by

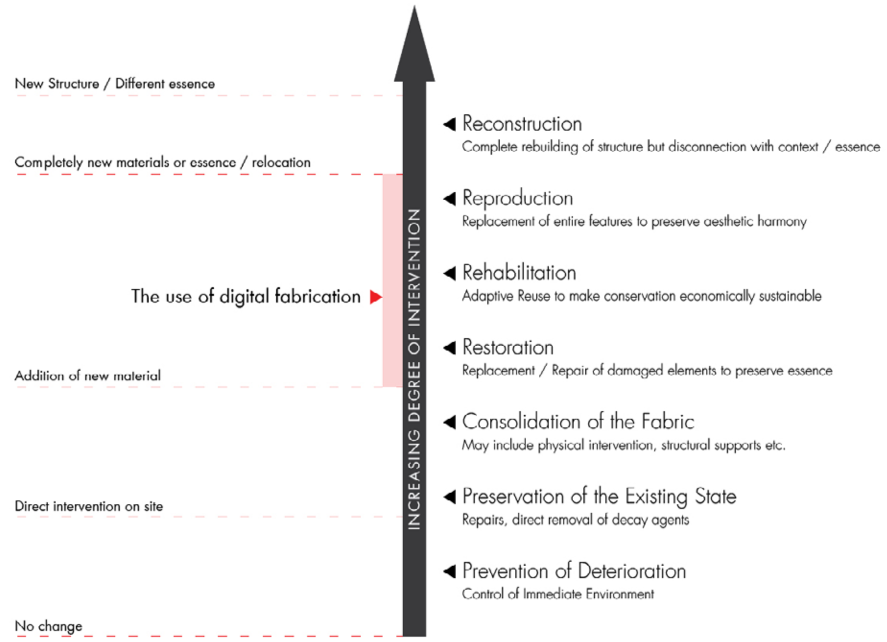


Figure 9. Degrees of Intervention. Source: Author

repairing it using a lacquer infused with gold, silver or another precious metal.

Figure 10. A Japanese cup repaired with Kintsugi. Source: thisiscolossal

This approach is compatible with some Western ideas of restoration since it accentuates the contrast between the old and the new, to appreciate the life lived by an object (or a building).

Having considered the stark differences in restoration theory from region to region (also the subtle differences within regions), comparison with the Western model of restoration would be more applicable to this project, especially since it incorporates the use of technology.

2.1 DEGREES OF INTERVENTION

(ACCORDING TO BERNARD FEILDEN)

According to British conservation architect Sir Bernard Feilden (whose works include the conservation of the Taj Mahal and Great Wall of China), architectural conservation encompasses a spectrum of seven degrees of intervention: '(1) prevention of deterioration; (2) preservation of the existing state; (3) consolidation of the fabric; (4) restoration; (5) rehabilitation; (6) reproduction; and (7) reconstruction' (Feilden, 2008).

Figure contextualizes Digital Fabrication with respect to the discussed degrees of intervention. The figure helps clarify that Digital Fabrication functions independent of these different degrees of intervention and is rather a tool that can be used by conservationists for any appropriate degree of intervention but primarily when additional material is required. Since Digital Fabrication involves a group of techniques, it can be applied to aid various types of conversation efforts which can range from preservation to reconstruction. Feilden's definitions of these degrees of intervention are summarized with their relation to Digital Fabrication in the following sections.

2.1.2 Prevention of Deterioration

This is the least intrusive degree of intervention and it involves controlling the immediate environment of the built heritage and thereby slowing decay and damage. According to Feilden, such procedures include but are not limited to: control of humidity, temperature and light and also measures to prevent damage from human intervention, like fire, arson, theft and vandalism. Deterioration can also be prevented by reducing air pollution in the general area and relocating traffic, thus preventing damage from vibrations. Such measures can be enforced by regular inspection and general cleaning of the site. Digital Fabrication becomes relevant at a higher level of intervention since it involves direct manipulation of the site and therefore its potentials lie higher on the spectrum.

2.1.3 Preservation

In preserving an example of built heritage, a direct intervention has to be made to the structure since preservation involves keeping the site in its existing state and preventing further deterioration. This can involve repairs that are necessary to prevent the site from decaying further and reducing the damage caused by the flow of water, chemical agents and different types of pests and micro-organisms. Since no new geometry is being generated, Digital Fabrication does not have many potential uses at this level of intervention.

2.1.4 Consolidation

Also known as 'direct conservation', consolidation necessitates the physical modification of the fabric of the built heritage with the introduction of

Figure 11. Restoration of the Parthenon. Source: drtana (Flickr)

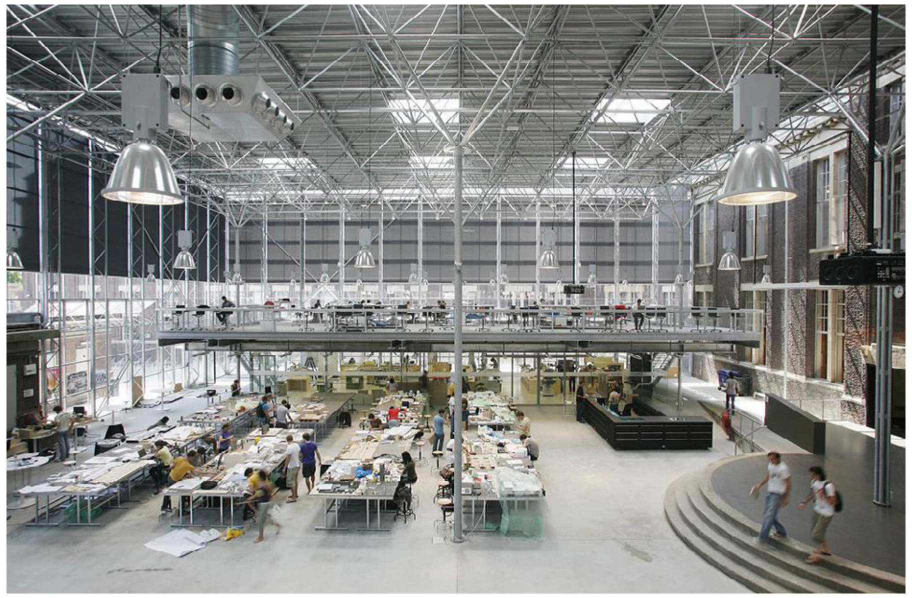


Figure 12. TU Delft Bouwkunde Model Room. Source: Eekhout Bouw

adhesives and structural supports in order to ensure the continued structural integrity of the construction. According to Feilden, consolidation should only be carried out if the structural elements have reached the limit of their structural integrity and can no longer face future hazards without failing. Feilden encourages the use of traditional methods to achieve these changes but where such methods are inadequate, appropriate modern techniques can be used, provided that they are temporary or reversible.

Keeping this in mind, Digital Fabrication should primarily be used for the regeneration of geometries that cannot be easily generated via traditional techniques, such as complex geometries that involve intricate craftsmanship. While it may still be possible to create such geometries, time constraints and economic viability can make Digital Fabrication the more feasible choice. Consolidation also lies within the Digital Fabrication framework since the involved technologies can be used to generate minimal intervention structural supports, particularly those requiring a certain degree of craftsmanship.

2.1.5 Restoration

According to Feilden, the core idea behind restoration is to revive the original concept or legibility of the historical site. Such an intervention can involve the replacement of damaged parts, the regeneration of decorative elements, as well as cleaning of the structure. All such interventions have to be made according to archaeological evidence and with proper respect of the original design and material according to Feilden. He goes on to say that while regenerated parts should integrate harmoniously with the structure, they should be easily distinguishable from the original material so that historical evidence is not falsified. Furthermore, he says that additions from all periods should be respected since any contribution can be considered a 'historical document' that needs to be preserved.

Restoration also includes 'anastylosis' or the restoration of a site by the rearranging of the original materials/structures on the basis of archaeological evidence. Feilden warns that if taken too far, such a technique can make the site 'look like a film set' and 'devalue the message of the site'. While anastylosis is not directly relevant to Digital Fabrication since it does not involve the generation of new geometry, other aspects of restoration, replacement of damaged components for example, can easily potentiate its use.

2.1.6 Rehabilitation

Adaptive reuse is a way of making conservation efforts more economically feasible. In this way, a historic site can retain its use or can house another function which in turn generate revenue which can be used in the maintenance of the site. An example of this can be the Architecture Faculty at TU Delft (BK City) in the Netherlands (pictured in Figure 12), the construction of which began in 1917 for use as a chemistry building, later becoming the main administrative building in 1948 ("The building: 'BK City',"). The building was transformed into a modern campus in 2008 after the original architecture building burned down (Rob van Hees, 2014). With the use of Digital Fabrication, it can be possible to introduce more durable materials to withstand the pressures of everyday use while maintaining the materiality of the original material and creating contrast.

Figure 13. Replica of David. Source: Wikipedia

2.1.7 Reproduction

This entails the recreation of extant artefacts that have been lost but their archaeological evidence remains. In many cases, damaged or decaying parts can also be reproduced and replaced. According to Feilden, the end goal is to retain the aesthetic harmony of the site. Another example can be the complete reproduction of an artefact to replace the original, if it needs to be protected from the elements. Feilden gives the example of Michelangelo's 'David' (Figure 13) which was removed from Piazza della Signoria, Florence to protect it from the weather and replaced with a replica. Digital Fabrication can aid this process by making the scanning and reproduction of elements faster and easier with the use of 3D-Scanning and additive manufacturing technology amongst others.

2.1.8 Reconstruction

The final degree of intervention in conservation, as defined by Feilden, reconstruction necessitates the use of completely new materials to replace an entire historic site that has been damaged by natural or man-made disasters. Such interventions according to Feilden, consequently do not have the patina of age but they must nevertheless be based on archaeological evidence and never conjecture. Feilden also classifies the moving of entire sites as reconstruction as such an action disconnects the site from its original context and therefore affects its cultural significance, something that conservationists always try to retain. While Digital Fabrication can easily aid in such a process, it goes out of the domain of this research since it primarily focuses on the repairing of existing geometry whilst trying to remain within the extents of conventional conservation values.

2.2 RELEVANCE

In the context of Digital Fabrication, the idea of restoration would not follow the strict definitions imposed by conservationists at this time since due to the constraints of current additive manufacturing technology, it would not be possible to truthfully recreate the geometry using the original materials. It is possible however to emulate their 'materiality' by selecting a printing material that has similar properties to the original.

An example of truthfulness in the selection of materials can be seem in the acquisition of the new marble for the reconstruction of the Parthenon, which was mined from the same quarry as the original marble, the Pentelicon quarry (Binns, 1984). While modern techniques may not be as truthful as the aforementioned, it can become the best choice when either economic constraints or the unavailability of skilled craftsmen render traditional techniques infeasible. The selection then becomes a matter of sentiment versus economy and time.

3. CASE STUDY – ANNIE PFEIFFER CHAPEL

3D Printing, Textile Tiles & Molds

The Annie Pfeiffer Chapel in Florida Southern College, Lakeland, Florida, USA is a structure designed by architect Frank Lloyd Wright and completed in 1941. It is part of a group of buildings designed by Wright, collectively known as the 'Child of the Sun'. Damage to the building has been caused by hurricanes, previous restoration attempts and daily wear and tear.

The restoration work was initiated by Mesick Cohen Wilson Baker Architects with the final phase of the restoration work due to finish by July 2015 (MCWB, 2014).

Figure 14. The Annie Pfeiffer Chapel (South West Corner) Source: Florida Southern (Flickr)

3.1 RESTORATION

The primary candidates for restoration using additive manufacturing were the 'textile' style concrete tiles that line the facade of the building. The use of additive manufacturing/3d -printing was key since the old hand-crafted molds had since been lost (MCWB, 2014).

MCWB chose to use 3d-printed Teflon in combination with wood to recreate the molds without the need for expensive and rare craftsmanship that would traditionally be required, minimizing costs and time consumed. It was not specified why the blocks were not directly printed but it can be speculated that this was either because of the unavailability of concrete printers or their current printing resolutions which are prohibitively low for the geometry of the blocks.

Figure 15. Examination of textile tiles. Source: MCWB Architects

3.2 FABRICATION

The use of 3D scanning was not necessary for this process since the original drawings of the tiles were available (Horton, 2014). The negative geometry was subsequently determined by using those drawings and he input for the 3D printers was generated. The entire approach was completely hybridized with the use of some handmade wooden elements and CNC milling technology.

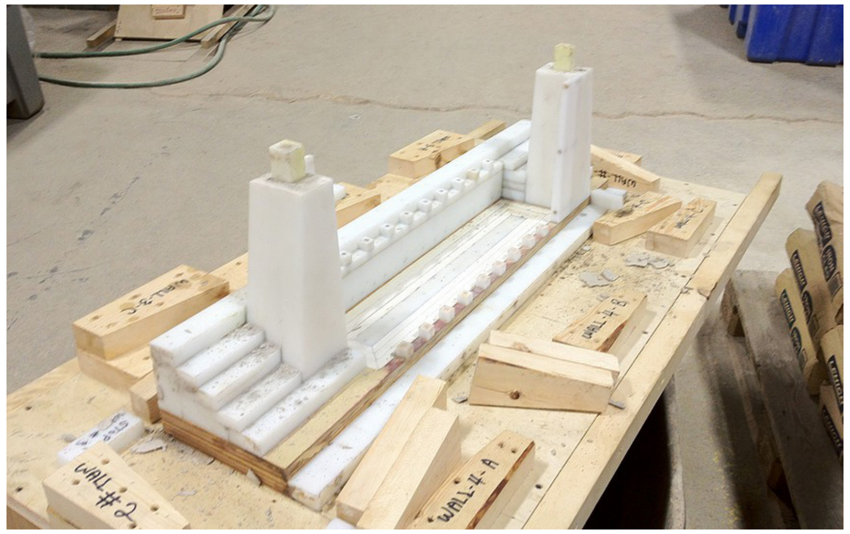


Figure 16. Hybridization of Techniques. Source: MCWB Architects

Architect Jeff Baker, a partner at MCWB reportedly said,

"We tried various printer types, different types of materials, and various software programs—all with seemingly infinite setting options—to determine how to print the parts and get them to release from the molds… it's clear that 3-D printing, combined with CNC machining, will be the way of the future for these and similar molds." (Horton, 2014)

The implication being that with current technology there is no single technology that can entirely cover all aspects of the restoration process but a hybridization of multiple techniques has to be carried out for optimum results.

Since the project does not have any documented papers associated with it, there is no way to determine the constraints and issues involved in the project. Attempts to contact the firm have been in vain. It can be deduced from the comment however, that the issue of designing the molds so that they release the parts smoothly was taken into consideration and that hybridization of the methods (using CNC machining) was important to get the optimum results.

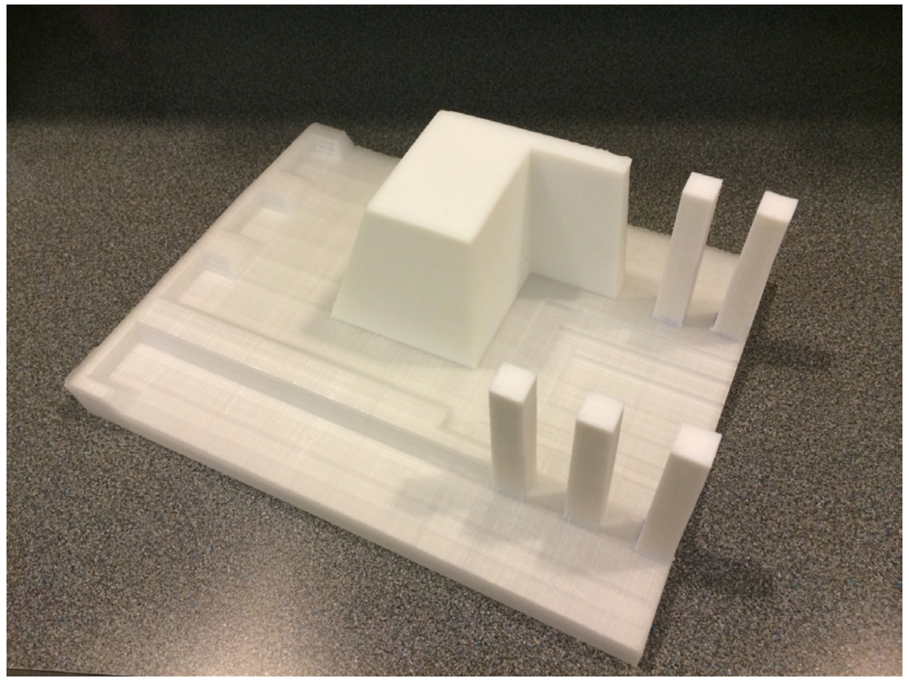


Figure 17. Section of 3D Printed Mold. Source: MCWB Architects

Figure 18. Prototype of manufactured tile. Source: MCWB Architects

4. CASE STUDY – CERAMIC TILE FROM THE GREAT SYNAGOGUE OF TIMISOARA

Ceramic Tiles, 3D Scanning, 3D Printing in Color & Price vs Quality Comparison

This case study documents a series of experiments performed at the Faculty of Architecture, Politechnica University Timisoara, Romania by Gheorghiu and Andreescu (2015). The chosen object was an ornamental ceramic tile measuring 233 x 233 x 35mm from the main façade of the 'Great Synagogue' built in 1865, from the 'Citadel of Timișoara', a city in modern day Romania.

In the recorded processes, the tile was reproduced multiple times using a variety polymers and not the original ceramic material. It was not specified why the original material was not used but it can be reasoned that it was because of the high cost and limited availability of ceramic printers. The process was performed in three steps, 3D scanning, data processing and 3D printing.

Although the scanned data was also gathered via a 'semi-pro' and a consumer laser scanner but the final data was finally extracted using digital photogrammetry (which was the first choice because of cost and availability) with an overlap of 75% - 80%. Reference markers were attached to the geometry for accurate scaling. It was suggested that a camera rig called 'Linear Motion Central System for Digital Photogrammetric Survey' which consists of a motorized four axis camera mount controlled via a programmable controller could be used to increase the speed and accuracy of the scans. Such a rig was however not available for the scans.

The data processing was done using software packages 'BDModeler' and 'Photoscanner' and the final result was a textured solid. The data validation steps included checking the scale and wall thicknesses of the model, the polygon count, the file format, the orientation of the normals and the manifoldness of the model. For the final step, four different printing technologies were used, FDM (using PLA), SLS (using Nylon 12), Project (using power infiltrate and CMYK binders) and Polyjet (using polymerized vero white plus).

It was determined that the Polyjet method was superior in both quality and in terms of price (122.50 EUR) whilst standard FDM printing provided a cheap (6-8 EUR) but low quality solution. The objective of the research was just the successful replication of the title and not the installation. It was also suggested that FDM using PLA could also be used successfully if post-processed with paint or plaster.

Figure 19. Scanning of tile via Photogrammetry. Source: Adrian Gheorghiu

Figure 20. Closeup of Tile. Source: Adrian Gheorghiu

Figure 21. Pro-jet Printing Result. Source: Adrian Gheorghiu

Figure 22. SLS Printing Result. Source: Adrian Gheorghiu

Figure 23. FDM Printing Result (PLA). Source: Adrian Gheorghiu

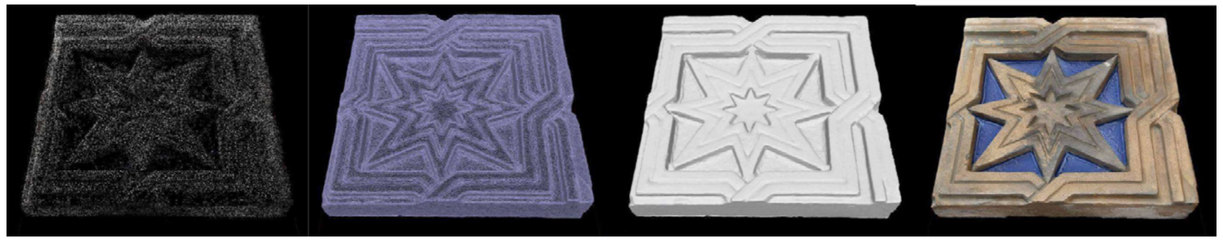


Figure 24. Levels of Data Processing (from point cloud to mesh). Source: Adrian Gheorghiu

5. EQUIVALENT TRADITIONAL METHODS

Repairing Techniques, Dutchman, Mortar Patching, Pantographs

5.1 DUTCHMAN REPAIR METHOD (INDENTING)

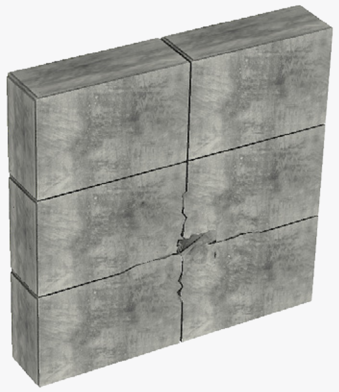
The Dutchman repair method is employed when a material is only partially damaged and the entire unit material does not need to be replaced.

This method is not limited to material type and the restoration possibilities range from masonry to woodworking.

Such repairs, particularly for stone repairs are generally secured using epoxy and stainless steel bolts for a secure fit ("Dutchman Repair," 2011). The general process for such a repair for stone is illustrated in the adjacent figures.

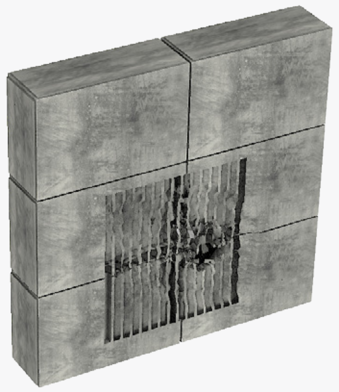
Figure 25. Dutchman Repair of column capital. Source: Schnell Contractors

GENERAL DUTCHMAN REPAIR



Step 1

Identifying candidates for Dutchman repair, generally with patches of concentrated damage.

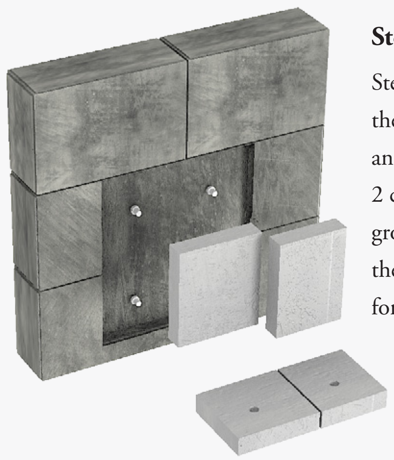


Step 2

Relief cuts are added to the selected area (preferably with a diamond saw) to ease removal of material.

Step 3

The material is then carefully removed with a chisel (preferably pneumatic).



Step 4

Steel rods are drilled into the exposed surface with an exposure of at least 2 cm, complementary grooves are drilled into the replacement pieces for proper binding.

Step 5

The stone is first dry-fitted to ensure uniform fitting. Then it is fitted either using a natural bond mixture (hydraulic lime) or epoxy. The joints can then be pointed in using mortar and left to cure.

5.1.1 Stone Fluted Column

This restoration carried out by the US based Tradesmen Group made use of the Dutchman method for the restoration of Grey Berea sandstone fluted columns on the east and west elevations of a courthouse building in Toledo, Ohio.

The carvings were performed off-site using detailed reference drawings and then installed with the aid of stainless steel bolts and epoxy for a secure fit.

The resulting repair has a contrast which may gradually decrease over as the new material gains patina and general wear and tear.

Figure 26. Fluted column repair (patch). Source: The Tradesmen Group

5.1.2 Stone Ionic Capital

Performed by the Canadian Atlantic Sandstone company, this Dutchman restoration was done on a section of an Ionic capital on a customs building in New Brunswick, Canada. The carving was performed in-situ using the existing ornament as a reference. It was finally attached using three steel pins and epoxy.

Figure 27. Dutchman Capital Repair. Source: Fundy Stonecraft

5.1.3 Stone Corner Repair

This restoration was performed by US based Treanor Architects and was posted on their blog. It documents the replacement of a weathered stone corner. There were no installation details provided but one of the noticeable aspects of the repair include almost negligible contrast between the old and the new material and the replication of the relief pattern on the stone.

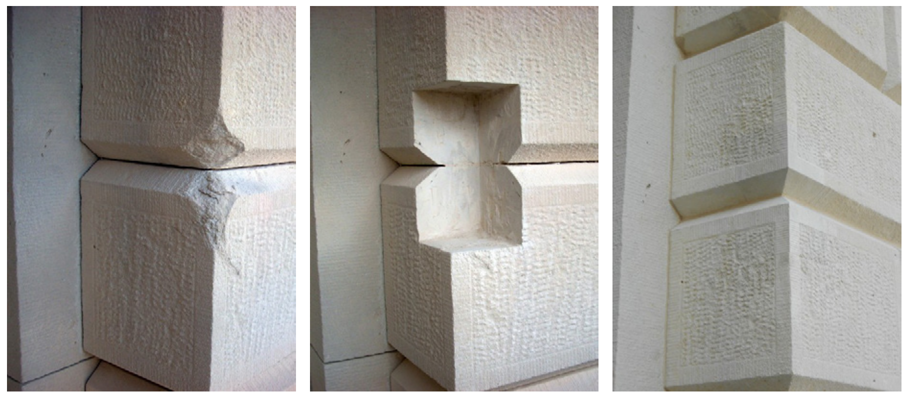


Figure 28. Corner repair. Source: Treanor Architects

5.1.4 Fluted Column (Wooden)

This domestic restoration uploaded by Youtube use 'cunnifjr', used an intuitive way of repairing the fluting on a wooden porch column by fitting blocks of wood using the Dutchman method into the damaged sections and then routing the fluting in-situ using a router bit of the same radius.

Figure 29. Fluted Wood Column Repair. Source: cunnifjr (Youtube)

5.2 STONE PANTOGRAPHIC INFILLS (ACROPOLIS)

For sensitive restorations where a minimal degree of intervention is required on the existing material, a tool called a stonemason's 'pantograph' can be used to copy the existing geometry. The original form of this tool (which works in two dimensions) has traditionally been used by stonemasons to transfer lettering onto tombstones.

An instance where this technique is being used is in the restoration of the Parthenon in Athens, with the aid of a specially developed three-dimensional stereo-pantograph being used to transfer the fracture geometry from casted gypsum copies of the missing segments (Toganidis, 2007). This new tool has flexible axes, making it easier to access blind spots.

The pantograph has a probe which moves along the surface of the geometry to be replicated, these movements are transferred to another end which then directly carves the same surface on a volume of material. Technically, this tool could also be used directly on site but that may possibly add more logistical challenges. The newly manufactured Pentelic marble pieces have a marked difference in shade from the original material and are installed at an offset from the original material to exaggerate the contrast between the old and the new (Toganidis, 2007. These are subjective aspects however and can vary according to the prevalent ethical guidelines of the time and region.

To connect the old and new marble, titanium clamps were developed for extra security (steel was used traditionally) and bound with white cement.

Perhaps a major disadvantage of using these methods are the immense costs attached and the time required, making them only viable for sensitive restorations like for the Acropolis.

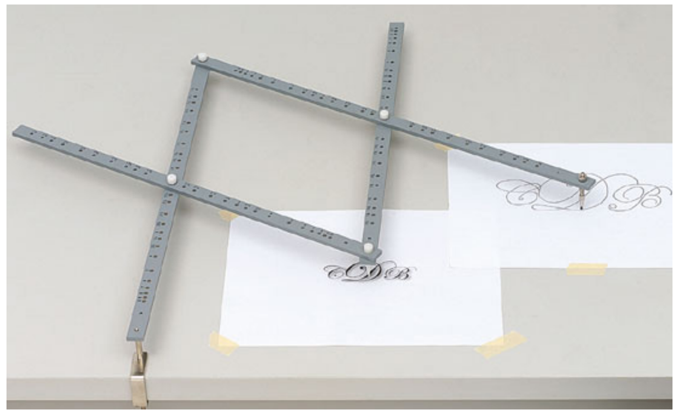


Figure 30. A 2D Pantograph. Source: Dickblick Online Store

Figure 31. Stereo - Pantograph used for the Acropolis restoration. Source: YSMA 2011

Figure 32. Newly carved Pentelic marble being fitted. Source: YSMA, 2011

Figure 33. Contrast between old and new marble with visible offset. Source: IIRPS Athens

Figure 34. Titanium binding rods. Source: M. Ioannidou, ICOMOS

Figure 35. Carved voids for binding rods. Source: IIRPS Athens

5.3 IN-SITU MORTAR PATCHING

When damage is either cosmetic or minimal, and using the same or similar material is not a requirement, in-situ patching can be performed using an appropriate mortar or filler. Such an intervention also reduces costs and time required on site.

In the case of stone, the 'repair mortar' used can vary in composition, ranging from natural options like a mixture of hydraulic lime with sand or aggregates and water. The mixtures can be prepared by the restorer or mason to match the texture and color of the surface to be repaired ("Stone repair & replacement," 2008). Synthetic options are usually manufactured in laboratories with polymers and aggregates, combined with a catalysing agent. These options are lighter than natural mortars and are quick drying. Dyes can be mixed into the mortars to match the color of the existing material if required.

For more complex morphologies like ornaments, such restorations are generally performed by experienced craftsmen using hand tools like trowels and chisels.

Figure 36. Manual Patching. Source: John Speweik

5.3.1 Stone Balustrades

Carried out by Plastic Surgeon Fine Finishers from the UK. Since there was limited time, molds could not be ordered for reshaping. The restoration was therefore performed freehand and in-situ with the aid of a variety of measurement tools.

Figure 37. Balustrade Patching (in-situ). Source: Plastic Surgeon Fine Finishers

5.4 COMPARISON WITH DIGITAL FABRICATION

METHOD	LEVEL OF INTERVENTION (LOWER IS HIGHER)	ECONOMY (LOWER IS MORE EXPENSIVE)	TIME REQUIRED (LOWER IS HIGHER)	LEARNING CURVE (LOWER IS HIGHER)
DUTCHMAN REPAIR	1	2	2	2
PANTOGRAPHIC INFILL	3	1	1	1
MORTAR PATCHING	2	4	4	3
DIGITAL FABRICATION	3	3	3	2

Table 1. Comparison of techniques with digital fabrication

NOTES

The use of pantography for the generation of infills is more expensive, requires more time and skill than all of the other techniques, mainly because of the requirement of specialized pantographs for the purposes of carving stone. It ties with digital fabrication when it comes to level of intervention however since both techniques minimize the modification of the existing fabric and material. Since the use of Digital Fabrication for restoration requires some degree of technical expertise, it can be compared to basic craftsmanship training. It can be argued however that a technically aware person might have less difficulty acquiring those skills as compared to a person not familiar with technology.

6. TECHNOLOGY OVERVIEW

This section covers the scanning and fabrication technologies that may be encountered during the restoration of built heritage.

6.1 SCANNING TECHNOLOGIES

In order to generate the geometry to be printed for restoration, the built heritage structure needs to be scanned. This has two purposes, to record the existing state of the structure for posterity and to aid in the interpolation of the replacement geometry. 3D scanning can be divided into two general categories:

6.1.1 Contact Scanning

This technique involves the use of physical probes that touch the surface of the geometry and thereby generate a point-cloud via which the geometry is generated. They are typically used for geometric shapes and not recommended for organic shapes (Mongeon, 2015). An example of a contact scanning machine is a CMM (Coordinate Measuring Machine), a machine generally used in the manufacturing industry for testing a part or assembly for errors.

Since contact scanning, as the name suggests, involves physical contact with the geometry to be scanned, it is not ideal for the scanning of built heritage as there is a possibility of damage occurring. Further disadvantages include slower operating speed and limited resolution because a finite number of points are measured (3dscanco, 2015). With all these disadvantages taken into account, contact scanning can be ruled out for use with Digital Fabrication.

Figure 38. Probe Head. Source: Wenzel

5.3.2 Non-Contact Scanning

The general principal behind such scanners is the use of radiation or sound waves to determine the distance between a reference point and the surface to be recorded. The radiation can be in the form of light (visible spectrum, including lasers) or x-rays. The sound waves are generally in the ultrasound frequency. The most common methods outside of the medical community however use light, especially for architectural scanning since this method is optimum for use on visible geometry. These scanners are available in many varieties, some of which will be covered in this section.

They are divided into two general types, passive and active, their difference in mechanism is illustrated in Figure.

on the scanner but is only absorbed by it, thereby the scanner only acts passively. These methods tend to be more cost effective since they only require a digital camera to record the reflected light and are also more compact. A few examples of passive techniques include:

1. Photogrammetry

A form of 'remote sensing', the American Society for Photogrammetry and Remote Sensing defines photogrammetry as,

"The art, science and technology of obtaining reliable information about physical objects and environment through processes of recording, measuring and interpreting photographic images and patterns of electromagnetic radiant energy and other phenomena" (ASPRS, 1980)

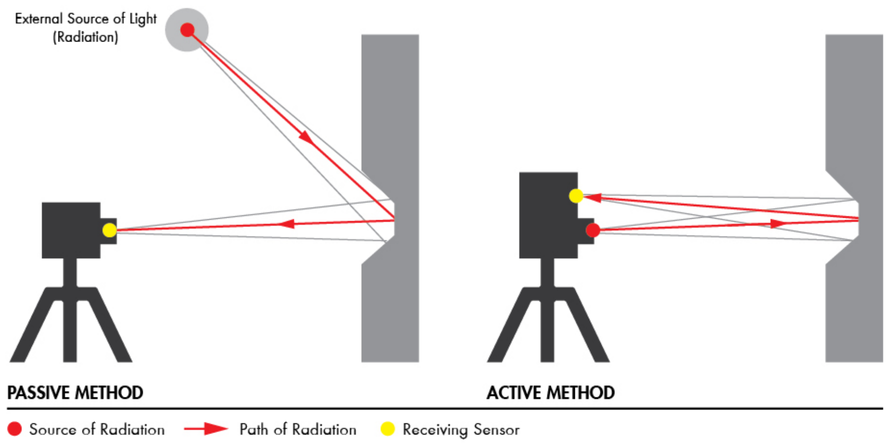


Figure 39. Passive vs Active scanning methods. Source: Author

5.3.2.1 Passive Methods

These scanners are passive because a probe (whether light or sounds) does not actively interact with the surface and instead algorithms are applied to received data to generate new data. The primary difference between passive and active methods is that in the former the radiation (in the form of reflected ambient light, a form of electromagnetic radiation) is not emitted from a source

This method for the purposes of 3D scanning is called stereo-photogrammetry, involves the use of subsequent photographs or other two dimensional images taken from different angles to predict the approximate location of surface points on the scanned object via the use of specialized computer vision algorithms. The algorithms used, combine multiple 2D images to predict a 3D Model by identifying identical feature points between images.

Various mainstream software packages are currently being used for amateur applications of photogrammetry, the most popular of which being Autodesk 123D Catch and Microsoft Photosynth. A comprehensive list is available online on the Wikipedia page for Photogrammetry Software.

Problems and Constraints

Since most of the results of photogrammetry are calculated digitally, the algorithms can on some occasions fail. According to Foster and Halbstein (2014), there are a number of issues that can be faced during this process. They can be summarized as follows:

Occlusions & No. of Photographs

Occlusion is the presence of an unwanted object in front of the object being scanned and the camera, this causes artefacts in the result because of the lack of information behind the object. Many current algorithms solve this problem using data from more images. Objects that have heavy occlusion can require photographs every 5–10° with an overlap of up to 50%. Low occlusion objects however only require images every 20° for optimum results.

Requirement of Features

It is integral to the way in which photogrammetry algorithms work that the images being processes have multiple features like patterns, strong lines or variety in depth. The algorithm uses these features to identify points for tracking. Considering this, it is more difficult for the algorithm to process the images if they have large empty or non-focuses areas, an example being blank walls. The addition of reference features using tapes and stickers can yield better results. Conversely, repetition of features can also cause problems since it can make it more difficult for the algorithm to identify unique features.

Reflectivity and Transparency

Although the technical reason is not explicitly stated by Foster & Halbstein, it is mentioned that reflective and semi-transparent elements like windows can pose problems. This is sometimes solved by spray painting a matte finish. It can be conjectured that these problems are caused because the glossy highlights and reflections visible on such objects are subject to change with the angle of the camera, thereby causing different images to appear in every photograph, which can cause problems when merging. Built Heritage can on occasion include extensive use of glass, however for applications of Digital Fabrication, the presence of glass is unlikely, yet glossiness may still be an issue.

Movement of Subjects

If the subject were to move significantly during the recording of the images, the algorithm would have difficulty aligning reference points (feature sets) and therefore the final result would have artefacts and distortion. This may not be an issue when scanning built heritage because of its static nature.

Consistency of the Lighting

For optimum results, photogrammetry requires diffused lighting conditions, any directional light has the potential to cause strong shadows which can interfere with the algorithm. Due to this, flash photography is not recommended since it creates directional lighting conditions. Cloudy skies (diffused light) outdoors and the use of diffusers indoors therefore produces optimum results. This can be an issue when recording built heritage especially with time constraints when it is not possible to wait for ideal lighting conditions.

2. Photometric Stereo

This technique uses a singular camera viewpoint but extracts 3D information via images taken from different lighting directions. The light sources are point sources placed at a certain distance. The surfaces are approximated using algorithms that record the change in the intensity of the image at different illumination angles, thereby predicting the orientation of the surface (Wu, 2003). This technique has limited applications for Digital Fabrication since the data would be polluted by other light sources, making the outdoor application (in an uncontrolled environment) of this method impractical, particularly during daytime.

3. Silhouette Methods

These methods pertain to the recording of the outlines of the scanned object from multiple angles. These silhouettes are then extruded to the origin of the camera and intersected with each other in 3D space (Karin Olsson, 2001). This intersection, called a visual hull is an approximation of the shape of the original object. The concavities of the objects are not recorded with this method and the final result is relatively crude. Due to these limitations this method is not useful for Digital Fabrication. It's relative simplicity in generating these volumes however can be used for quick volumetric analysis.

5.3.2.2 Active Methods

Such scanning involves the active use of radiation as a probe for determining the surface points of the geometry being scanned. As opposed to passive techniques, in active techniques the radiation is emitted from a source on the scanner, reflected back from the surface to be scanned and then detected by a sensor on the scanner. As mentioned earlier, these probes can be in the form of visible light, ultrasound or x-rays. This section however will only cover laser (visible light) scanning methods. These scanners typically require the use of a 'laser ranger', which is device on the scanner responsible for either measuring the distance or slant range to a selected reflective object. For laser light based scanners, there are three primary methods of data conversion:

1. Time of Flight (Time Pulse Method)

These systems reflect laser light off the target surface which is then detected by a light detector within the same system. Since light travels at a known fixed speed within a known medium like air, the distance to the point can be determined by the time elapsed. Typically, a laser pulse is generated by the scanner and is reflected off a rotating mirror or prism (to increase the field of view), the timer is initiated as soon as the pulse leaves the scanner and stops once it is reflected back and received by the receiving optics, as illustrated by the figure.

The range can be calculated using the following relationship:

$$R = v.\frac{t}{2}$$

Where,

R is the distance or range from the target surface,

v is the speed of electromagnetic radiation (known value),

t is the time elapsed measured by the ranger in the scanner.

The elapsed time in combination with the angle of the mirror help determine the coordinates of the point. This is repeated multiple times depending upon the desired resolution and a point cloud is generated. ToF methods can generally be used between distances ranging from 2m to 300m, with a measurement accuracy between 3mm and 6mm (Heritage3D, 2011) and are therefore suitable for architectural heritage scanning applications and consequently for digital fabrication.

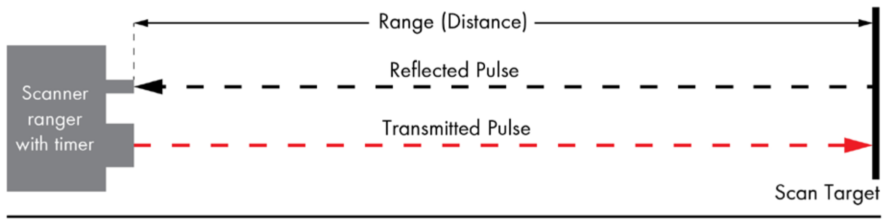


Figure 40. Time of Flight Mechanism. Source: Author

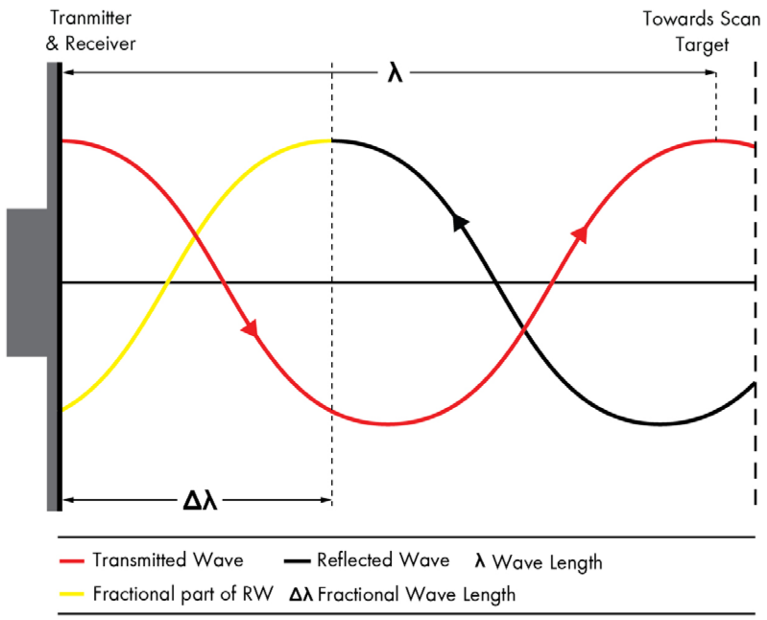


Figure 41. Phase Difference Mechanism. Source: Adapted by Author

2. Phase Comparison Method

This method features a range finder which emits a continuous beam rather than a pulse, they are often referred to as CW (Continuous Wave) lasers. The emitted beam consists of a carrier wave which is modulated using a sinusoidal signal to include measurement information. The beam then reflects off the object or surface and is then detected by the scanner in a weakened state (because of atmospheric interference). The signal is then amplified and demodulated, to separate the carrier wave from the measurement data in the modulation.

The difference in phase (often denoted by φ) between the incident wave and the reflected wave is then recorded. As illustrated in figure 3, it has to be realized that the beam has a fixed wavelength and a finite number of waves can fit inside a certain distance the wave travels, the location of the reflected wave w.r.t. the original wave can therefore be used to find the distance.

The final range of the scanned surface is therefore determined by:

$$R = \frac{(M\lambda + \Delta\lambda)}{2}$$

Where,

R is the distance from the surface,

M is the number of wavelengths (integer),

λ is the known value of the wavelength,

Δλ is the fractional part of the wavelength.

Phase comparison systems have a higher rate of capture that other active methods and therefore can generate a denser point cloud (higher resolution), they also consequently have a higher computation cost (Heritage3D, 2011). Furthermore, because of the limited power of CW lasers, their range is typically limited to less than 100m (Gordon & Charles, 2008). The range of such scanners, albeit less than ToF methods, is still adequate for recording built heritage, with the added bonus of higher accuracy, making them ideal for digital fabrication uses.

3. Triangulation

This method uses the cosine law by construction a triangle using the illumination direction and the observation direction derived from the angles of the source of the light and the angle at which the light is received.

The source and receiver are kept at a fixed distance from the surface called the 'baseline', ensuring that the cosine parameters remain the same for every point scanned. The recorded angle and the second known separation, between the lens and receiver, help determine the location of the point and eventually a point cloud is generated. This method is typically used for distances less than 1m with an accuracy of 0.1mm but some scanners can extend that up to 25mm but with significant loss of accuracy (Heritage3D, 2011). Additionally, the measurements can be affected by sunlight and ambient light (Heritage3D, 2011), making them unsuitable for outdoor use, which is one of the primary requirements for scanning built heritage for digital fabrication purposes. Therefore, triangulation scanners are not optimum for this method.

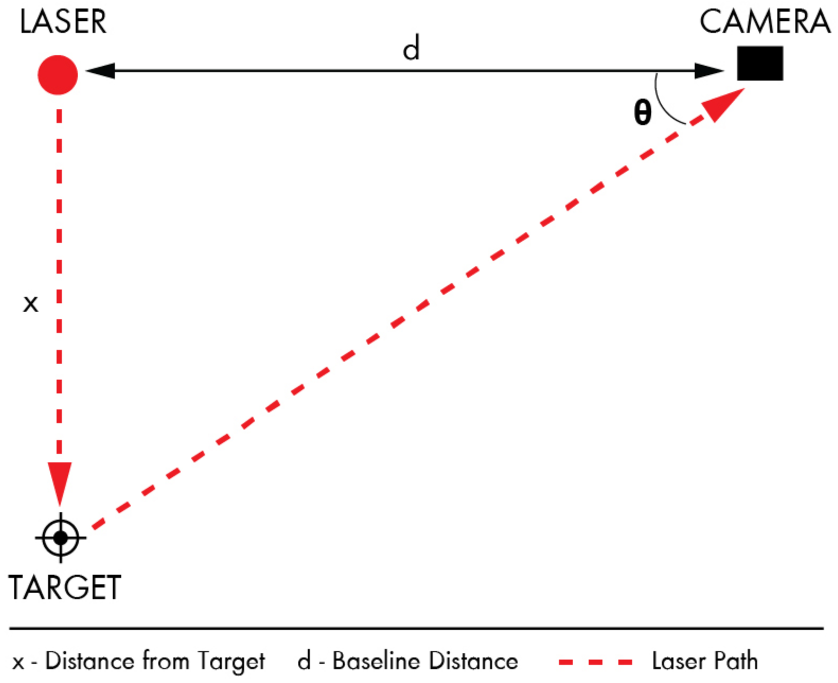


Figure 42. Triangulation Mechanism. Source: Author

4. Microsoft Kinect

Although not a formal method of scanning, Kinect was released as a peripheral for the Xbox 360 gaming console in November 2010 with the intention of being used as a gesture recognition device to be used to actively interact with the console.

After the SDKs (Software Development Kits) for Kinect were released, its applications were expanded. For example, the Kinect Fusion software library enables the use of the built-in RGB camera and infrared projector to gather visual information and depth information respectively, thereby extrapolating a 3D mesh in real time. Due to this mode of operation, Kinect is considered an active form of scanning.

Although the real time scanning of geometry is not required for the purposes of scanning of built heritage, the static scanning applications of the Kinect system can be used in case other more formal systems are not available. This system can possibly also be used to acquire draft scans to determine the feasibility of a project before it is formally scanned.

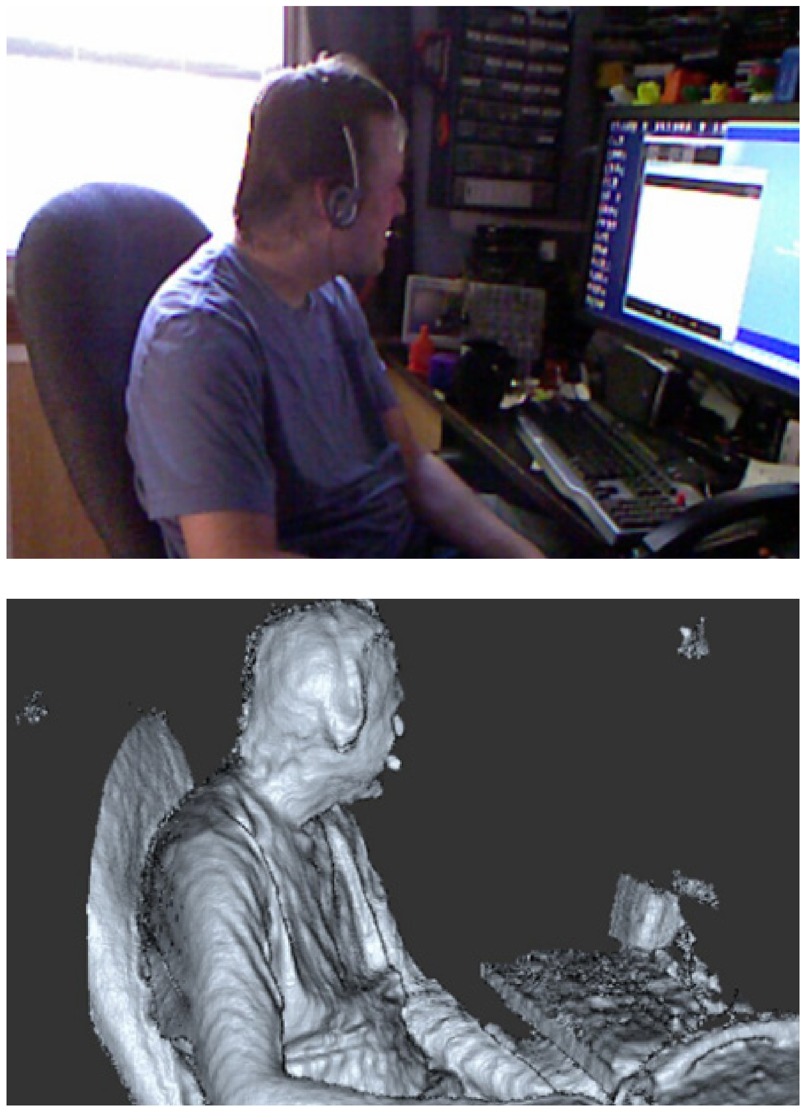


Figure 43. Kinect live scanning and meshing. Source: 3D Printing Wizard

6.2 MANUFACTURING TECHNOLOGIES

This section will briefly mention the history of digital manufacturing and its relevance to modern conservation. It shall only focus on the available technologies that are immediately relevant to conservation and only briefly mention other technologies that could be used in some instances (metal printing for example). Additive manufacturing till now (amongst others), has not had much of an impact on the field of the restoration of built heritage, particularly building restoration. One of the few examples that can be found is the restoration work being done on Frank Lloyd Wright's Annie Pfeiffer Chapel in Lakeland, Florida, U.S.A. by Mesick Cohen Wilson Baker Architects discussed earlier in this report. In the project the procedure involving additive manufacturing focuses on the reproduction of the damaged 'textile' tiles on the facade of the structure rather than just the repairing of the existing tiles.

6.2.1 Additive Manufacturing

Traditionally referred to as Rapid Prototyping and rather recently as '3D Printing', additive manufacturing is by no means a recent development with roots going back to 1984 (Gibson, Rosen, & Stucker, 2015). Strictly speaking, the term 'additive manufacturing' describes any process whereby material is added onto existing material to create a product, as opposed to the removal of material that is seen in techniques like carving and milling. The use of computers however has enables the introduction of '3D Printers', machines that enable the printing of geometries slice by slice. ASTM (American Society for Testing and Materials) International, a global standards organization has formally defined additive manufacturing as,

'A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.'

These machines generally work layer by layer, extruding or curing the material in a malleable state (often molten) onto a defined plane using instructions from the computer (containing the master digital model) before moving on to the next plane and binding the material with the plane underneath.

Nowadays, these techniques are not only being used to manufacture prototypes but also the final result, enabling the mass customization of consumer and industrial products and since the AM process does not require the creation of molds and presses, making the economics of scale irrelevant. It is also for the reason that it is now possible to print end products that Additive Manufacturing is no longer referred to as rapid prototyping (Gibson et al., 2015, p. 2).

Additive manufacturing has also invaded the domestic realm, with compact 3D printers purchasable at relatively affordable prices. Examples include the Ultimaker from Geldermalsen, the Makerbot (also comes with 3d scanning possibilities) and numerous schematics and kits that help you build a 3D printer at home.

6.2.1.1 *Relative Merits*

Although additive manufacturing is often associated with speed (as seen with the traditional term 'rapid' prototyping) the actual manufacturing of the product is considerably slower than traditional methods since modern printers (with the exception of a few) often take hours to print more complicated geometries. The 'rapid' nature of this technology however is evident from the removal of 'pre-manufacturing' steps like the preparation of molds and having to adapt the designs to industry standards. Additive manufacturing skips these steps since the final product is directly derived from the digital model, this technique is therefore often referred to as 'What You See Is What You Build (WYSIWYB)' (Gibson et al., 2015, p. 9). Consequently, the final product also has potential to be much more geometrically complex than those achieved via traditional techniques.

Compared to subtractive manufacturing techniques like CNC milling which require the removal of material from a block of material to extract the product and molding and casting techniques like injection molding and die casting, which require the production of molds (sometimes quite extensive), additive manufacturing features negligible waste of material. Another potential for additive manufacturing is that it was conceived at the brink of the age of 'the internet of things'. British economist Jeremy Rifkin defined additive manufacturing as the 'manufacturing model that accompanies the internet of things economy' and something that would 'provide everyone access to the means of production' (Rifkin, 2015).

Conversely, current additive manufacturing technologies also have considerable disadvantages. Since AM processes work with layers, they often require post-processing to produce smooth surfaces, therefore the final quality of the product is frequently lower than those manufactured via traditional methods. (Gibson et al., 2015, p. 11). Other drawbacks include the limitation of size, since 3D printers can only print inside a finite set of predetermined coordinates. This issue can however can be counteracted by mounting the nozzle on mobile robotic arms which can provide much more freedom of movement. High volume production is also not feasible, industrial usage of additive manufacturing is limited to instances where less than 10,000 units are required (Crump, 2009). The materials currently being used are also limited, since not all materials can be extruded or often have to be adapted to the extrusion process, losing many of their material and structural qualities in the process (Crump, 2009). Despite these shortcomings, additive manufacturing still provides considerable advantages, it may not replace traditional techniques completely, especially when it comes to high volume production, but it can easily prove to be a better alternative for manufacturing customized complex geometries. Considering the pace at which 3D printing technology is progressing (Sykes, 2014) , these shortcomings can quite soon be a thing of the past.

6.2.1.2 *Types of Printing (by material)*

Since this project deals primarily with architecture, this section will classify the available technologies with respect to the raw material input or the material that they try to emulate the materiality of.

1. *Concrete*

It has to be noted that concrete is not a homogeneous material but a composite material consisting of construction aggregate bound together with fluid cement. Therefore, different printing technologies may use Currently there are three main concrete printing techniques available, 'D-Shape', 'Contour Crafting' and 'Concrete Printing'. All these technologies have produced prototypes and are still under constant development.

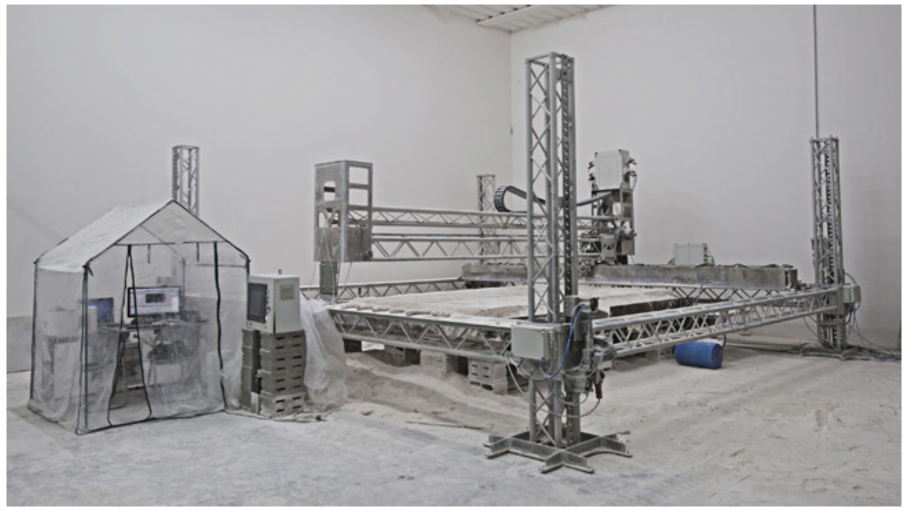


Figure 44. D-Shape Machine. Source: 3D Printing Industry

Figure 45. Contour Crafting Machine. Source: Our Tech Future

D-Shape

This processes makes use of a 'powder deposition' method, using sand and stone powered as the granular material and a chlorine based binder (S. Lim, 2011) which selectively solidifies the areas of the powder that need to be hardened.

Each layer of powder is compacted and a mounted nozzle then deposits the binder. The rest of the powder acts as a temporary support. The loose powder is then removed revealing the final structure which has a print resolution (layer thickness) of around 13mm (S. Lim, 2011).

There is also a possibility that some of the powder can be left inside any internal voids if proper measures are not taking to avoid it (Witte, 2015). D-Shape has the advantage that it produces a high strength result but disadvantages include slow speed, rough surface, limited size (due to printing frame) and the need for post-processing (removal of the powder).

Contour Crafting

As the name suggests, this technique is used to print contours of the extruded shape. The latest iteration of the technique has a print resolution of 4 - 6mm uses two nozzles which print simultaneously (S. Lim, 2011). From each nozzle, a cement based paste is extruded against a trowel (sometimes two) which allows for a smooth finish (S. Lim, 2011). A third nozzle is often used to print concrete inside the void between the contours to add structural strength (Witte, 2015).

Contour crafting was primarily developed to provide a high speed AM solution for the construction industry (S. Lim, 2011), since it prints vertically, it is optimal for the printing of walls. This provides the opportunity to also integrate piping, insulation and wiring systems inside the voids in these walls (Witte, 2015). A disadvantage of contour crafting is that since it is primarily used to print vertical elements under compression, so when voids like doors and windows are required, a separate lintel has to be added before the printing can continue (S. Lim, 2011).

Concrete Printing

This technique extrudes a concrete mixture using a single nozzle mounted on a frame and without a trowel and prints a resolution of 6 – 25mm (S. Lim, 2011). Additionally, the printed material gives a compressive strength (72-102 MPa) which is 80-100% of the casted equivalent, making this technique a very feasible replacement for traditional concrete casting (S. Lim, 2011). It is also possible to integrate reinforcement as part of post-processing (Witte, 2015).

2. *Ceramics & Clay*

A recent research paper by Travitzky et al. (2014) covers the problem of additively manufacturing ceramic materials in detail. The paper has classified these technologies according to their process, these technologies include 3D Printing, Selective Laser Sintering, Extrusion Freeforming, Stereolithography and Laminated Object Manufacturing.

The paper concluded that although Stereolithography exhibited the best surface quality, it used a very limited and expensive variety of materials, meanwhile 3D Printing provided a limited surface finish but allowed the use of a much wider array of materials and also gave more control over the shape and micro-structure of the geometry (Travitzky et al., 2014). Some of these technologies from the paper are summarized in table

3. Wood

Although wood cannot be directly printed, its appearance can be emulated using wood-like particles or sawdust. Belgian company i-materialise and Japanese company Rinkak provide Selective Laser Sintering (SLS) solutions for printing objects that give the appearance of wood. According to the imaterialise (2015) website, their proprietary powder is heated to near its melting point and bound together layer by layer using a laser, as is standard SLS procedure. It is however not mentioned how this powder derived from wood is melted since wood combusts before it can melt (Cheng, 2010). However, low strength (imaterialise, 2015) and low resistance to water still keeps these materials from becoming proper substitutes for wood. A better option for replacing wooden components for restoration purposes would be subtractive manufacturing techniques like multi-axis CNC milling.

4. Polymers

Traditionally, architecture did not commonly make use of polymers or polymer components, thermoplastics and thermosets have only recently gained popularity. They can be found in the production of utility components, window and door systems, flooring etc. Nowadays, the field of architectural

Point	Line		Plane	
3D Printing	Selective Laser Sintering	Extrusion Freeforming	Stereolithography	Laminated Object Manufacturing
Initial Powder Form	Initial Powder Form	Initial Paste Form	Initial Liquid Form	Initial Sheet Form
Indirect Method: The particles are bound together using a binding agent that is sprayed on using inkjet technology.	The ceramic powders are selectively solidifed layer by layer using a powerful laser beam.	A ceramic paste is continuously extruded to form multiple layers. Can be compared to traditional ceramic crafting techniques (pottery).	Resins containing ceramics are polymerized to form solid shapes using heat lamps, lasers or light beams.	Sheets of ceramic material are cut using a laser or mechanical tool and then laminated together (bond-first), or vice-versa (cut-first).
Direct Method: Ceramic powder is suspended in a volatile liquid which is then printed on an absorbent substrate that remove the liquid.		Wire A ceramic wire is melted, deposited and then resolidifies to create the final geometry.		

Table 2. Ceramic Additive Manufacturing Techniques. Adapted by author from (Travitzky et al., 2014).

conservation primarily deals with buildings from the pre-plastic age. In the context of digital fabrication however, plastics can be used in the in-direct application of additive manufacturing, primarily for the production of molds. Polymer 3D printing technologies today can achieve much higher resolutions of printing than concrete printers for example, because the nature of the material suits the process (it is possible to print much thinner layers). This provides the possibility of being able to print molds at a much higher resolution than is permitted by concrete printing techniques without the need for post processing via milling. Some selected relevant techniques will be explored in this paper.

Fused Deposition Modeling (FDM)

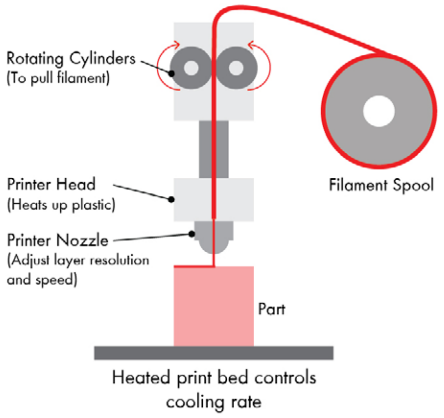


Figure 46. Source: Author

The most common method of additively manufacturing polymers today is Fused Deposition Modeling (FDM), this technique makes use of a heating chamber that liquefies polymers fed in the form of a filament (Gibson et al., 2015, p. 160). The filament is fed into the chamber via a spool in a 'tractor wheel arrangement', which is also responsible for the extrusion pressure. The parts manufactured via FDM are some of the strongest from polymer based AM processes (Gibson et al., 2015, p. 161).

FDM printers are found in many different configurations, some common ones are Cartesian, Delta and Polar. As the name suggests, Cartesian printers use the Cartesian coordinate system (X, Y and Z-Axis), with the print bed (the surface being printed on) often shifting downwards (along the Z-axis) as the print progresses while the print head moves along the X and Y-axes (Campbell, 2015). Delta printers also use the same coordinate system but feature a print head suspended via three moving arms (forming a D shape, hence 'Delta') and a fixed print bed, whilst Polar printers use polar coordinates i.e. a circular grid for the printing process (Campbell, 2015). In FDM, the material is extruded from the nozzle at a particular point, with multiple cylindrical extrusions forming each layer, since this nozzle is circular, it is not possible to print sharp corners (Gibson et al., 2015, p. 164). Other limitations of this technology are the speed (which is limited by the feed, liquefaction and the extrusion head

movement rates) and the anisotropic nature of the material (since it is printed in layers) (Gibson et al., 2015, p. 165). The printed parts usually have a higher tensile and shear strength in the X-Y plane than along the Z plane because of how the material is laid down (Stratasys, 2015). Techniques have been developed to increase the strength of these parts however, such as a recent paper by Yale scientists recording experiments with filling voids in the printed geometry with high-strength resin (Belter & Dollar, 2015).

Stereolithography (SLA)

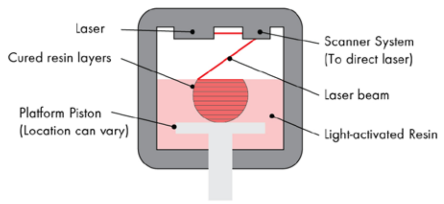


Figure 47. Source: Author

This technique uses the solidification or 'curing' of a photosensitive polymer (epoxy or acrylic resin) in liquid form via the use of a light source; the light source provides energy to the liquid and induces a chemical reaction (the curing process), bonding the molecules together and forming the final cross-linked polymer (Bártolo, 2011).

For the next layer, the platform is lowered and re-flooded with resin. This process is then repeated for each layer (which are also bound together) to form the final geometry. The resin is heated to 30° to 40° C to decrease the viscosity of the resin so that it wets the new surface better but apart from that, temperature does not drastically affect the curing process (Strauss, 2013).

The two main methods of projecting the light are either via a laser (slower because the laser projects a point) and a DLP (Digital Light Processing) Projector (which cures the entire computed plane at once and is thus faster). Like other printing methods, if there are overhangs or recesses, support material might have to be generated, which is later removed either manually or with the aid of a chemical bath.

Material Variation

Both FDM and SLA are compatible with a wide variety of materials, with the ideal material being one that is more suited for the type of end product being manufactured, with factors like speed, strength and the required detail taken into consideration. The two most popular FDM materials are the thermoplastics ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid) whilst other materials like PVA (Polyvinyl Alcohol), Nylon and PC (Polycarbonate) are also used for specialized applications, amongst many others. Compared to PLA, ABS is stronger, more flexible, and can be sanded, painted and glued together using ABS glue. Whilst PLA has the added advantage of being more environmentally friendly since it is biodegradable and is derived from renewable resources. PLA is also relatively tough, produces a higher resolution, is faster and can be painted (preferably with primer) but it is also brittle once it cools down, more prone to water absorption than ABS and is difficult to glue together (Matterhackers, 2015).

SLA materials are not as readily available as ABS filaments since every 3D printer manufacturer has different conditions under which their material is printed, like the kind of irradiation (direct light or laser) or the viscosity of the resin required. These manufacturers then make proprietary thermoplastic and elastomer photosensitive resins available that are not interchangeable between printers, making the materials more expensive and rare (Grieser, 2015).

Comparison

Compared to SLA, FDM printers have the advantage of having better material availability, are stronger (since the thermoplastics are directly extruded) and are more economical since the technology is relatively less complex and requires less maintenance (3Dsupplyguys, 2015b). SLA printers on the other hand can print at a higher resolution because of the precision achieved with lasers and DLP, and although the final product may need to be 'baked', the surfaces produced are smooth so no further post-processing is required afterwards. Despite these facts, the prohibitive pricing, technical sensitivity required (whilst handling the resin, for example) and restrictive availability and brittleness of the materials has affected the popularity of SLA printing when compared with FDM (3Dsupplyguys, 2015a).

Relevance

For the purposes of this research, the required 3D Printing methodology can be divided into two main categories: Direct Manufacturing, involving printing the required geometry (positive) via a 3D Printer using an appropriate printable material and In-direct Manufacturing, involving printing the mold (negative) required to produce the needed geometry.

Although printing the positive (direct) can have material limitations (especially since the object is printed in layers) it can be useful in recreating intricate geometries for the purpose of being used as a reference to create a mold. In this way less material is wasted, and the process can be economized.

The mold (negative) can potentially also be printed so that another material can be casted in it. This possibility helps skip the need to create a mold but since the mold needs to be larger than the positive, it requires a larger manufacturing volume which can be quite limited in modern 3D printers.

There are possibilities for hybridization as well, such as manufacturing certain parts of a mold via cnc milling and only using 3D printing for geometry that can not be manufactured via other methods. Another hybridization method is manufacturing general volumes via low resolution 3D printing techniques such as concrete printing and then applying the final details using CNC milling.

6.2.2 Subtractive Manufacturing

As the name suggests, subtractive manufacturing deals with the removal of material from a stock to leave the desired form. In the field of digital fabrication, these machines are fed CNC (Computer Numerical Control) data and often referred to as CNC milling machines.

There is a distinction between different kinds of digital subtractive manufacturing methods, namely cutting and machining. (Hauschild, Karzel, Hellstern, Kollmann, & Schönbrunner, 2011) These techniques are summarized in the following sections.

6.2.2.1 Cutting Techniques

Cutting refers to the separation of flat materials with little to no variation in thickness. A distinction can be made between the few cutting process, namely shearing, jet-cutting and thermo-cutting.

Shearing

Shearing uses a die-head which is guided over the flat material using CNC data which controls the horizontal and vertical movement of the die. This is a purely cutting mechanism with a possibility of cutting up to 10 mm of sheet metal. Shearing is an entirely 2D process as the size of the head limits any 3D processing (Hauschild et al., 2011).

Jet-cutting

Unlike shearing, this technique involves no cutting edge and uses either a laser jet , gas (plasma cutting) or water. The most common techniques, at least for architectural applications uses a mixture of water and an abrasive agent (like sand particles) to add abrasiveness. The abrasive agent can be excluded for softer materials but is required for harder materials like metals. The jet is shot at up to 1000 m/s and the cutting diameter can vary from 0.5-1 mm, with a thickness of up to 500 mm, depending upon the material. This technique can provide smooth cut edges with minimal loss of material and requirement for post processing. (Hauschild et al., 2011).

Thermo-cutting

This technique as the name implies involves the use of concentrated energy to raise the temperature of the cutting point to ease the separation of particles. Two of the more popular techniques are laser cutting and wire cutting.

Laser Cutting

Laser cutting uses as a high energy light beam to make an initial incision on the surface, afterwards a 'process gas' pushes the molten material on the surface downwards, to slice through the entire surface. Modern laser cutters can achieve speeds of up to 40 m/minute and can be quite efficient and economical and can be used on a large variety of flat materials (Hauschild et al., 2011).

Wire Cutting

Wire cutting on the other hand is more of a prototyping tool than a final manufacturing tool. It is mostly used to quickly manufacture volumetric geometries via the use of a linear electrically heated wire primarily used to cut foam materials like polystyrene. Continuous passes can enable the manufacturing of complex volumes from a simple volumetric block. Even though there are material limitations, the manufactured foam product can be used as an initial part of a longer manufacturing process, as a guide for the making of molds for example (Hauschild et al., 2011).

6.2.2.2 Machining Techniques

Machining techniques (also known as milling) a set of motors rotates a tool and guides it along the material for the component to be manufactured. The milling head can be of varying sizes and materials depending upon the expected quality of the print and the kind of material used respectively.

2-axis milling is generally used in case laser cutting or water jet techniques are not viable, with the milling head being used as a cutting tool. This is not ideal since the manufacturing is limited by the speed of the machine and certain internal corners cannot be milled because of the limited minimal radii of the milling heads. Furthermore, there is considerable waste of material caused by the milling action. 2-axis machines generally use a set of instructions or tooling paths generated by standard CAD programs.

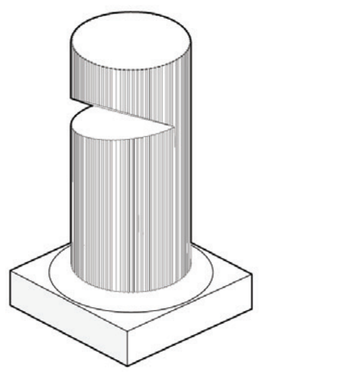
Multi-axis milling machines generally range from 3 to 5 axes with the selection of the appropriate machine depending upon the complexity of the geometry to be manufactured. These machine generally require a 3D model in the industry standard STL format. Other software packages then use this file as a reference to generate the tooling paths as well as the accuracy and feed rate required. An important aspect of using milling machines is the accurate positioning of the part to be milled on the milling bench, which has to be adjusted according to zero point of the system for the most precise milling (Hauschild et al., 2011).

Multi-axis milling is often done with the aid of jointed-arm robotics to provide maximum degrees of freedom. These require extensive supervision however since the robots require human guidance to generate appropriate tooling paths to avoid self intersections. Robotic arms are generally only used when 6 or more axes are required for the milling to proceed.

7. GENERAL METHODOLOGY

3D Scanning, Interpolation, Manufacturing Workflows

For the restoration of damaged ornaments via digital fabrication, a commonality can be found between all the different work-flows, ranging from the identification of viable candidates to the actual manufacturing of the products. Any variation in techniques would then be encompassed within these general steps. The steps (as deduced by the author) are as follows:



7.1 IDENTIFICATION OF CANDIDATES

The first step in the restoration of built heritage is the identification of candidates that qualify for additive manufacturing. The preliminary prerequisites can be listed as follows:

i. The repair of the structure would traditionally require a skilled craftsman.

ii. The geometry to be replaced is complex or double-curved making the use of traditional casting or carving methods difficult.

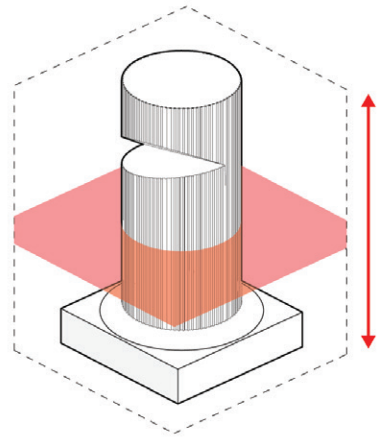
iii. It is possible to additively manufacture the target material using current technology.

iv. It is possible to emulate the material and structural qualities of the original material with the printed material.

v. There is minimal internal damage and no voids that cannot be scanned.

vi. The restoration process would does not unnecessarily endanger any built heritage.

vii. It is possible to reversibly repair.



7.2 SCANNING PARAMETERS AND CONSTRAINTS

Before the geometry can be scanned, it has to be prepared for the scanning process. Depending upon the scale, complexity and reflectivity of the geometry, as well as the type of scanning technique being utilized, number of measured have to be taken before the 3D scanner can be used.

According to a manual released for their software HORUS by BQ, a Spanish manufacturer of open source 3D scanners, the following conditions are necessary for optimal laser scanning:

i. Optimal lighting conditions

The object to be scanned should be lit with indirect light of medium intensity. This helps avoid any shadows forming on the objects and also reduces reflectivity and glare, increasing the performance of the laser scanner.

If the texture or color of the object has to be scanned, then an additional light may be required, if not, the laser itself is enough to illuminate the scanning surface.

ii. The material of the object

The object should ideally have a matte finish; any reflectivity or glossiness can produce a glare which can interfere with the scanning process. If a transparent or shiny object has to be scanned, Makerbot (2013) recommends using temporary measures like cornstarch, talc, dry shampoo, flour, 'developer's paint' or tempera paint. All of these options are reversible and can be removed after the scanning process.

iii. The object color

Red or dark colors in poor lighting conditions or bright colors in bright lighting conditions can affect the reflectivity of the laser and therefore produce inaccurate results.

The aforementioned solution suggested by Makerbot can possibly also be used to solve this problem.

iv. The shape of the object

Cavities, hidden faces, furry surfaces (Makerbot, 2013) can drastically affect the result. These issues can be fixed in the subsequent adjustment of the point cloud in the processing software. (HORUS, 2015)

7.2.1 Preparing the site for scanning

The measures taken are usually dependent upon the kind of equipment being used for the scanning. The measures taken by Delfttech, the firm providing the scanners are as follows:

i. The day before the scanning has to be performed, the mirror and lens of the scanner are checked and cleaned if necessary. The batteries are also fully recharged.

ii. On site, any reference targets are placed on objects to be scanned if required by the scanning process.

iii. Before scanning can begin, a tripod is placed at the selected location and levelled to make sure it is horizontal.

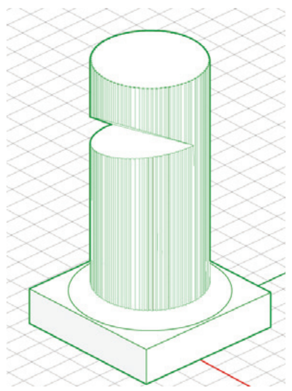
iv. An adjustable tribrach (a piece of surveying equipment used to quickly attach or detach instruments) is attached to the tripod.

v. The lens and mirror are rechecked and cleaned if necessary.

vi. The scanner is mounted onto the tribrach on the tripod and the tribrach is then adjusted to completely level the scanner.

vii. The scanner is switched on, and set-up with the name and path of the scan job, the scan number, the scan resolution and the scan quality.

viii. After the scanning process, the scanner, lens and mirror are cleaned and the batteries recharged to prepare the scanner for the next job.



7.3 DATA VALIDATION AND INTERPOLATION

New geometry has to be interpolated in the software packages provided by the manufacturers or other third party commercial or open source software.

Data from the scanner is generally collected in the form of a 'point cloud' which is a collection of points recorded by the laser on the scanner inside a three dimensional coordinate system (usually a local coordinate system of the scanner) (Hermary, 2014). After the scanning process, some of the important undertaken steps are:

7.3.1 Geo-referencing

Only if the collected point clouds need to be transferred into a different coordinate system, for example, when merging a scanned segment of a building with a model of the building (Lovas, 2010).

7.3.2 Selecting an area of interest

Not all the scanned data is always relevant, unnecessary data or data from the periphery may be cropped out (Lovas, 2010).

7.3.3 Data conversion

This step depends upon the nature of the geometry, whether it is regular or organic and free-flowing.

The two types of geometry that the point cloud is converted to are Polygonal Models or Rapid NURBS solids. Essentially, the point cloud data usually in ASCII formats (essentially a list of points), needs to be converted to a manipulatable format that can be read by 3d modeling software.

The choice of format also depends upon whether the model is to be used for digital modeling (actual state, irregular geometry) or reverse engineering (ideal state, regular geometry). For the former, the point cloud is converted to a polygonal model, which consists of multiple tessellated triangles or 'polygons' formed by connecting the point cloud to generate the entire model (Direct-Dimensions, 2015). This STL format is usually preferred for this type of geometry and it is ideal for rapid prototyping or visualization applications.

This method also suits digital fabrication for restoration since it records all the imperfections of the scanned object, which is essential for the recording and restoration process. For reverse engineering, rapid NURBS solids are generated by adding an additional step on top of the polygonal model, by wrapping NURBS surfaces over the polygonal frame (Direct-Dimensions, 2015), typically exported in IGS format.

An advantage that this format offers is that the data can be parametrized and is therefore easier to manipulate in software that offers parametric modeling (e.g. Autodesk Inventor, SolidWorks etc.) These two methods can also be hybridized to utilize some of the benefits of both (Direct-Dimensions, 2015).

The software packages used by Delfttech (some packaged with the 3D scanners being used) are, Z+F Lasercontrol Professional Plus (packaged with Z+F scanners), LFM (multiple sources) and Leica Cyclone (multiple sources, not limited to Leica). The meshing is generally performed using MeshLab, Leica Cyclone, 3D Studio Max or GeoMagic. Other freeware or shareware packages can also be used.

7.3.4 Data Inspection

If required and if the original drawings of the selected geometry are available, the scanned model can be compared with the drawings to record any dimensional deviations (Direct-Dimensions, 2015). These deviations can then be represented as a color map that is overlaid on the model with the aid of certain software packages.

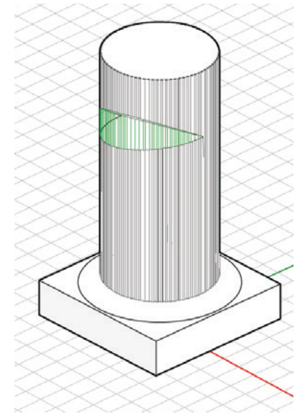
7.3.5 Interpolation

This step determines the geometry to be manufactured, this would include sections that need to adhere to the scanned candidate(s) and ones that need to be modeled from scratch with the aid of documents or repeating features.

Careful considerations would have to be made to include any tolerances required for the binding material.

It would also have to be determined whether the new geometry would have to be manufactured in one piece or multiple fragments, depending upon the nature of the scanned geometry.

Steps also have to be taken to ensure that the nature of the geometry generated conforms with the manufacturing technique chosen. An example of this can be the generation of manifold meshes for the purposes of 3D printing or in the case of milling ensuring that there are no hidden surfaces or recesses that the milling tool cannot reach.



7.4 PREPARATION AND MANUFACTURING

After the meshing process, the model needs to be prepared for manufacturing via the chosen process. The production process would either be direct or indirect (via the use of molds).

The choice of process would determine the materials and equipment to be used. It is required that there are no physically impossible artefacts in the scanned model, such artefacts have to be removed and the model cleaned.

These steps can be performed with any of the modeling software listed before and may vary between different software packages.

7.4.1 Additive Manufacturing Workflow

Generally, a well prepared water-tight mesh can be used for a variety of manufacturing applications. Gibson et al. (2015) for example, describe additive manufacturing as an eight step process. These processes can be summarized as:

Step 1: Computer Aided Design

The creation of the 3D model to suit the parameters of the 3D printer, in the case of digital fabrication, the conversion of the point cloud to a mesh.

Step 2: Conversion to STL

Conversion to the standard STL file format accepted by nearly all 3D printers, it defines the closed surfaces on the exterior of the model.

Step 3: File Transfer and STL Manipulation

Once the file has been transferred to the machine, it can be manipulated to determine the orientation, position and scale.

Step 4: Machine Setup

This step pertains to setting up the machine by providing an energy source and suitable environment as well as build parameters like layer thickness, temperature, timing etc.

Step 5: Build

The printing process is mostly automated but may require supervision in case of unforeseen circumstances.

Step 6: Removal

The printed piece has to be removed from the machine which requires actively interacting with the machine or in some cases waiting till the safety interlocks (engaged when temperatures are too high or there are moving parts) are disengaged.

Step 7: Post-processing

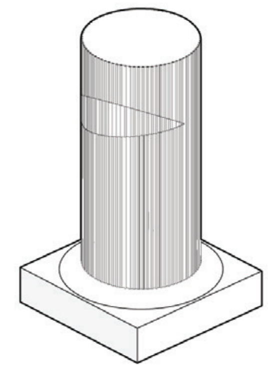
This is mostly a manual process and may involve sanding, removal of supports etc. Chemical baths are sometimes used to expedite the removal of support material.

Step 8: Application

Final touches like primer and/or paint can be added to prepare the product for use, depending upon the kind of material used. The 3D printer should also be reset and prepared for the next print, any required maintenance should be carried out.

7.4.2 Other Considerations

According to a white paper by Stratasys (2014), the generated STL file should not have any overlapping or miss surfaces, inverted normals, or bad edges (non-manifold). These errors can be detected by any STL viewing tool. Additionally, the wall thicknesses have to be appropriately determined according to the material filament being used (if the geometry is to be hollow or not completely solid). Every material has a minimum acceptable thickness for optimum results (Stratasys, 2014). Different materials have different 'self-supporting' angles (usually around 45 degrees), beyond which the material can tend to tip over. If the design of the print accounts for these angles, then the support material and consequently the build time can be reduced.



7.5 INSTALLATION ON SITE

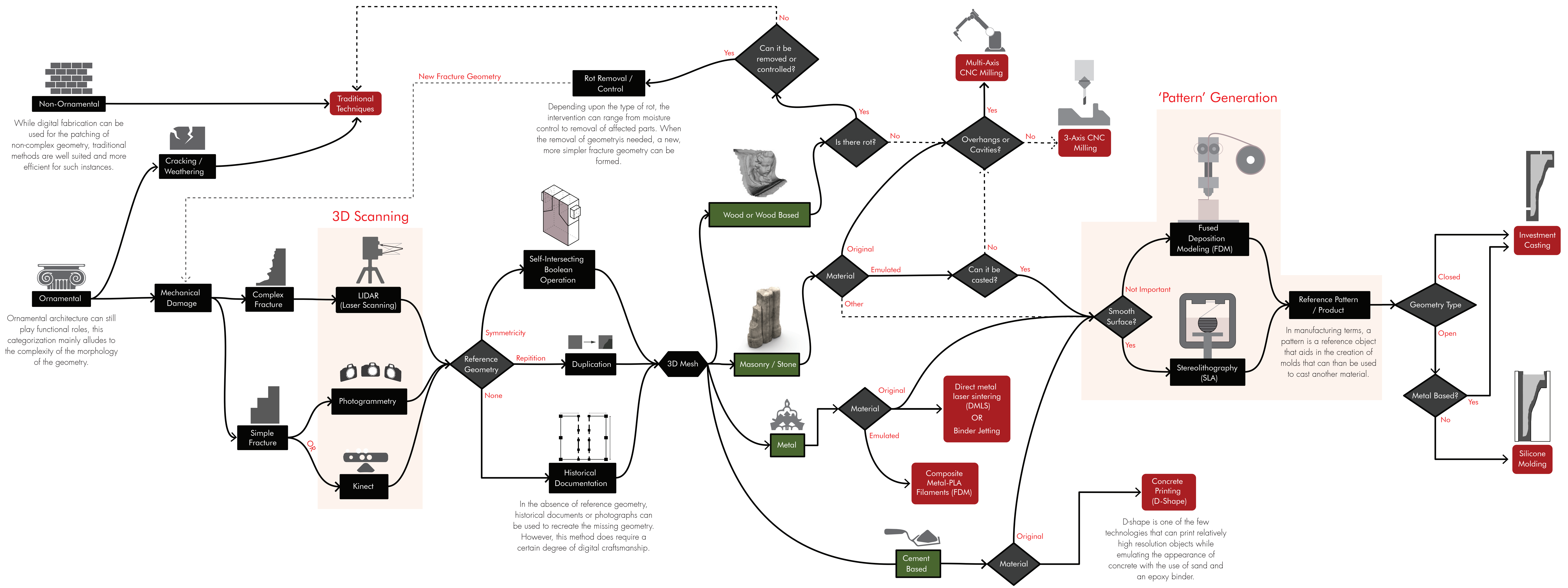
The selected candidate(s) would then be repaired on-site with the printed additions installed with appropriate binding materials (preferably ones that allow reversibility). This process may or may not involve cleaning the existing fracture surface on the candidate to be restored.

7.6 ADJUSTMENTS AND DOCUMENTATION

Finishing adjustments and imperfections in the digital fabrication intervention can now be fixed and any changes to the site should be documented along with the materials and techniques used.

7.7 WORKFLOW SELECTION FLOWCHART

PATCHING VIA DIGITAL FABRICATION AND LIDAR



8. HARDWARE INVENTORY

Laser Scanners, 3D Printers, Specifications

Restoration using digital fabrication requires the symbiosis of different fields of technology to achieve the final result. These technologies include the use of hardware for the input of data, the analysis and subsequent manipulation of that data, and for the production of the physical output. In this section the available hardware and their specifications will be listed. The comparison of their results can be found in subsequent sections.

8.1 3D SCANNERS

The laser scanners for this research were acquired from Delft based scanning company Delfttech, which according to their website provides '3D laser scanning & engineering, consultancy, software solutions and training & education'. The hardware was used under the supervision of their engineers to ensure proper usage and maintain the accuracy of the results. The scanners acquired were the Leica HDS3000 and the Zoller + Fröhlich Imager 5010C.

8.1.1 Leica HDSv3000

Figure 49. Source: Leica Geosystems

Manufactured by Swiss company Leica Geosystems (not to be confused with the German optics company Leica Camera), this pulse based laser scanner uses a time-of-flight system to record the point cloud. The ranger finder works in conjunction with a rotating mirror to increase the effective field of view. Details about the mechanism of action of such systems are discussed in the Technology Overview section.

The scanner features an 'integrated high resolution camera' and can be linked to external digital cameras to increase the field of view. The raster images generated from the camera can be mapped to the mesh generated from the point cloud, giving full color meshes.

8.1.1.1 Connectivity

The scanner is marketed towards professionals and has an accuracy that is considered survey-grade. It can be linked to a standard modern laptop using an Ethernet cable, making a laptop with an Ethernet port a requirement (many ultraportable laptops lack one).

8.1.1.2 Dimensions and Weight

Weighing 17kg with the additional weight of 12kg for the power supply, and measuring 265mm x 370mm x 510mm, it is not the most portable device on the market but with adequate transportation can easily be easily assembled on a tripod (also provided) on site. Other relevant specifications can be found on the adjacent table.

8.1.1.3 Export Formats

The scanner directly exports the point cloud as ASCII point data (these include the XYZ, SVY, PTS, PTX and TXT formats). Other formats include DFPX, Leica's DBX format and the Land XML format. Indirectly (via the use of plugins), AutoCAD, MicroStation, PDS and AutoPLANT formats are also supported.

Table 4. Relevant Specifications of Leica HDS3000 Scanner

Type of Instrument	Pulse, Time of Flight Ranger Finder
Operating Temperature	0° to +40° C
Laser Class	3R
Field of View	
Horizontal	360° (maximum)
Vertical	270° (maximum)
Scan Range	300m
Scan Rate	Up to 4,000 points/sec
Scan Resolution	
Spot Size	From 0 – 50m range, 4mm (FWHH[a]), 6mm (Gaussian[b])
Maximum Density	1.2mm
Scanning Optics	Single mirror, panoramic
Scanner Drive	Servo Motor
Power Supply	36V
Power Consumption	<80W avg.

Note: *All specifications from Leica Geosystems specifications list.*

[a] *Full Width Half Height approximation (measured till 50% of center maximum)*

[b] *Gaussian approximation of intensity (maximum at center of spot)*

8.1.2 Zoller + Fröhlich Imager 5010C

Figure 50. Source: Z+F Imaging

Manufactured by German engineering company Zoller + Fröhlich, which started off as a supplier of control systems for the automotive and engineering industry (started manufacturing laser scanners in 2002), the Image 5010C is a relatively compact phase comparison scanner.

Like the HDS3000, the Imager 5010C is a high-end product and also features an integrated camera (CMOS sensor) and a rotating mirror for increased field of view. Furthermore, the scanner conforms to IP 53 standards and is therefore dust and water resistant. Additional relevant specifications can be found in the table.

8.1.2.1 Dimensions and Weight

The Imager is lighter and more compact that the HDS3000, weighing in at 9.8kg and with a size of 170 x 286 x 395 mm. The power supply is also significantly lighter and compact at 0.54kg and 35mm x 67mm x 167mm. The separate battery weighs in at 1.2kg and measures 170mm x 88mm x 61mm.

Table 5. Relevant Specifications of Zoller + Fröhlich Imager 5010C Scanner

Type of Instrument	Phase Comparison (Phase Shift)
Operating Temperature	-10° to +45° C
Laser Class	1
Field of View	
Horizontal	360° (maximum)
Vertical	320° (maximum)
Scan Range	187.3m
Scan Rate	Up to 1.016 million pixels/sec (interpreted as points)
Scan Resolution	
Spot Size	At 0.1m range, 3.5mm
Maximum Angle Res.	100,000 pixels/360° (horizontal & vertical) - Adjustable
Scanning Optics	Encapsulated Rotating Mirror
Scanner Drive	Unspecified, but device rotates along vertical axis
Power Supply	24V
Power Consumption	<65W avg.

Note: More specifications can be found on the Zoller + Fröhlich specifications list.

8.1.2.2 Connectivity

The scanner seems to be more user friendly, with an integrated touch screen for access to the control panel and instant previews of the scanned images.

The scanner can also be controlled remotely over WLAN (wireless) and Ethernet (wired) and features two USB ports for the addition of storage media to store the scanned data.

8.1.2.3 Export Formats

The scanner supports standard ASCII formats, OSF, PTG and ASTM-E57 for the export of the point cloud data.

The data is exported using the proprietary LaserControl software packaged with the scanner.

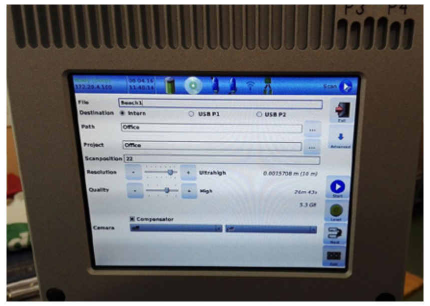


Figure 51. Z+F Display. Source: anonimou (Forum Post)

Figure 52. Z+F Pointcloud Sample. Source: Santoku

8.2 3D PRINTERS

Two different 3D printers were used for the duration of this project. The first option was a Form 1+ SLA (Stereolithography) printer from Formlabs available in the Building Technology faculty. The second option was an Ultimaker 2+ Extended FDM (Fused Deposition Modeling) printer (the standard version was also available) in the Architecture faculty modeling hall.

8.2.1 Formlabs Form 1+

Figure 53. Source: Formlabs

The Form 1+ is a stereolithography printer (see technology overview section) which can print objects using propriety photo-polymer resins within a resolution range of 25 - 200 microns (0.025 - 0.2 mm) and a relatively fast rate (as compared to FDM printers).

The printer has a relatively small build volume of 125×125×165 mm however. The printer has a USB interface and using the Preform software provided with the product for the placement and slicing of the models.

A disadvantage of using this printer however is that the packaged software (Preform) does not have the capability to change the fill density of the object. This needs to be done manually via either third party software of by removing the geometry inside to create a shell structure for saving material.

These shortcomings are made up by its high resolution printing capabilities that far surpass those of traditional FDM 3D printers. The printer also prints are a relatively fast speeds when compared with FDM printers. These two qualities combined make it an ideal candidate for use with restoration projects.

The available resins range from standard opaque and transparent resins to high performance cast-able and dental resins, expanding its applications from simple manufacturing to medicine.

Some sample 3D prints can be seen in the images below.

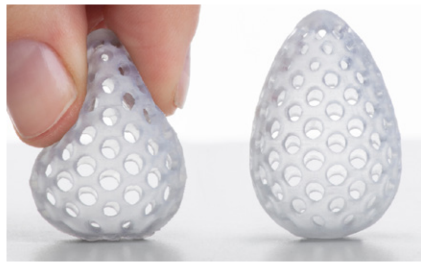


Figure 54. Flexible Sample Source: Formlabs

Figure 55. Dental Samples Source: Formlabs

8.2.2 Ultimaker 2+ Extended

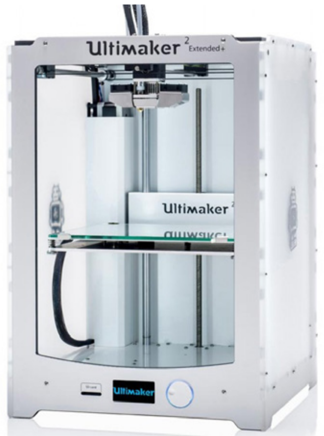


Figure 56. Source: Ultimaker

The Ultimaker 2+ Extended is a special edition of the standard 2+ and features a larger build volume of 223 x 223 x 305 mm, 100mm higher than the standard version. The print nozzles are available in different sizes, giving the printer the ability to print at a high resolution with a layer thickness as low as 20 microns. The disadvantage being really long print times.

The printer also features a heated build plate which can reach a temperature of up to 100°C. Heated build plates prevent warping of the geometry (which occurs due to shrinkage while cooling) by keeping the extruded filament warm during the printing process.

The Ultimaker 2+ Extended supports ABS, PLA and CPE polymer filaments (as does the standard version) and comes packaged with a free software called Cura, which unlike Preform from Formlabs, has the ability to reduce the fill density of the prints.

Lower fill densities drastically lower material usage and print time at the cost of structural strength. The variation in fill density is achieved by modifying the resolution of the internal rectilinear lattice generated by the program. Cura only offers one infill pattern however but due to the open source nature of Ultimaker printers, third party packages can be used to change the infill patterns.

The extended size of this version of the Ultimaker 2+ makes it a good candidate for use with restoration applications. A sample 3D print can be seen in the image below.

Figure 57. Ultimaker Sample.
Source: Printer 3D Review

9. EXPERT OPINIONS

Multiple professionals in the field of architectural restoration were interviewed to gain subjective insights into the future of digital fabrication and their point of view regarding the use of technology in the field of conservation.

9.1 VAN MILT RESTAURATEURS

INTERVIEWEE: HUGO VAN MILT

Restoration Architect & Manager at Van Milt Restorers

LOCATION: LUNTEREN, GL, NL

Could you give some context about your company and your role in within it?

"Van Milt is a restoration company and we have existed for 30 years now. My father founded the company and I joined around 16 years ago and now I am the leader of the pack. I think of how things work and how to guide and start the projects to make sure it is a success for all the parties.

In restoration, we now know that there are a lot of developments going on. Laser scanning is not new to me, I know it's been going on, but what you're working on is different. I will show you later."

How often do you make use of Digital Fabrication in your line of work?

"We produce our own stones, specially formed bricks, we call them 'profiel stenen'. We use a 3d scanner to scan them and then make a mold to produce the stones. It's not a very big market for us so we do it sometimes but not all the time."

Figure 58. Crafted head in van Milt basement. Source: Author

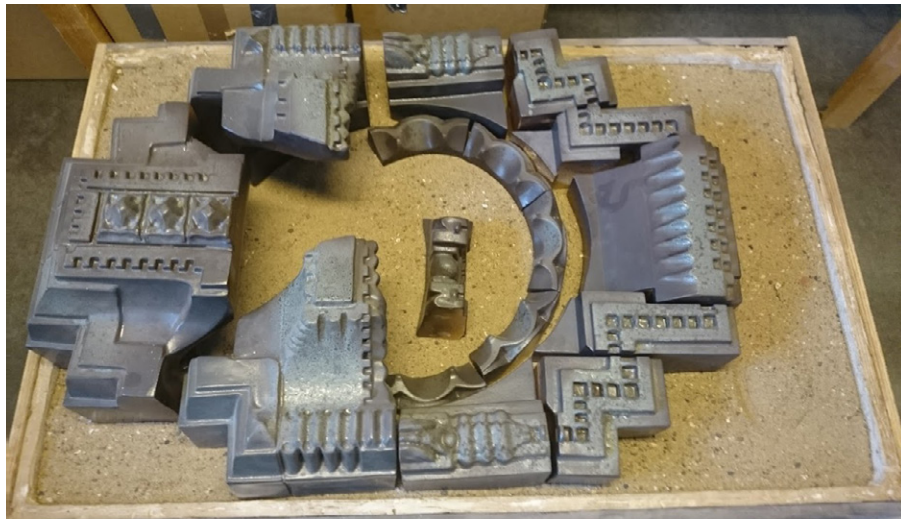


Figure 59. Fabricated facade element from BK City. Source: Author

Do you employ a team of craftsmen for the production or do you outsource it?

"Yes, we do. I will show you their work downstairs."

Do you think new technologies can replace the craftsmen in the near future, especially if the results are identical?

"It's not going to replace them since there will always be a need for a good craftsman, but I think in some cases the craftsman can be replaced.

You have these machines that cut the stone, you put instructions in the computer and the machine carries them out but it does not look at the quality of the stone. If there is a little crack in the stone it just continues and breaks the stone. A craftsman can see the crack and avoid it.

Maybe in the future there is a machine like a 3d scanner that can scan the stone before it is worked on. Even today a lot of people are out of work because of these CNC machines but there will always be special projects where you will need them. I think it's a new market and will continue expanding in the field of restoration. We haven't used 3d printing in any of our projects yet because we have a lot of trouble finding the correct materials to make our products with.

We do really traditional restoration and one of the reasons for that is that if we go to the 'monumentenzorg' (the service responsible for the maintenance of monuments) and tell them that we're going to use 3d printing they'll tell use that that's not going to happen since they want exactly the same materials and techniques involved in the original project. But perhaps this will change in the next 20 years as the technology evolves."

What are the shortcomings that you would expect with digital fabrication?

"I think it makes everything too easy, everything becomes some kind of Disneyland, where everyone can produce anything with their 3d printer. I would not find it ideal when for example a limestone ornament is replaced with printed gypsum and painted. Even though you can't see the difference we all know it is fake. Some objects could be made hollow, while you don't see the difference, when you knock on it, you can feel it.

I think then the monument is fake. If you replace the Eiffel tower with a plastic replica, it is still the Eiffel tower but it's not real."

What are your views on the restoration of the Parthenon?

"I'm not saying I don't like it. If you go to Belgium or France for example, they have a different way of restoration, they have a preference for cleaning the existing heritage and if something is too old they just replace it. I don't really mind that but in some cases, I don't agree with it since people assume something is old while it really isn't."

Would you consider investing in in-house Digital Fabrication technologies?

"Sure, we would use it. That's an option."

What development do you think would convince the restoration industry to switch to digital fabrication?

"If the machine can use the material that we are allowed to use for restoration then I think that's the main factor that would convince us."

Do you think the use of technology affects the authenticity of a restoration if the end result is the same?

"In such a case, I think it makes no difference."

9.2 PROF. IR. ROB VAN HEES

Professor of Heritage & Technology, Conservationist and Researcher

LOCATION: DELFT, NL

Do you think that Digital Fabrication technologies can replace the role of the traditional craftsman in the near future?

"I expect the traditional craftsman to be important for the final touch: there is an analogy nowadays with laser guided machines for elaboration of natural stone. Too perfect may become 'visible'; there is a fascination in imperfection or rather 'just-not-perfect' which can not be replaced by a machine."

Which technologies do you currently make use of?

"Photography, making hand-drawings, analysis of material properties (LDT - Laboratory Developed Tests), analysis (NDT - Non-destructive Testing and LDT) of on-going degradation processes."

Could you give an example of an instance during a restoration project where digital fabrication may have been very useful?

"Making copies of carvings that got lost during earthquakes and where apart from photos only fragments are left."

What kind of shortcomings to do you expect from digital fabrication technologies if they are used in their current state?

"Limited availability of different materials, adapted to, compatible with the existing materials; too high degree of perfection.

Furthermore, the limited possibility of variation in material properties: physical properties like pore-size distribution, mineralogy and chemical properties."

Would you consider investing in these technologies for in-house applications?

"If by in-house you mean in the university then yes because research and innovation are certainly possible related to this technology."

What changes are necessary for industry wide adoption of Digital Fabrication technologies?

"Broader choice of different materials and material properties."

In what way do you think that the use of technology affects the authenticity of the restoration?

"There is a risk of there being too much perfection, as discussed earlier."

9.3 DRS. HENDRIK-JAN TOLBOOM

Natural Stone Specialist at Cultural Heritage Agency (Rijksdienst voor het cultureel erfgoed)

LOCATION: AMERSFOORT, NL

In the future do you think the craftsman will be completely replaced?

"I think there will always be in the need of the creativeness of the human being, the machine will not design for you. You have to decide what the machine makes. I don't think that's a big problem though.

Craftsmen will change, their techniques will change, their tools will change but they will still be craftsmen. They they don't, then we will have a problem. A craftsman is person that can handle techniques.

One of the strongest arguments in favour of digital fabrication is that working with stone can product particles that are not very healthy for the people working, that's something that the machines will nullify, as well as the fact that they can run all day."

A lot of people argue that the touch of the hand has a significance. Do you think its just sentiment?

"The interesting thing is that there are some surfaces that are very hard to make by machine but very easy by hand, then in the future we'll have to ask ourselves how hard is it for us to accept the structure that the machine makes.

Yes but it's also an aesthetic question, to put new and old together, and do we accept the structure that the machine makes or the one made by hand tools. So that's a difficult question, its only good that we become conscious of this problem, more than we do now because at this moment we are using machines and then afterwards we're using hand tools more or less to cover up the machined surfaces."

What kind of technologies are you using in your line of work?

"We use CNC machines and 3D scanning. We don't use 3D printing because the materials currently available are not useful to us as replacement materials.

We use 3d printing to make models of course but not for making the final product. I use natural stone and you cannot print natural stone."

What about emulated materials like ground sandstone suspended in resin that can be 3d printed?

"I think we cannot use that in an environment outside exposed to the elements, these materials are for indoor use."

Why do you think that when restoring damaged ornaments, the preferable method right now is to replace the entire element by CNC milling a replica instead of just replacing the missing fragments?

"That depends on the type of stone amongst other things. When we replace something, if you can replace the parts, of course we can do it but in a lot of cases, what is left over is hardly use-able."

What changes would you like to see in the future?

"I think there's still room for more accuracy with regards to CNC milling but for printing of course there's a limitation of materials. The problem being that with 3D printing, we have to use mortars for restoration. There was a preference for mortars in the past because of the absence of CNC milling. Nowadays, we can CNC mill stone, it's a more attractive option for use since we can use the same natural stone as used in the past."

Do you think that the use of technology affects the authenticity of a restoration? For example, would something hand made have more value than something machine-made?

"I wouldn't say that. However way something is made it is always a product of the time. If a craftsman makes something right now, it is the product of the current time, when a machine makes it, its the same principle. The only question being, is it more or less authentic?

When we look at 'traditional' stone-masonry nowadays for instance we see that modern machines are used everywhere for all kinds of applications. So, in a way I think it has gone too far. People don't understand the process in some instances, you cannot tell how something was made, they only notice it when they're told. It's hard to say what's better or worse. Are these changes positive or negative? That's a question you cannot answer that easily."

Do you have any examples of on-going projects which warrant the use of technology but current technology hasn't quite caught up fast enough yet?

"On some chimneys, you can have really fine engravings in white marble. These engravings cannot be recreated as finely as they were in the past. We've lost the techniques for making these really detailed pieces. Current machines do not have the sensitivity to produce such work."

What is your opinion on patching ornaments with un-weathered pieces with sharp edges, as in the Parthenon restoration, versus adding weathered pieces to create a more seamless experience?

"This is always an issue. For example, in England, they tend to create new pieces with artificial weathering because they're concerned that by slowly introducing new pieces into a structure, you can lose the overall form. With regards to the Parthenon restoration, I think the additions are too sharp, when a stonemason makes something by hand, there's always imperfections, some of them intentional. When something is too new or too sharp, it is noticeable."

10. TEST CANDIDATES

Experimentation, Failures and Compromises

10.1 DAMAGED STONE COLUMN SEGMENT

Location	Dept. of Arch., TU Delft
Material	Belgian Blue Limestone
Function	Column (possibly mullion)
Intervention	Replacing missing geometry

One of the two candidates initially selected for tests using Digital Fabrication is a stone segment from a column found in an archive in the basement of the Faculty of Architecture (BK City) at TU Delft maintained by the Heritage and Architecture faculty.

Most of the artefacts stored in the archive have little to no origin information available so conjecture has to be made regarding their origin and nature.

10.1.1 Material

With help from Rob van Hees, a restoration specialist in the faculty with expertise in material, an acid drop test was performed on the stone surface. The effervescence (bubbles) produced signified that the stone composed of calcite (a carbonate mineral) with the bubbles produced caused by the production of Carbon Dioxide which occurs when carbonates react with acids. The column segment could therefore possibly be composed of limestone.

This test isn't very conclusive since many different kinds of stones can contain calcites or other carbonates. It does rule out non-carbonate based minerals however. Conjecture led to the deduction that it is possibly composed of dense Belgian Blue Limestone because of its shade and the region it was found in.

10.1.2 Morphology and Function

The presence of long vertical recesses on either side of the column segment suggest that they were indents for the insertion of window frames (possibly a mullion). Judging from the style and colouring of the column it can be reasoned that it was possibly a part from a church building.

Variation in erosion on either side of the stone (one more than the other) gives insight into the orientation of the stone. The more eroded side could either have been oriented towards the outside with environmental elements causing the erosion or it could have been oriented inwards, located at a lower level with the erosion being caused by continuous haptic contact with the inhabitants of the building.

10.1.3 Restoration Target

The column segment has a considerable missing fragment, possibly caused by mechanical damage since it is unlikely that such extensive damage occurred because of natural occurrences (especially due to the region not being a major seismic zone).

The fracture surface has quite intricate details requiring the need for high resolution scanning. Apart from some small missing segments and eroded paint and corners, no other extensive signs of damage could be noted.

10.1.4 Selection Criteria

Two major features contributed to the selection of the column as the test candidate: it featured symmetricity (had symmetrical geometry) which would aid during the 3D interpolation of the missing fragment and it was readily accessible. The latter was a factor due to the proof of concept nature of the research.

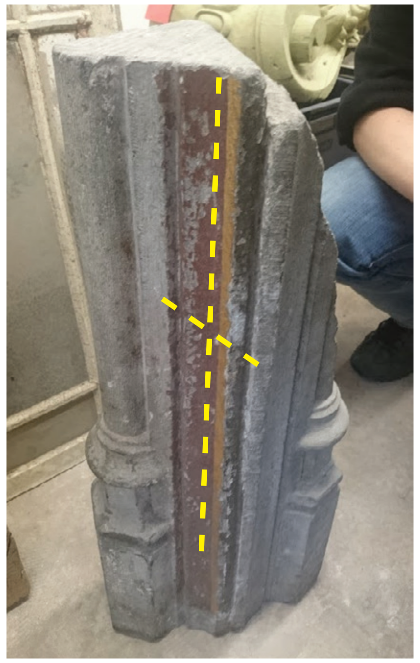


Figure 60. Source: Author

Figure 61. Source: Author

Figure 62. Source: Author

Figure 63. Fracture surface. Credit: Marcel Bilow

Figure 64. Close-up of fracture surface, the high frequency detail is visible. Source: Author

Figure 65. Close-up of surface linear indentations. Source: Author

Figure 66. Faded surface coloration. Source: Author

Figure 67. Linear surface indentations on the torus. Source: Author

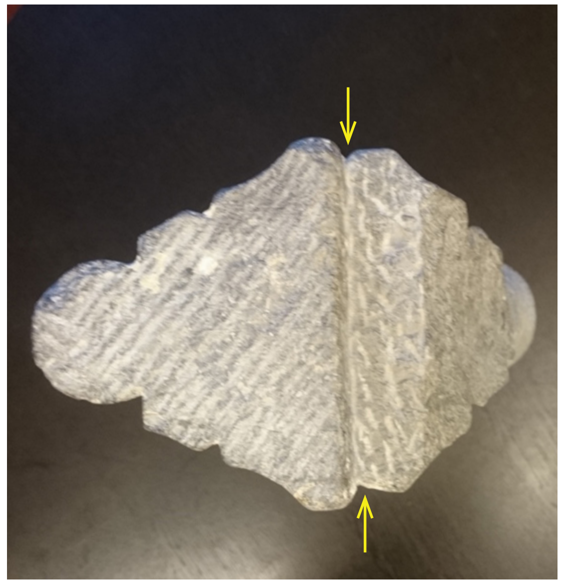


Figure 68. Column profile with possible window frame indentations. Source: Author

Figure 69. Fracture surface on top. Source: Author

Figure 70. Linear indentation on vertical surface. Source: Author

10.1.5 3D Scanning

The 3d scanning for the project was aided by a Delft based company called Delfttech. It was determined that for the kind of geometry to be scanned, it would be ideal to use the Phase Difference based Zoller + Fröhlich Imager 5010C scanner.

The scans were carried out in an improved setup prepared inside a room in the Architectural Engineering and Technology faculty. The column fragment was placed on an elevated platform for better exposure to the laser scanner. Six printed reference targets were used to orient the laser scanner in the room, as depicted in the adjacent photograph. Generally, reference spheres can be used for laser scanning but printed markers are preferable if flat vertical surfaces like walls are available.

The scans were performed with the apparatus set to 'normal quality' and high resolution. These settings were chosen on the recommendation of the scan operator by considering parameters like time spent per scan, final data size and the complexity of the geometry. Seven scans were performed at intermittent intervals around the column fragment. Each scan took 3.5 minutes without color capture and 7.5 minutes with color capture. These scans were then stitched via the scanner firmware into one cohesive point cloud with the reference markers providing a fixed coordinate system for the stitching.

The point clouds were exported in .xyz and .pts formats for maximum compatibility. The point clouds were previewed in Autodesk Recap and then exported into the .asc format to be later imported for meshing.

Figure 71. Printed Reference Markers. Source: Author

Figure 72. Source: Author

Figure 73. Scanning in Progress. Source: Author

Figure 74. Source: Author

Figure 75. Source: Author

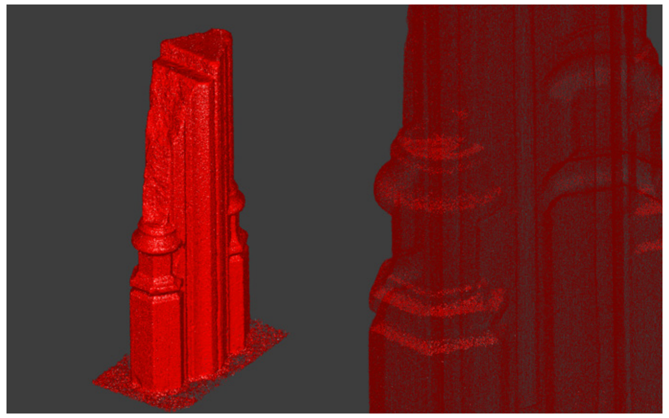


Figure 76. Imported Point Cloud. Source: Author

10.1.6 Mesh Generation

Multiple software packages were experimented with for the optimum meshing results. The most important aspect of the meshing was to find a balance between noise control and retaining high frequency details.

All laser scanning data has a certain degree of noise that comes with the point cloud. This noise generally follows a regular distribution, making it possible to remove it during the meshing process using specific de-noising algorithms.

During the research, multiple de-noising methods were experimented with via different software packages to find the optimum result. Eventually, the mesh exported from the open source mesh processing software CloudCompare was used.

10.1.6.1 System Specifications

One of the major bottlenecks in the meshing process are the specifications of the computer system that the meshing is being performed on, the RAM in particular. For this project, the meshing was performed on a Lenovo Y700 laptop with an Intel Core i7-6700 HQ 2.6 GHz processor and 8 Gigabytes of DDR5 RAM, running the Microsoft Windows 10 64 Bit operating system.

10.1.6.2 Poisson Surface Reconstruction

The first meshing tests were performed on another open source mesh processing software called Meshlab. The Poisson Surface Reconstruction method was used with both CloudCompare and Meshlab. This method interpolates surfaces using a best fit method via the Poisson algorithm. The following figure from Microsoft Research shows a 2D simplification of the mechanism:

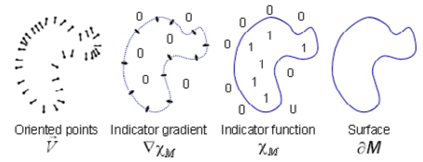


Figure 77. Poisson Logic. Source: Nader Salman

There are three important parameters that need to be taken into account during the generation of a Poisson mesh, these are the **Octree Depth**, **Solver Divide** and **Samples per Node**.

Octree Depth

The octree depth determines the resolution of the three dimensional grid within which the meshing calculations are performed, lower values give low-poly results while higher values result in more detail up till a certain point after which it gives diminishing results. Each increase in value divides the enclosing cubic grid by 8.

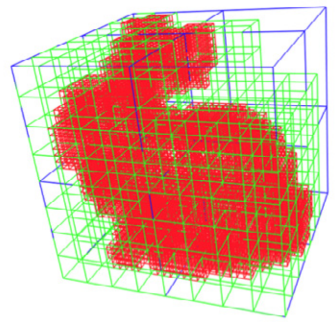


Figure 78. Standford bunny at Octree 5

Source: Alexander Agathos

The optimum octree depth is dependent upon the density of the point cloud from the scans. An **optimum value of 12** is recommended by the authors of Meshlab for high resolution scans. This value was also found to be optimum for the column mesh, higher values beyond 14 failed to provide any extra details and often resulted in insufficient memory.

Solver Divide

This parameter determines the iterations (or depth) of the calculations, lower values help control memory usage. A value of 7 is recommended by the authors of Meshlab (default value is 8).

Samples per Node

This value determines the number of points to be used in the calculations per node. It can be used to exclude isolated or anomalous points thereby smoothing the resulting mesh.

It can be used to control noise levels during the mesh, reducing dependence on noise reduction algorithms in post production. The authors of Meshlab recommend values from 1 - 5 for noise-free samples and 15 - 20 for high noise samples. Illustrated below is the smoothing that occur by varying the samples per node.

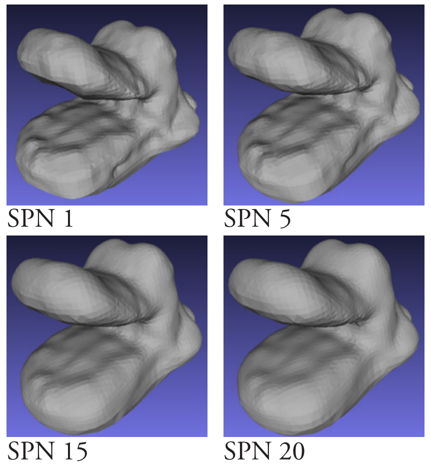


Figure 79. Detail loss with varying SPN

Source: 3D Scan 2.0

Computing Normals

Before any mesh generation process can occur, the algorithm needs to know the orientation of the normals to determine which way the newly generated surface should face. Mesh surfaces only have one side so the orientation of the normals is important for proper meshing. The normals are generally computed with respect to the shape of the geometry. After generation they can often face the wrong direction and need to be inverted for a usable mesh.

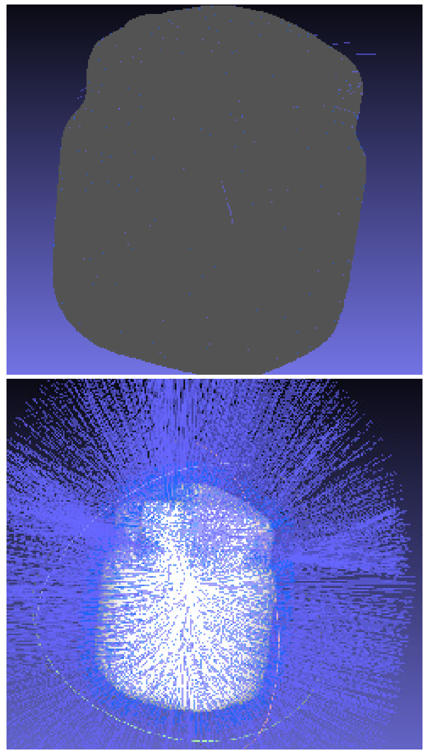


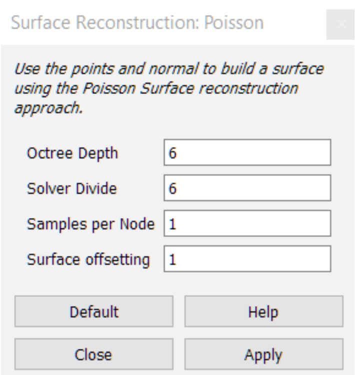
Figure 80. Un-oriented (top) and oriented (bottom) normals. Source: Stack Overflow

10.1.7 Mesh Comparison

Since the geometry had to be manufactured and had to be complementary to the existing fracture surface, it was important to retain as much detail as possible. This was done via trial and error by generating different meshes with varying software packages and parameters, namely the octree depth and samples per node.

10.1.7.1 Meshlab 1.3.3 64 Bit

The first software used for the meshing generation was Meshlab. The point cloud is first imported into the software and is automatically assigned its own layer. The normals are first calculated from Filters > Point set > Compute normals for point set. After the calculation is complete, a Poisson mesh can be generated from Filters > Remeshing, Simplification and Reconstruction > Surface Reconstruction Poisson. The meshing parameters are then set from the follow dialogue box:



The octree depth was set at 12 (higher values would cause an insufficient memory error), the solver divide was set at 7 and varying values of the samples per node were used to find the optimum noise to detail ratio.

A comparison of the meshes generated with the original mesh (with samples per node set at 1) and the corresponding values can be seen in the adjacent figures. Green values indicate the centralized displacement of the mesh. It can be seen that at a SPN value of 20, the mesh is

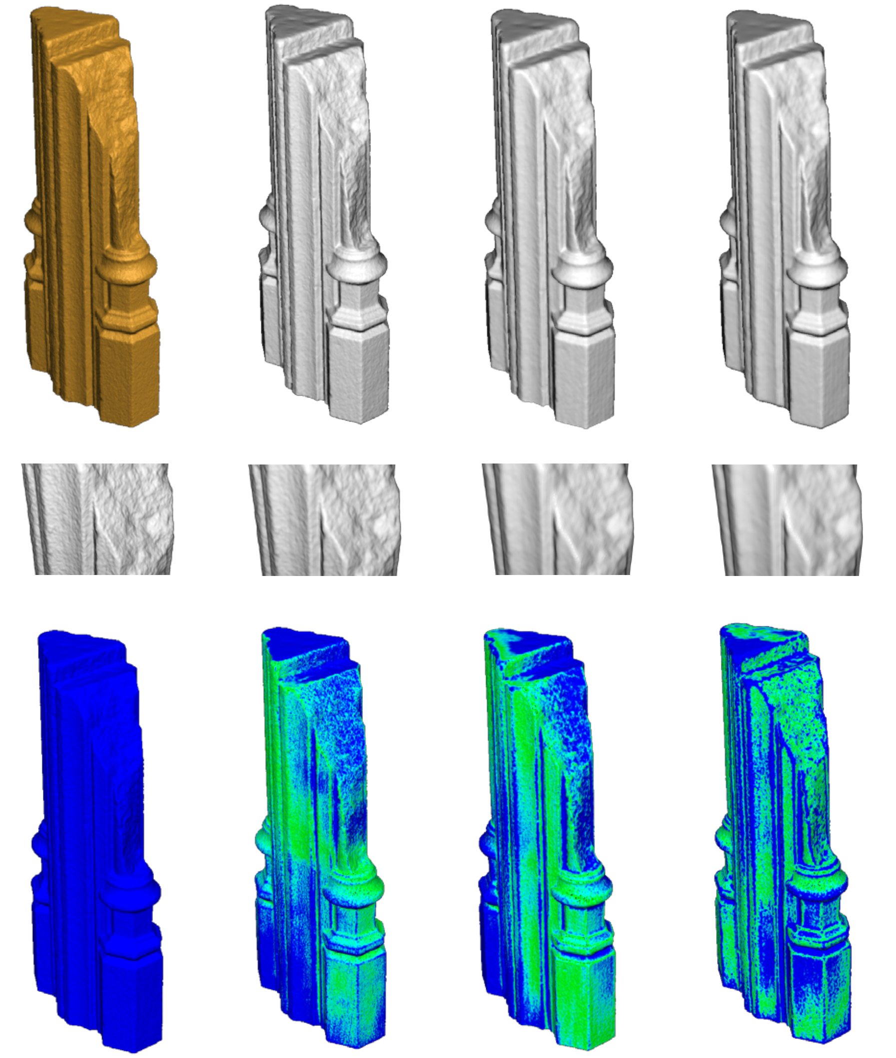


Figure 81. Geometric variation with samples per node. Source: Author

the smoothest and displacement starts to affect the fracture surface, which would have an effect on the fitting of the manufactured fragment. The average displacement remained quite unpredictable however. A value of 15 was selected as a compromise between noise and detail and was exported in the PLY format for further processing with Geomagic Wrap. When the mesh was compared with the existing stone surface it was found that the laser scanner had failed to capture the horizontal and vertical engravings on the surface. This can possibly attributed to the limitations of the scanning technology (perhaps the minimum spot size of 3.5 mm). Meshlab was eventually abandoned in favour of CloudCompare due to the inconsistent results that it was providing (the meshing would intermittently fail, leaving a bizarre looking unwrapped mesh, as pictured). Another reason for not using

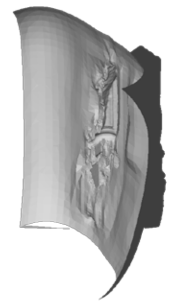


Figure 82. Failed Meshing. Source: Author

Meshlab for the final manufacturing was the limitation of not being able to increase the octree depth further than 12 due to inefficient memory management, this was not found to be a problem in CloudCompare. The exported mesh was still processed in Geomagic Wrap however and a 3D prototype was produced, the results of which can be seen in the interpolation section. Other insight gained from Meshlab included recording the difference between varying values of SPN and their effect on the mesh.

10.1.7.2 CloudCompare 2.6.2 64 Bit

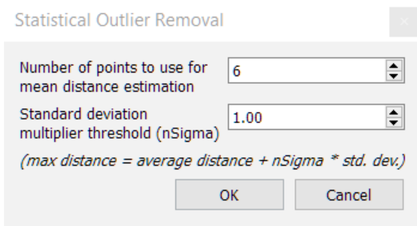
The final meshing was done on CloudCompare due to its superior memory management capabilities. Specifically for increasing the octree depth, despite the fact that values beyond 12 displayed little gain in detail, the gain was found not to be negligible. Another reason to use CloudCompare was that it gave consistent results and the meshing was successful a majority of the time. Meshlab still gives the user more control over the meshing process and multiple meshing options however.

CloudCompare does not feature a native Poisson meshing algorithm but it does come packaged with a powerful plugin that does the Poisson meshing. The following workflow was performed:

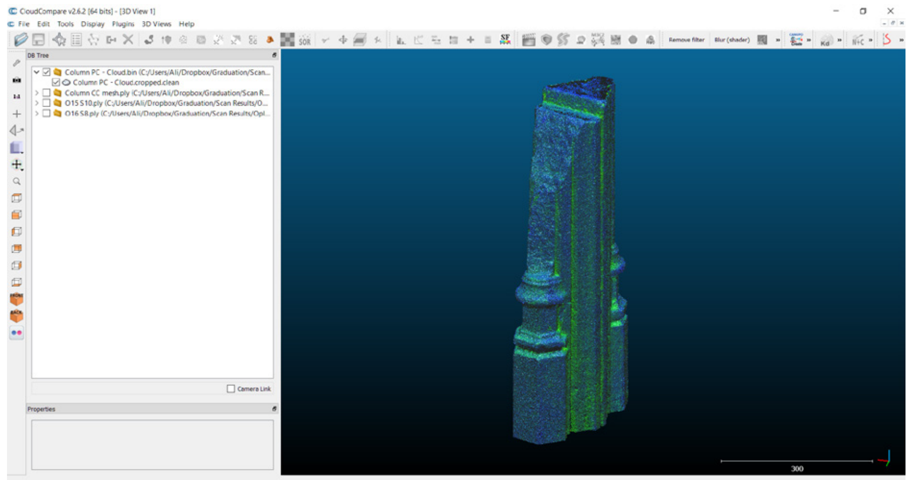
1. Importing the Point Cloud

There is no limitation to the kind of point clouds that can be imported into CloudCompare, it supports both ASCII formats and non-ASCII formats. The cloud can be imported via: File > Open > Location of point cloud file. The .pts format was used for this particular project.

2. Cleaning of Point Cloud

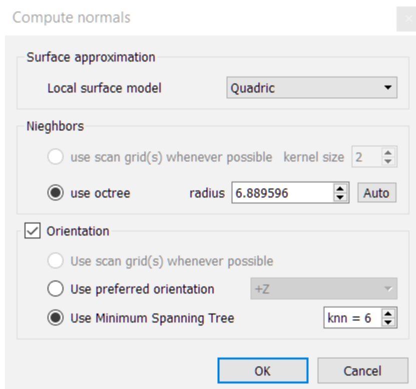


It is a good practice to remove statistical anomalies from the point cloud so that errors during meshing are minimized. The SOR filter (Statistical Outlier Removal) tool from CloudCompare can help remove any points that don't lie



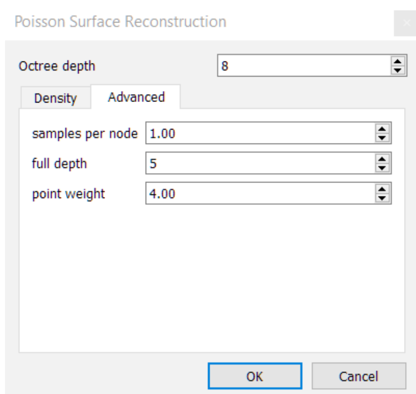
within the statistically probably range. This tool can be accessed from: Tools > Clean > SOR Filter The default values were used with good results.

3. Computation of Normals



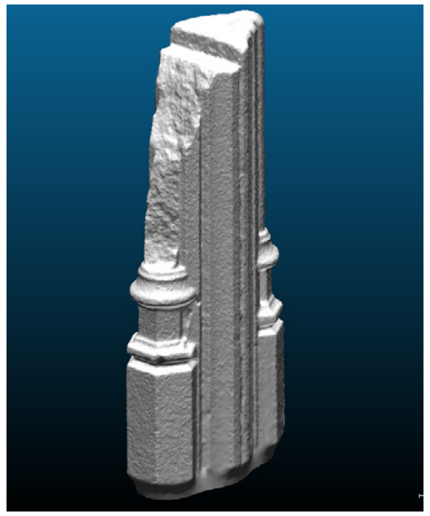
It is essential for the normals to be computed before the meshing can begin. This step cannot be skipped. The normals can be computed from: Edit > Normals > Compute A quadratic local surface method proved to give consistent results.

4. Generation of Mesh



Once the point cloud has been prepared, the mesh generation plugin can be used, which is accessed from: Plugins > Poisson Surface Reconstruction> Advanced.

Since CloudCompare manages memory more efficiently than Meshlab, higher octree depth values can be used, very high values can tend to increase the generation time quite drastically however. The initial values were set using the lessons learned from Meshlab, and two meshes with generated using different octree depth and samples per point values. The first mesh with an OD of 15 and SPN of 10 and the second with an OD of 16 and SPN of 8. The OD:16- SPN:8 mesh (pictured below) was finally chosen as a compromise between noise and detail. The retained noise could potentially also help accentuate the character of stone in the final casting.



5. Exporting the Mesh

The mesh needed to be exported in a format that was readable by Geomagic Wrap, which was used for generating the missing geometry (interpolation). The PLY (Polygon File Format) was chosen for the exporting because of its ability to store surface normals and coordinates.

Geomagic Wrap®

10.1.7.1 Geomagic Wrap 2015

Geomagic Wrap is part of a series of tools from US based 3D Systems. It is a software package specifically designed for processing and editing 3D scan data. Since it is retail and not provided by the TU Delft software repository, an extended trial license was requested and from the 3D Systems sales department for the duration of the project.

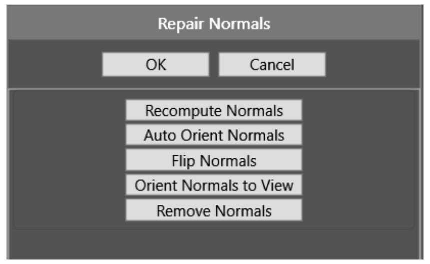
Compared to other mesh processing software, Geomagic provides less mesh processing options but is more user friendly. It is packaged with the 'Wrap' mesh processing algorithm developed by Herbert Edelsbrunner , there are less assumptions in the processing, with the effect that there is less extrapolation of data(Ramos & Sadri, 2007). This is one of the reasons that once the mesh is processed in Geomagic Wrap it is possible to find holes in the geometry which need to be patched subsequently.

The workflow for mesh processing in Geomagic Wrap is as follows:

1. Importing the Point Cloud

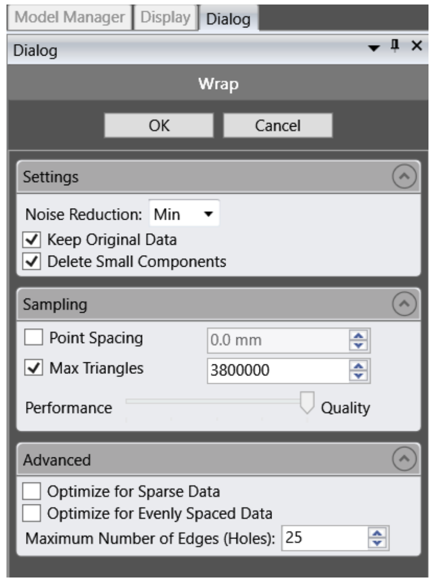
The point cloud can be imported via Menu Button > Import > Location of point cloud file. Geomagic supports all point cloud file formats. The percentage of the data to be maintained during data reduction processes and the import units can be specified from dialogue boxes before the importation completes.

2. Computation of Normals



The normals can be computed via Shading > Repair Normals > Recompute Normals from the toolbar (the point cloud has to remain selected).

3. Generation of Mesh



The mesh can then be generated by clicking on the 'Wrap' button on the toolbar. For this project, the noise reduction at this stage was kept to a minimum to give more control at a later stage if required. 'Keep original data' was kept activated in case more meshes needed to be generated from the point cloud. The sampling was kept at maximum quality to generate the most detailed mesh.

The generated mesh had 2.9 million polygons, but that was mostly because of noise. The mesh had multiple holes which could be later patched but there was a risk that this would have an effect on the fracture geometry, which would have consequences at a later stage.

The mesh fixing features of Geomagic Wrap will be discussed in the interpolation section.

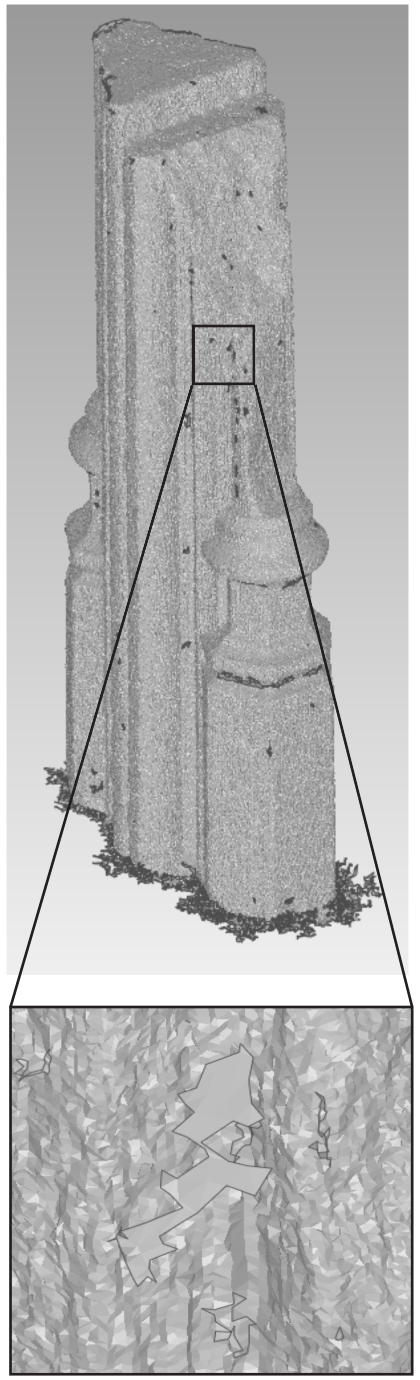


Figure 89. Generated Mesh and Holes. Source: Author

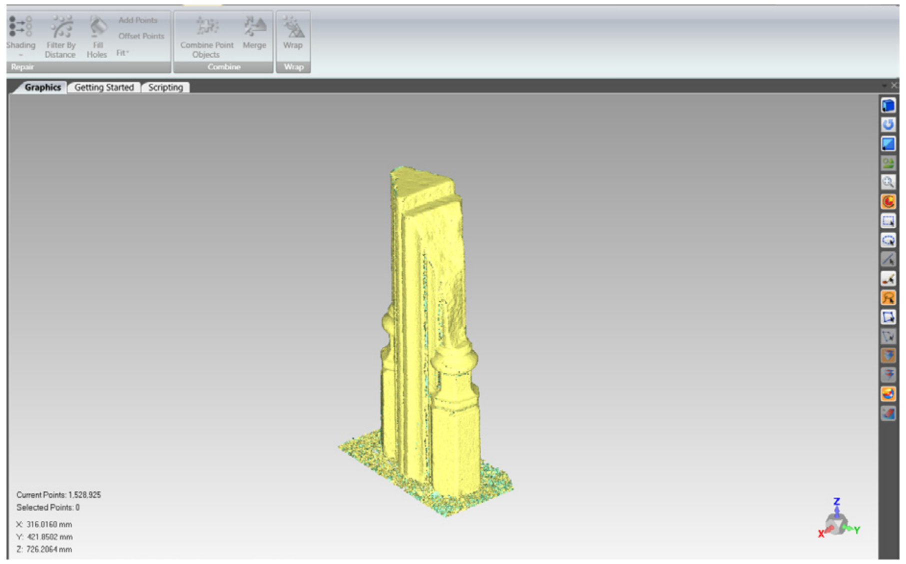


Figure 90. The Geomagic Wrap interface

Detail Comparison

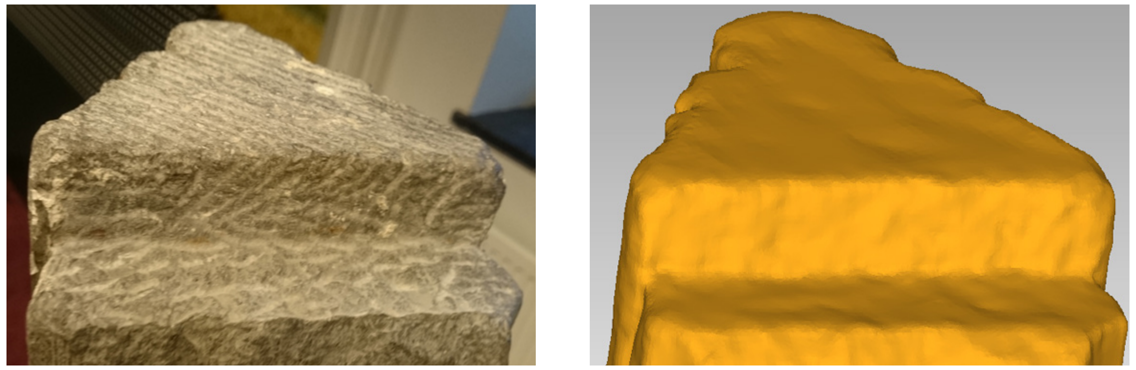


Figure 91. **Top of Column** - Most of the indentations on the surface were lost.

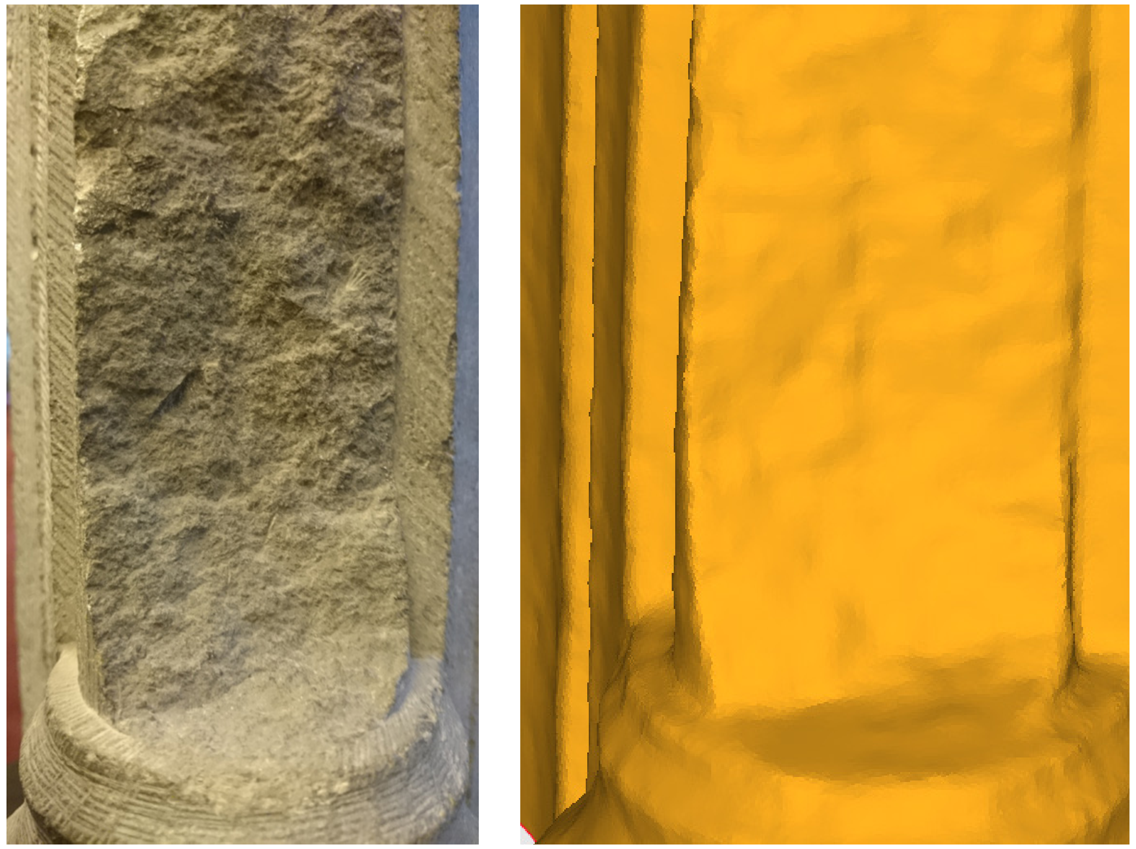


Figure 92. **Fracture Surface** - Loss of high frequency detail due to noise control is evident.

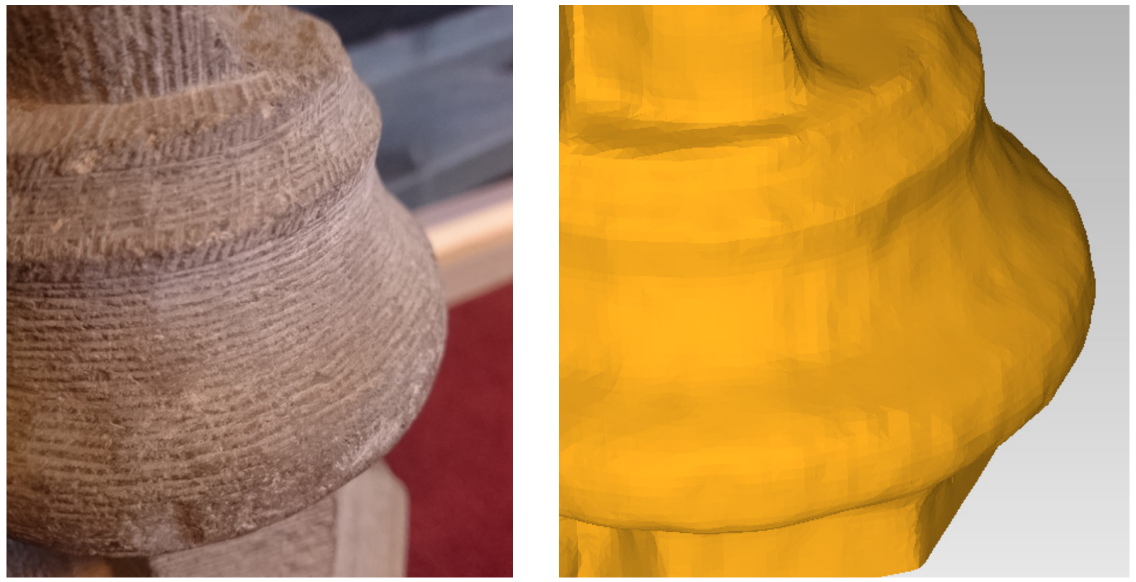


Figure 93. **Torus** - Linear indentations on the surface were lost.

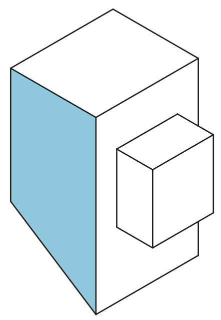
10.1.8 Mesh Interpolation Principle (Generation of Missing Geometry)

Each type of geometry requires a different approach for the generation of missing fragments, depending upon factors like symmetricity, repetition of geometry and the complexity of the fracture surface.

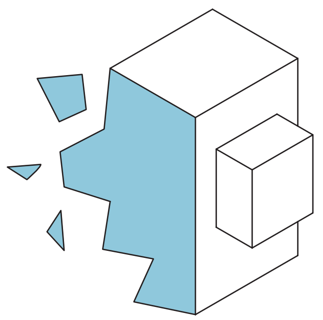
For the column fragment in this case, there were two possible approaches, the first one being extracting the fracture surface polygons and the mirrored geometry from the other side and stitching the vertices together. Since the geometry is quite complex with hundreds of thousands of vertices, this process would have been quite cumbersome.

The second approach was the Boolean approach. In polygonal modeling, Booleans operations generally subtract, intersect, merge or split overlapping meshes by detecting geometry that lies within or outside the overlapping sections. The method employed for the column segment is described in the adjacent figures.

Since the object in question is hand-crafted, perfect booleans cannot be achieved and there would also be extra surfaces present, requiring post-processing.

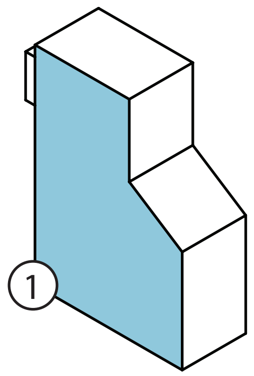


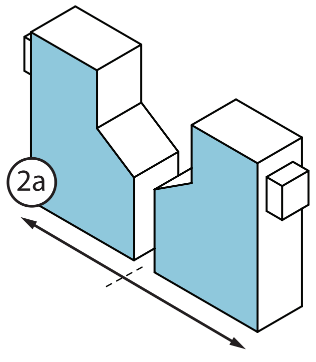
Expectation

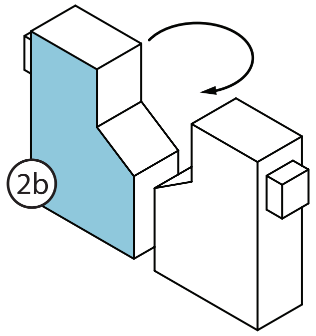


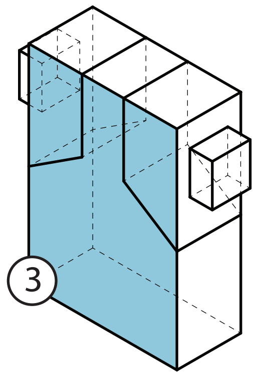
Reality

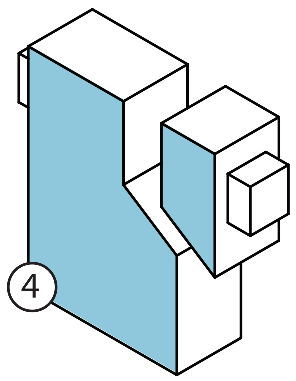
Interpolation using Boolean Operations











1. Identification

If the geometry exhibits symmetricity like the column fragment, it is possible to use the symmetrical data to predict or 'interpolate' the missing sections using boolean operations. While efficient for perfectly geometrical meshes, it can become a problem with laser scanned data, particularly if the scans are of hand crafted geometry, as will be discussed later.

2a - 2b. Mirroring or Rotating

There are two possible options for orientating the geometry for the boolean operations. The selection should ideally be on the basis of which orientation provides the best coverage of the mesh.

However, it can be postulated that there could be subtle differences between the right and the left hand side when it comes to hand-crafted objects because the tool in contact with the object is usually held in the non-dominant hand independent of which side is being crafted. Mirroring takes into account this possibility.

It is also possible however that for smaller objects, the craftsperson changes their direction of approach for the other side, inverting the sides, in which case rotation would be preferable.

3. Alignment

For perfectly geometrical mirrored or rotated volumes, alignment is not a problem but for hand-crafted objects, symmetricity depends upon the skill of the craftsman. The two objects (original and mirrored/rotated) need to be aligned using features on the surface as references for the boolean to occur perfectly.

4. Boolean Operations

In this instance, the missing geometry can be generated via a subtractive boolean operation that removes the overlapping geometry and just leaves the missing components. As mentioned earlier, this boolean would not be perfect because the hand-crafted nature of the object and would require extensive post-processing subsequently.

10.1.9 Mesh Manipulation & Interpolation (Geomagic Wrap)

The Boolean capabilities of multiple software packages was experimented with before Geomagic Wrap was selected as the primary mesh editing software.

Autodesk 3dsmax failed to give results despite taking a considerable amount of time for the boolean calculations.

Rhino 3d did provide a use-able boolean (pictured below) however but only after the mesh was decimated to about 50% of the original polygons, causing a considerable loss of detail on the fracture surface. Without the decimation, the boolean operations would fail.

The final mesh was not generated on Geomagic Wrap but rather on CloudCompare, as discussed earlier. Geomagic Wrap's superior mesh editing tools however still warranted its use.

Geomagic Wrap's Mesh Doctor (used for repairing imperfect meshes, removing spikes, holes and self intersections for example), Remesh tool (for creating a more uniform tessellation of polygons) and knife sculpting tools (for slicing and removing unwanted sections of the mesh) were indispensable during the duration of this project.

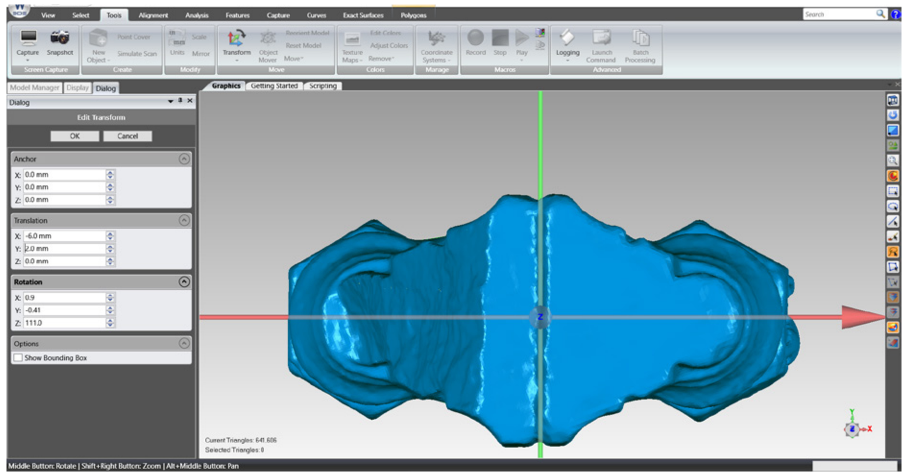
10.9.1 Manipulation in Geomagic Wrap (step by step)

1. Importing the Mesh

The mesh, earlier exported from CloudCompare as a .PLY file can be imported via Menu button > Import > Location of mesh. Millimeters were selected as the import unit since those were the units CloudCompare was operating with.

The imported mesh (**Octree value of 16 and 8 samples per node**) had a polygon count of 641, 606. While on the higher side, it was still sufficient for most 3D printers to process (which can make use of up to 1 million polygons per model).

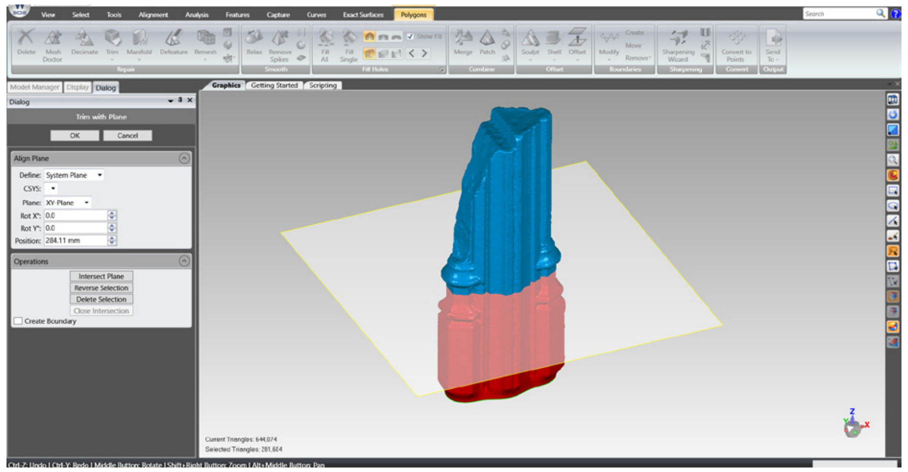
2. Alignment with the Coordinate System



After importing, the mesh was aligned with the local coordinate system for easier manipulation of the subject and mirroring.

The transformation was done using the Transform tool (Tools > Transform > Edit). Since the object is not perfectly geometrical, the transformation was performed visually, with the elongated side aligned with the x-axis.

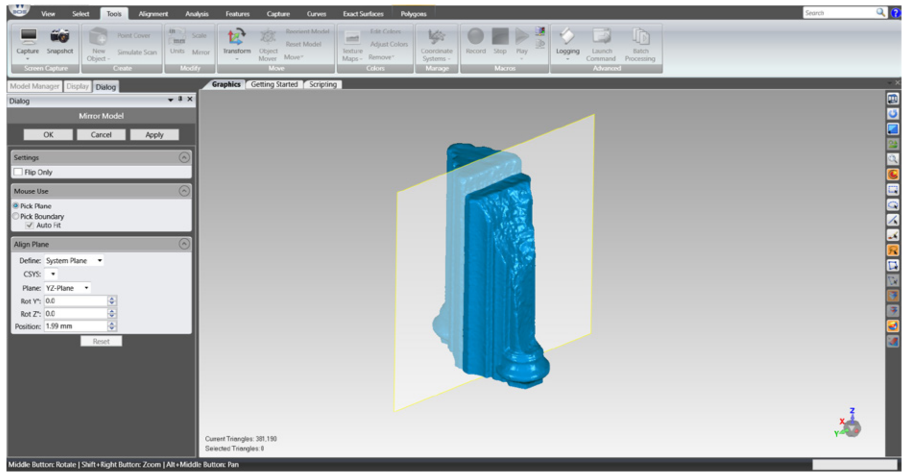
3. Cropping Unnecessary Data

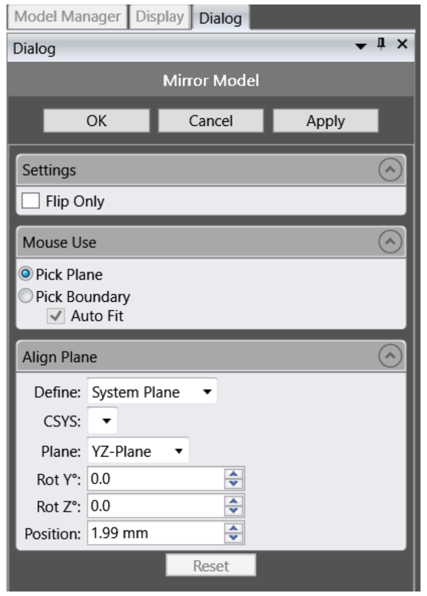


For the boolean operation, only the fracture surface and the geometry opposite was required, therefore the geometry immediately below the torus was cropped off using the Trim with Plane tool (Polygons > Trim > Trim with Plane), with the geometry trimmed using the XY System Plane. The intersection was then closed off using the same tool.

The cropping was performed to save time during the boolean process and avoiding the intersection of unnecessary geometry. The torus and some other features were left un-cropped so that they could be used as references while aligning the two mirrored geometries.

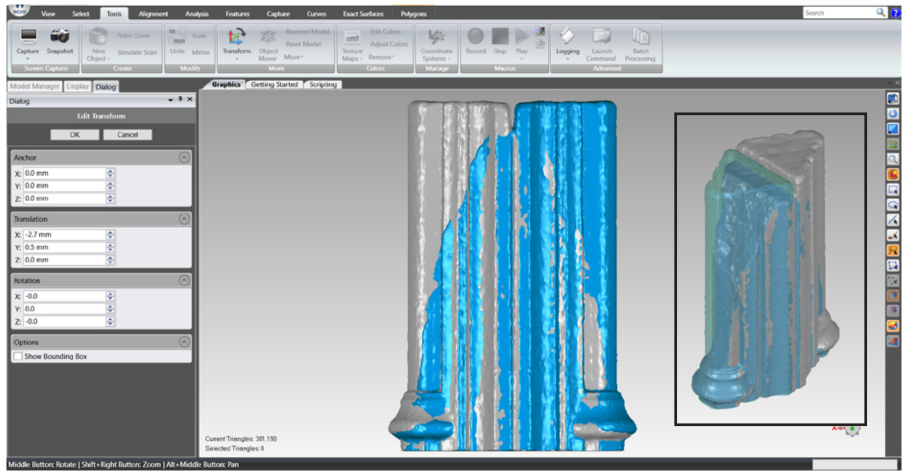
4. Mirroring

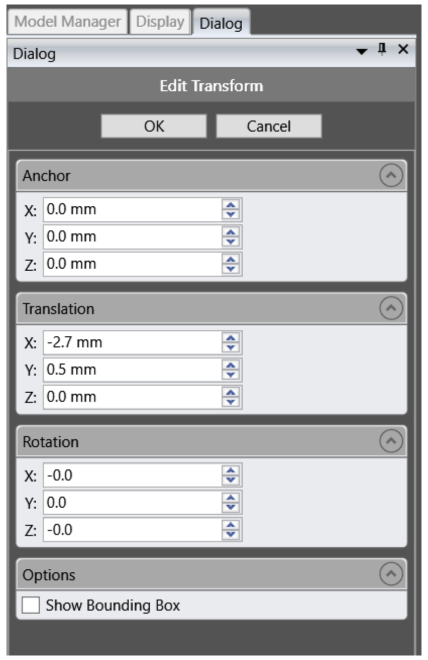




Since the model was already aligned with the local axes, the mesh was mirrored using the YZ system plane via the Mirror Tool (Tools > Mirror).

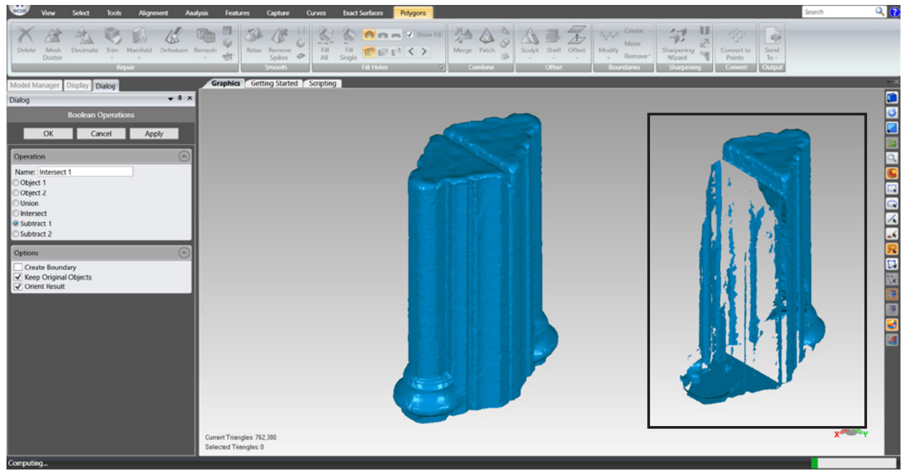
4. Aligning the Meshes

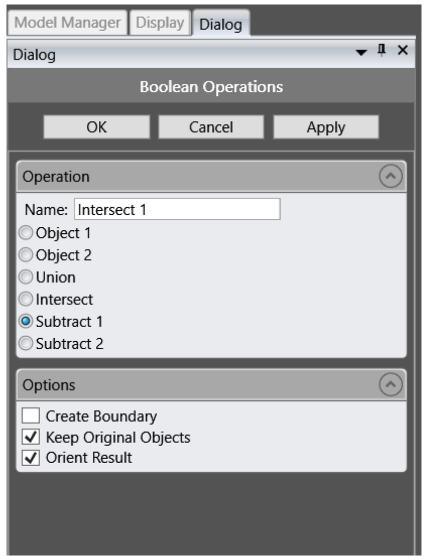




The two meshes (mirrored and original) were aligned with respect to the geometry that needed to be generated via the boolean operation. This was done with the aid of the recognizable features that were present on the geometry, such as the vertical recessions and tori. This also needed to be done visually to achieve maximum overlap of the surfaces to provide the most accurate boolean. Again, the Transform tool ((Tools > Transform > Edit) was used for the incremental transformation.

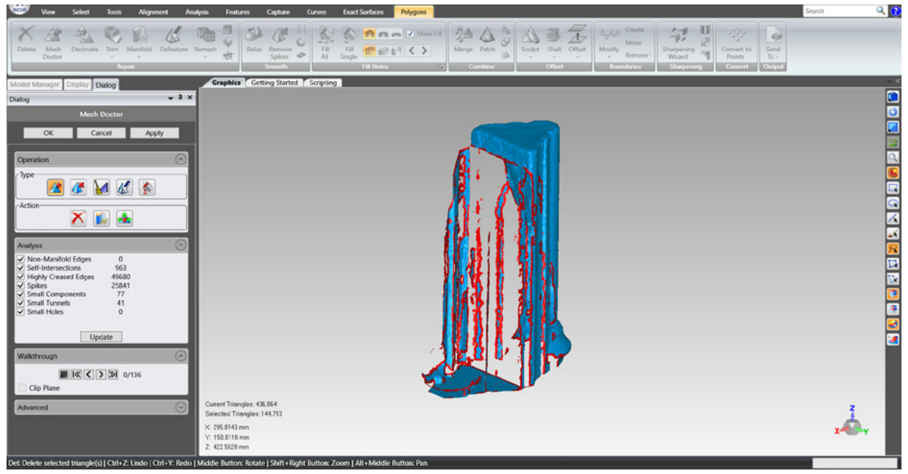
5. Boolean Operation

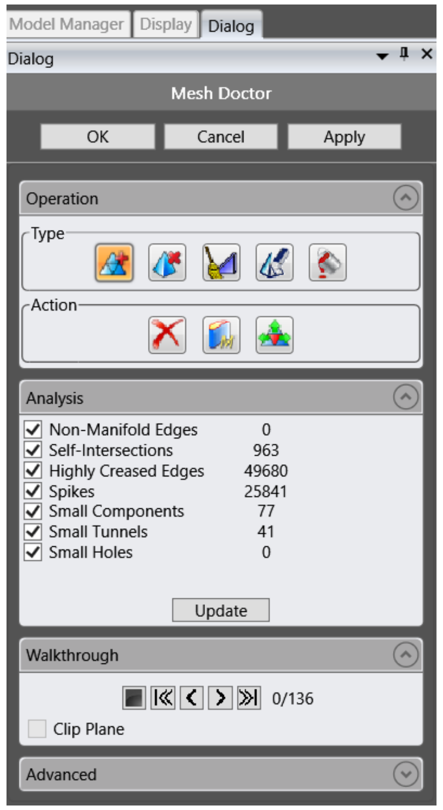




A subtract boolean operation was performed with the two meshes selected from Polygons > Boolean > Subtract 1 or 2 (any since the meshes are duplicates). The mesh result was not perfect and was cleaned up in subsequent steps.

6. Cleaning the Mesh

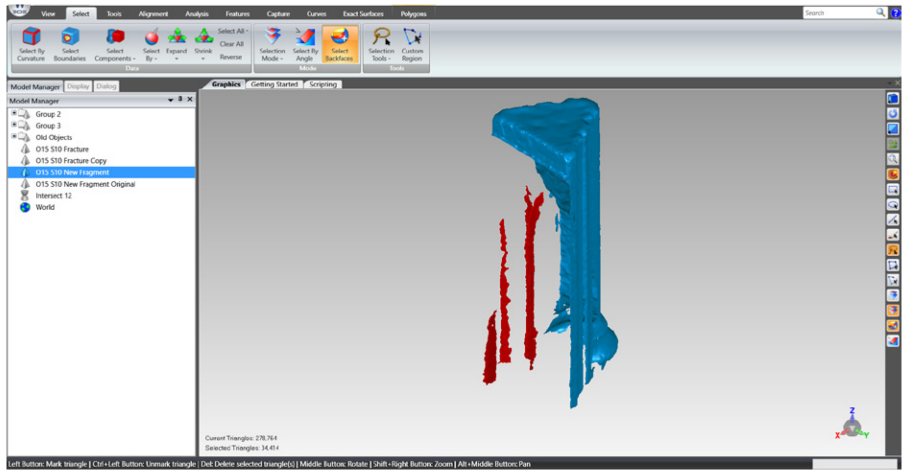


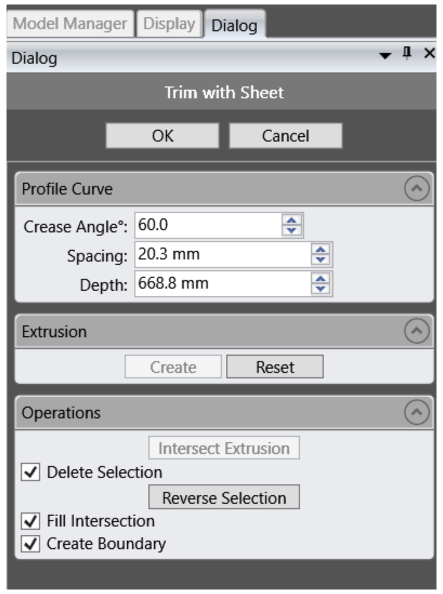


Because of the geometry being hand crafted (as mentioned earlier), the imperfections in the sculpted piece were made evident after the boolean, some of it may also be due to errors in the alignment of the meshes (since it was performed visually). These imperfections can be cleaned using an array of tools available within Geomagic Wrap.

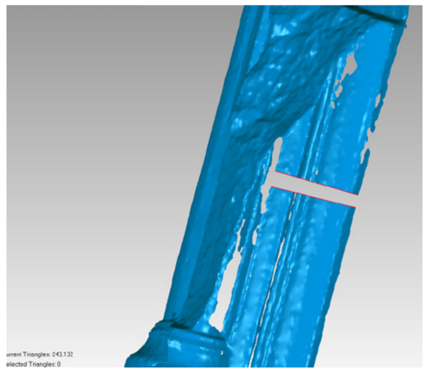
The mesh was first passed through Mesh Doctor, an automated tool that detects highly creased edges, spikes (sudden extreme jumps in geometry, possibly caused by noise), and self-intersections. Mesh Doctor can be accessed from Polygons > Mesh Doctor. After the processing, most of the troublesome and isolated geometry was automatically removed.

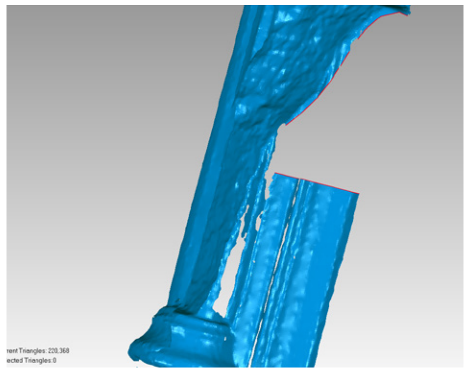
The remaining isolated geometry was selected and removed using the Lasso tool (Select > Selection Tools > Lasso). It should be ensured that the selection mode is set to 'select through' to ensure all of the geometry is selected.

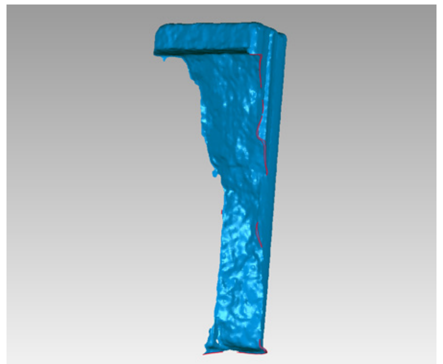




The attached geometry was then removed using the Trim with Sheet tool (Polygons > Trim > Trim with Sheet). This tool projects a sheet referenced from a manually drawn curve parallel to the line of sight of the viewport. The viewport had to be rotated multiple times to get the best slices.



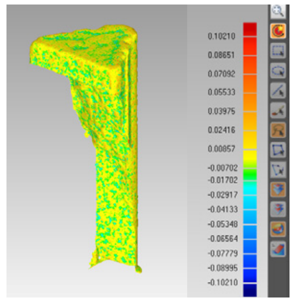




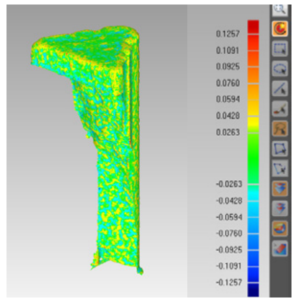
7. Polygon Decimation

Decimation is a technique for reducing the number of polygons in the mesh while retaining the general shape of the volume. The reduction in polygons can result in faster performance of mesh calculations.

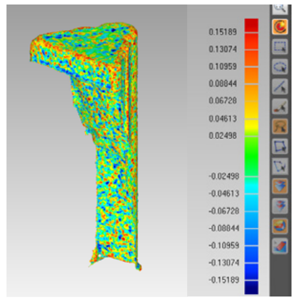
The decimation tool can be accessed from Polygons > Decimate. To retain the existing geometry as much as possible, the Curvature and Mesh Priority were set at Maximum. The deviations recorded with the fragment are illustrated in the diagrams below.



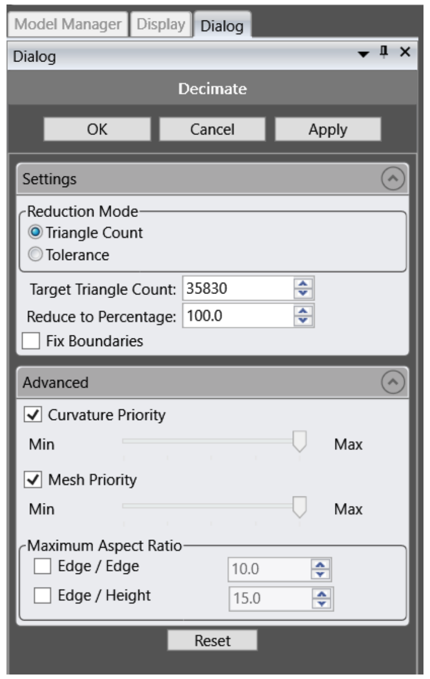
50% Triangles



25% Triangles



10% Triangles



After experimentation, it was decided to skip decimation for the final model to avoid any possible loss of geometry due to the amount of accuracy required for the process. However, in certain cases (when the number of polygons exceeds 1 million, for example) decimation would be required. The un-decimated mesh and the fracture geometry were then exported in .PLY format for sculpting in Geomagic Freeform Plus.

Geomagic Freeform® Geomagic Wrap®

10.9.2 *Sculpting in Geomagic Freeform Plus and finishing in Geomagic Wrap*

For the project, a 15 day trial version of Geomagic Freeform Plus was used to remove unneeded geometries that could not be achieved using the Geomagic Wrap trim tools or boolean operations.

The geometry was reimported into Geomagic Wrap to fix discrepancies however. Freeform is a sculpting tool which can be used in conjunction with graphics tablets or ideally haptic devices from Geomagic which provide contact feedback. For this project, a Wacom Intuos 4 graphics tablet was used for the sculpting.

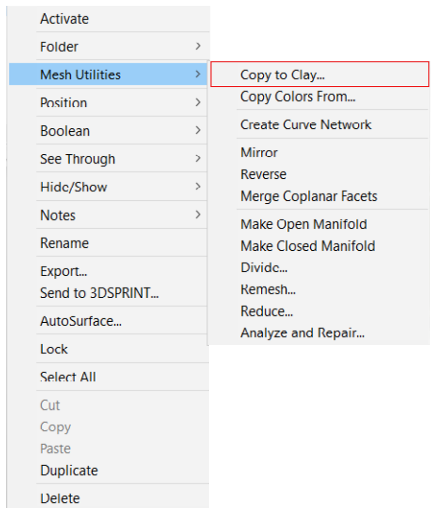
1. Importing the Mesh

The mesh was imported into Freeform Plus via File > Import Model > Location of Mesh. The object was imported as a mesh but needed to be converted to clay for the sculpting tools to work.

2. Conversion to Clay

The mesh was then converted to clay as a copy via the context menu on the object list, which can be accessed from Right Click > Mesh Utilities > Copy to Clay. This creates a 'clay' copy of the mesh, enabling the sculpting tools.

'Clay' is essentially a conversion of the mesh to 'voxels' which are three-dimensional representations of geometry in space, like pixels but in three dimensions. This conversion helps the software emulate the consistency of clay, making the process of sculpting more intuitive, as opposed to meshes which are represented by polygons defined by vertices (points in space).



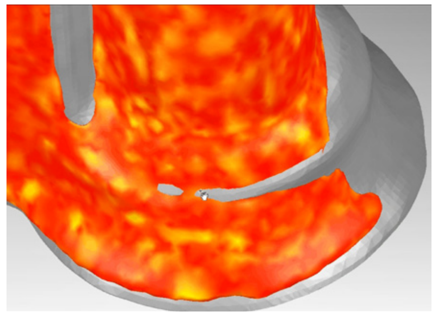
3. Sculpting the Clay

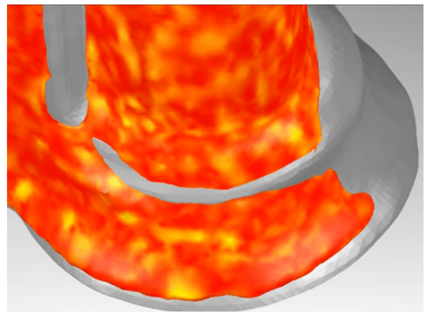
There are multiple sculpting tools that can be utilized in Freeform Plus. Three of the sculpt tools that were primarily used for the removal and adjustment of geometry were the **Carve, Smudge, Smooth and Hot Wax** tools.

For this project, the carve tool was used to make rough cuts in the new fragment geometry along the fracture surface. These cuts were then further defined using the smooth tool, this tool also helped avoid the generation of any jagged geometry. The hot wax tools were also used on occasion but sparingly due to their rapid deformation of the geometry.

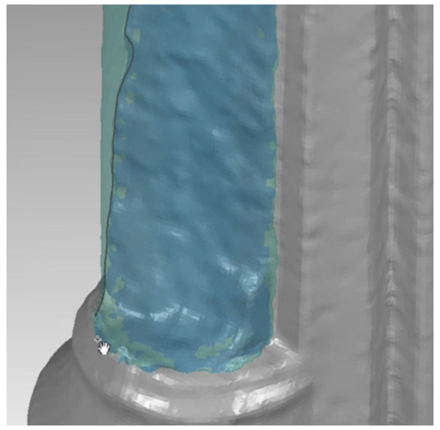
The smooth tool was also used to smooth out any sharp geometry. This was done intentionally to make the molding process more streamlined by helping avoid the breakage of geometry during casting.

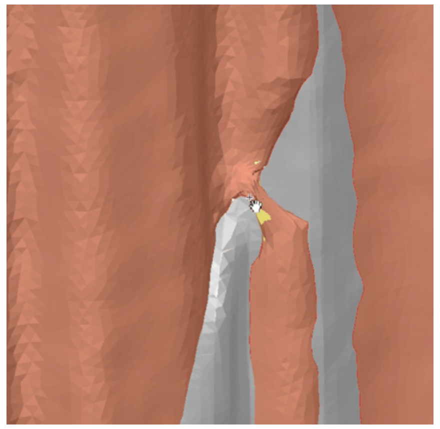
Not all of the sculpting tools were available to use however due to the unavailability of a Geomagic Haptic device, which was required for these tools to function.

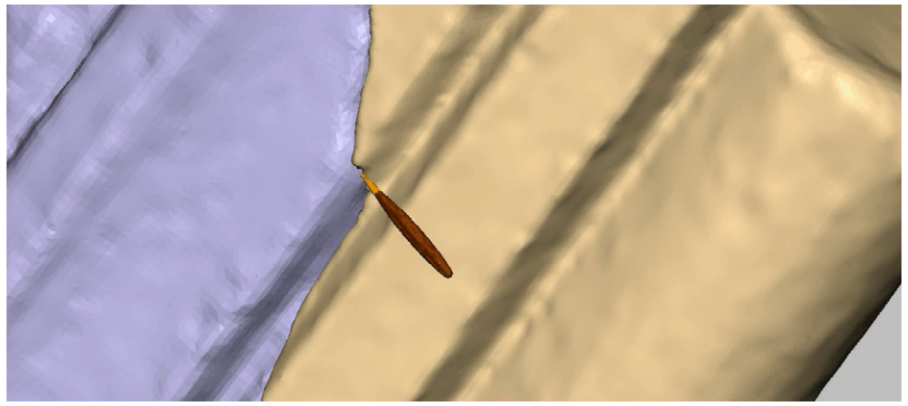


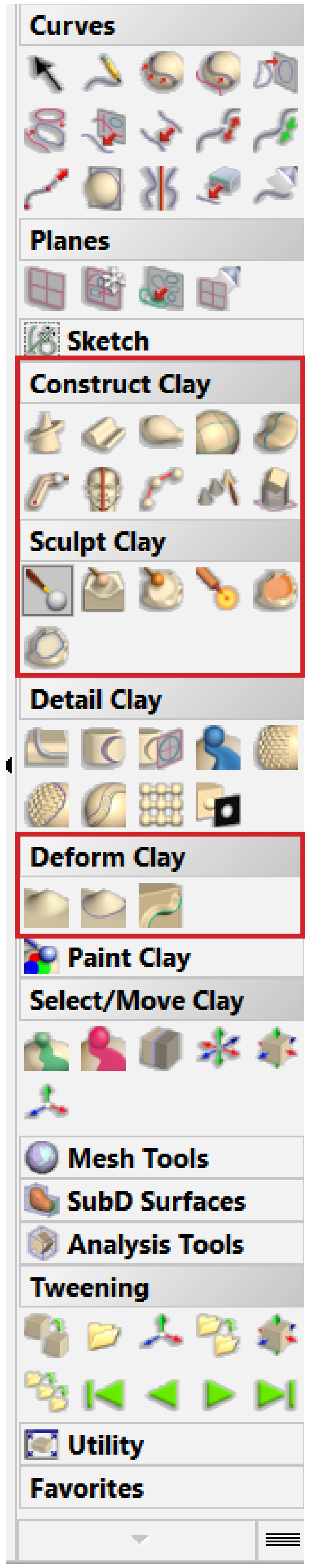


Another modeling aid was the transparency mode or 'See through' mode, accessed from Right Click > See Through > Turn on. This helped aid the modeling process by making the fracture surface visible, helping make sure that the fragment conformed to its edges while modeling.



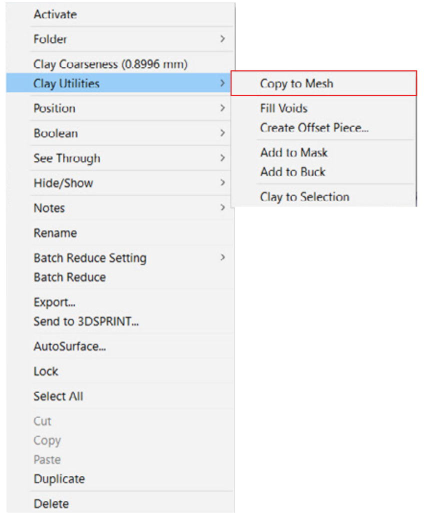






4. Conversion to Mesh and Export

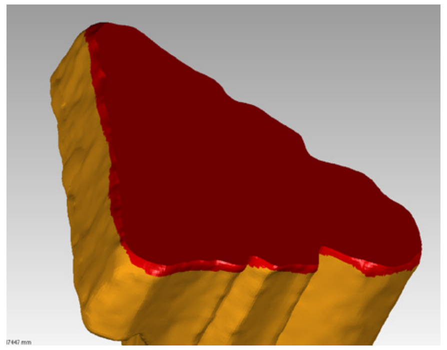
After the conclusion of the sculpting, the clay was converted back to a mesh via the context menu accessed from Right Click > Clay Utilities > Copy to Mesh, creating a new mesh using the clay as a reference. No loss of detail was noted during the conversions. The newly generated mesh was then exported in the .PLY format for further processing in Geomagic Wrap via File > Export Model.

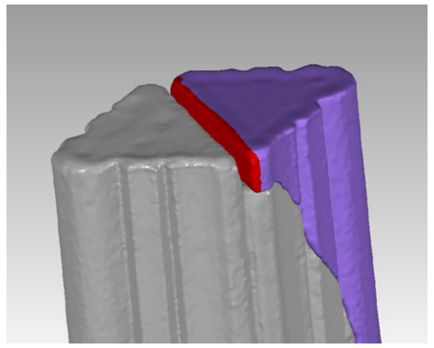


5. Finishing in Geomagic Wrap

The mesh was reimported into Wrap and passed through Mesh Doctor again to remove any errors in the geometry.

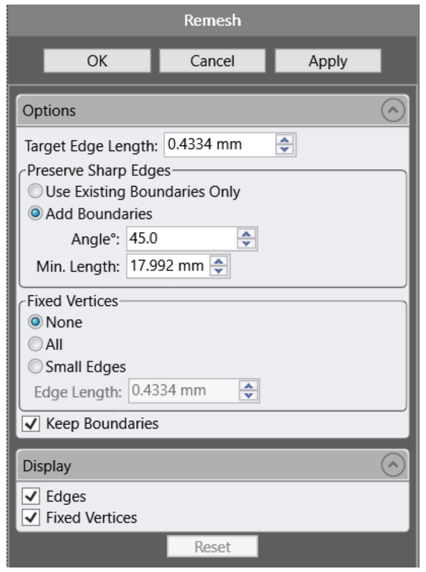
The surfaces on the top and front of the mesh were flattened to more closely match the original stone column. These distortions had occurred earlier during the meshing process but were easily fixed using a combination of the Trim with Plane tool and the deletion of polygons to create holes which were then filled with the Fill Hole tool (Polygons > Fill Single) on the Tangent setting. Some of the sharp edges produced were then smoothed out using the Relax tool (Polygons > Relax).

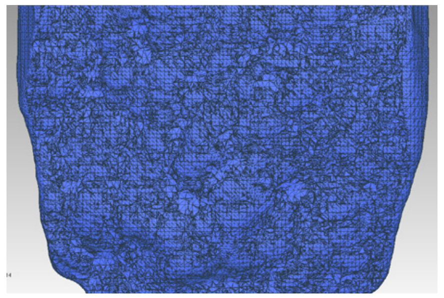




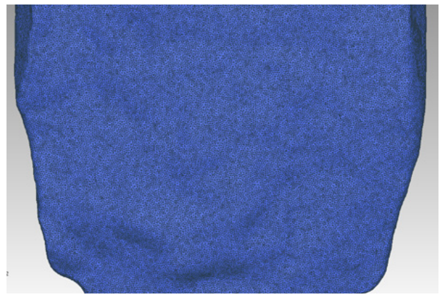
6. Remeshing in Geomagic Wrap

By this point, all the required editing of the mesh had finished. The mesh was then Remeshed using the Remesh Tool (Polygons > Remesh) for a more consistent distribution of polygons. The 'Target Edge Length' value has to be experimented with to make sure that there is no loss of geometry during the process, smaller values ensure that the smallest details are retained. Remeshing ensures that no problems occur during the 3D Printing process.





Before Remeshing



After Remeshing

7. Finalising the Mesh

Finally, a manifold check as performed from Polygons > Manifold > Make Manifold (Closed) this makes sure that the mesh is watertight and therefore suitable for 3D printing. At this point, the Boolean operation was repeated using the original fractured column mesh and the newly generated mesh to make sure that no part of the fracture surface had changed. No change was recorded. From this point onwards, the mesh was ready to be manufactured.

10.1.10 Manufacturing

Multiple approaches were considered for the manufacturing of the missing fragment. Some of the factors that were considered during the selection of the manufacturing technique were:

1. Compatibility of Materials

One of the factors affecting the selection of the new material is the physical compatibility of that material with the existing Belgian limestone. A material with different thermal expansion and contraction rates for example would not be able to bind with the original material and cracking would occur. In the case of stone, milling techniques would provide the possibility of recreating the elements in the original stone material but at a much higher cost. Alternatively, especially if milling facilities are unavailable, castable stone substitutes such as concrete (colloquially known as liquid stone) could be used.

2. Contrast between Old and New

As discussed in earlier sections, a contrast between the existing elements and the new restorative elements adds a layer of honesty to the restoration. It allows the person experiencing the site of built heritage to individually determine the state of the site before the intervention while at the same time get an idea of how the site was originally meant to be experienced.

This contrast can be approached by using a different material than the original, creating the missing element with no state of wear i.e. in the original state (the difference can be appreciated in the adjacent images), or offsetting the new geometry from the original (as is the case with the Parthenon restoration.

3. Availability of Techniques

In war torn regions or the third world, there are often minimal cutting edge manufacturing technologies readily available or importing such technologies could incur unplanned costs. In such circumstances compromises have to be made. These compromises then have an effect on the state of the final restoration.

Option: Creation of new geometry

Following the footsteps of the Parthenon restoration, new geometry would be easier to manufacture and give insight into the original state of the structure.

Option: Reusing existing geometry

Compared with using new geometry, using the existing geometry has a relatively complex workflow but the results would be less distracting and would give insight into the state the structure would be in had it survived without drastic damage and just experienced regular wear and tear.

Preferential Workflows

For the restoration of the column segment there were certain preferential workflows that could have been followed. The selection of the workflows was decided upon considering the aforementioned factors. The workflows are as follows in order of preference:

1. Direct Multi-axis Milling of Stone

Depending upon whether a conservation charter is being followed (such as the Burra and Venice charters) there could be certain stipulations that may need to be enforced. Ideally, the missing stone fragment on the column could have been manufactured using stone (even the same Belgian blue limestone) but due to the unavailability of multi-axis stone milling equipment and the prohibitive costs of commercial options, this workflow was discounted.

2. Casting with Cement

The option to create a mold using a digitally fabricated 'pattern' or reference of the missing geometry was more accessible and would possibly achieve similar results despite not adhering to charter stipulations.

One risk however was losing detail after every stage of the mold making process. This loss of detail would be experimented with during the prototyping stage. The results and workflow options can be seen in the prototyping section.

Casting was eventually chosen as the preferable option due to it being more accessible combined with the possibility of giving usable results with similar properties to the original material, and the ability to reuse the mold to create a variety of prototypes.

3. 3D Printing Concrete

While concrete 3D printing technology is still in its infancy, it should be possible to get usable results via hybridization with other manufacturing technologies. An option was to print a rough volume of the missing fragment and then finish it using a CNC milling machine, refining the details. As the technology develops, this workflow may be the preferential option even without hybridization.

Chosen Workflow

The final chosen workflow for the manufacturing of the missing fragment was casting cement. This could be done using one of three possible ways, using investment casting (lost polymer method), creating a silicone negative using a 3D printed positive or by directly printing the mold.

Investment Casting

The potential investment casting process is illustrated in the adjacent diagrams. This process was later discarded for a number of reasons. The primary reason being that since the top of the geometry to be manufactured was flat, a closed mold was not needed and hence the investment casting process was unnecessary. Secondly, the leaking polymer could potentially damage the oven being used and hence required an oven dedicated for this process.

Silicone Molding and Casting

3D Printing the mold directly on the other hand would also present problems. Firstly, the mold would require thick walls for reinforcing the poured cement and would therefore require a larger build volume on the 3D printer as compared to just directly printing the positive. Build volume being one of the major constraints of modern consumer polymer 3D printer, this would be infeasible.

Therefore, it was decided to manufacture the positive and then create a mold using the positive as a reference. This would be done by layering (using a brush-able silicone mixture) and pouring (using a standard molding silicone mixture) silicone around the print, reinforcing the silicone mold with either poured gypsum or milled wood and then removing the printed 'pattern' to pour the cement. The specifications and ratios involved in the process are discussed in detail in the prototyping section.

The basic process is illustrated in the figures on the next page.

Figure 131. **Investment Casting Process (Secondary Workflow)**

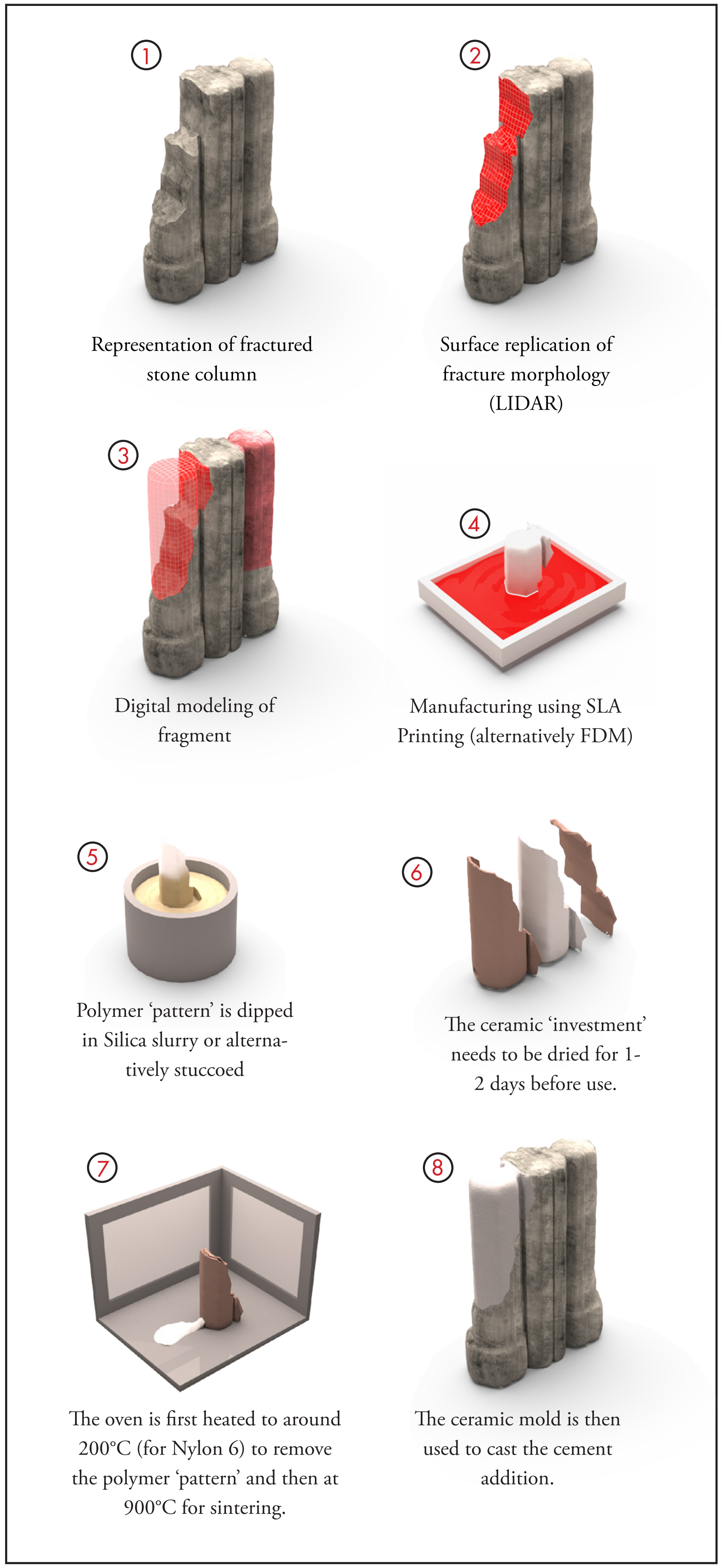
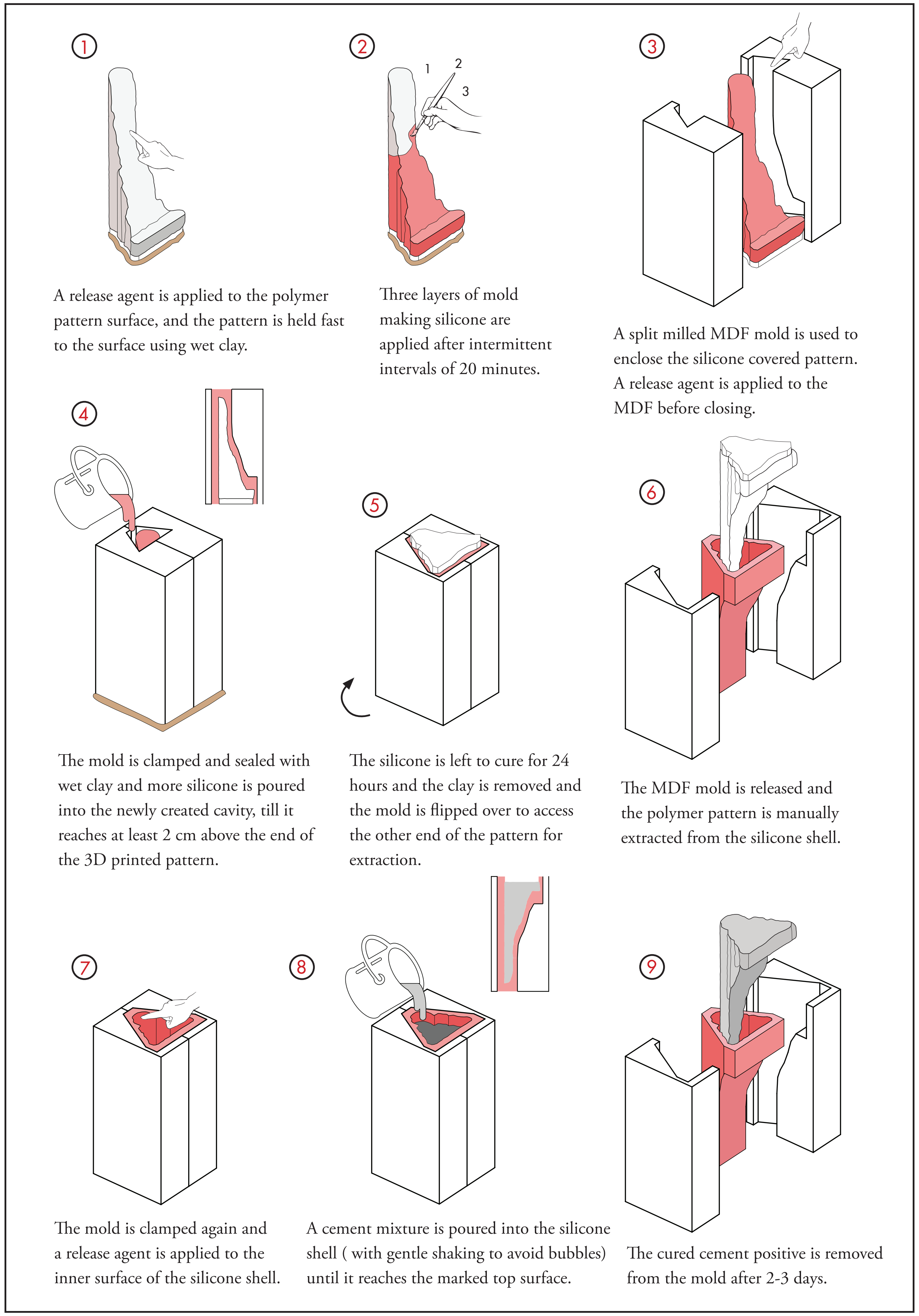


Figure 132. **Silicone Molding and Casting Process (Primary Workflow)**



Prototyping

Prototypes were created at various stages of the research. One of the first 3D prints were sections of the missing fragment created to test the conforming of the processed complementary fracture surface on the existing fracture surface on the stone.

The first sample was created at an earlier stage using the mesh exported from Meshlab (the CloudCompare mesh was finally used, due to the ability to use a higher octree depth value) using a Project 360 a powder based printer using a proprietary 'VisiJet PXL' gypsum based material. The print did conform to the fracture surface as pictured but the print eroded readily due to the powder based nature of the material. Any further exploration with this material was therefore suspended. Another problem was the excess smoothing of the mesh exported from Meshlab, particularly the vertical filleted corners which seemed to have a larger radius that the actual stone.

Ideally, the final print was to be printed using the Form 1+ printer available at the AE+T faculty using their proprietary clear resin. This printer was chosen due to its high speed and resolution capabilities as well as providing a relatively smoother surface compared to FDM printers. All prints were to be printed at 0.1 mm as a compromise between detail and time. However, the first test print failed halfway (as pictured), the problem was diagnosed as a faulty resin tank. Part of the fracture surface had successfully printed and was tested on the stone, providing a much better fit as compared to the ProJet printer. This seemed to be a positive development and it was decided to continue using the printer.

Figure 133. Testing Morphologies and Failed Prints. Source: Author

The resin tank was replaced and a 3-part full scale mesh was modeled, with each part fitting inside the build volume of the printer. The parts were to be connected using three cylindrical insertions with a tolerance of 0.1 mm. Since the Preform program did not support reducing the fill density, a decimated copy of the mesh was offset inwards and subtracted from the original mesh to create a shell to save material. The first part (bottom fragment) failed at the 40% mark. It was deduced that the curing laser was faulty and further tests were therefore suspended.

Due to these faults, the secondary option of using the available FDM printer was opted for despite the fact that this choice would result in visible lines marking the layer thickness on the surface. It is possible to smooth the surface either by dipping the printed parts in a corrosive liquid (tetrahydrofuran for PLA for example) or sanding but this would result in loss of accuracy and was not considered.

The visible lines were not necessarily considered to be a setback for the process, they could potentially give insight into the chosen process for the restoration and would communicate more information to the viewer. Another advantage of using FDM was the considerably larger build volume available, making it possible to create the final print in 2 pieces rather than 3.

Figure 134. Three part model with cavity for Form 1+ Printer. Source: Author

Scale Model Tests

While the full scale section tests were being carried out, experimentation was also started on creating a cast at a smaller scale. These experiments were performed on a 1/3 scale model of the original fragment printed in one piece in PLA with a layer thickness of 0.1 mm.

The objective of the tests was to test the mold making process, the interaction of the mold making materials with the printed polymer and finding the right mixture and type of cement to cast sufficient detail, the right shade and strength.

The tests were performed in Stevin Lab II of the faculty of Civil Engineering, TU Delft under the supervision of Telesilla Bristogianni.

Silicone Specifications

For this project, the Mold Max 30 series of silicone from Smooth-on was used for the mold making applications.

The silicone kit consists of two constituents, a Part A and Part B. After Part A has been measured out on a scale, Part B, the curing agent is added at a 1:10 ratio (measured on digital scale) and mixed. The standard Mold Max 30 Part B makes the silicone suitable for pouring but does not have the adhesion required for brushing.

For this project brushing was chosen as a necessary measure to capture the highest detail possible on the silicone and to avoid bubbles that can occur during pouring. A different Part B (Mold Max Stroke) had to be used for the brushing applications. Unlike the Mold Max 30 Part B, this Part B was colorless and had to be mixed longer to ensure that it had mixed with all the silicone.

The Molding Process

A release agent was applied to the print surface (Vaseline, Petroleum Jelly).

The print (pattern) was held upright using wet clay to start the molding process.

The pattern was brushed with three layers of silicone (using Mold Max Stroke Part B).

The enclosed pattern was embedded in clay half way to make sure that the poured gypsum only covers half of pattern. Vaseline was then applied to the clay and silicone surfaces as a release agent.

The pattern enclosed from five sides with plywood panels (with release agent applied to the inner surfaces) which were then held together using clamps.

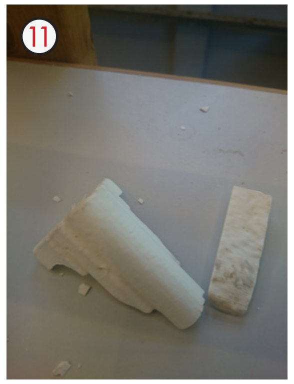
Mixed gypsum (plaster) was then poured (1 part water, 2 parts gypsum) and the mixture was left to cure for an hour.

Holes were dug on the gypsum surface to ensure that the two parts of the mold would adhere together. A clay funnel was created to make room for the material to be casted later.

A gypsum mixture of the same composition was poured to create the complementary part of the mold. A release agent was applied to all exposed surfaces before the pouring.

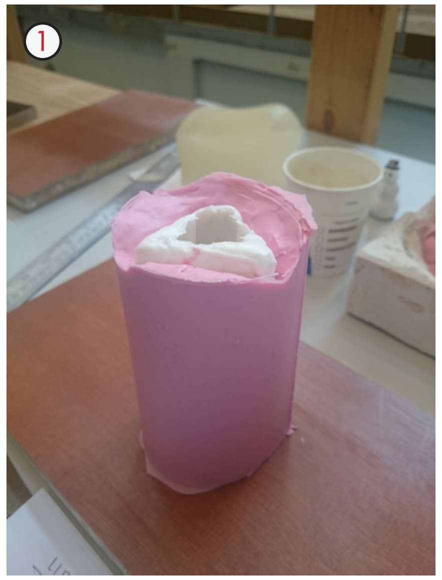
The clamps and plywood were removed and the mold was inspected.

On this instance, the mold was damaged during the removal of the 3D print pattern but it was still usable.



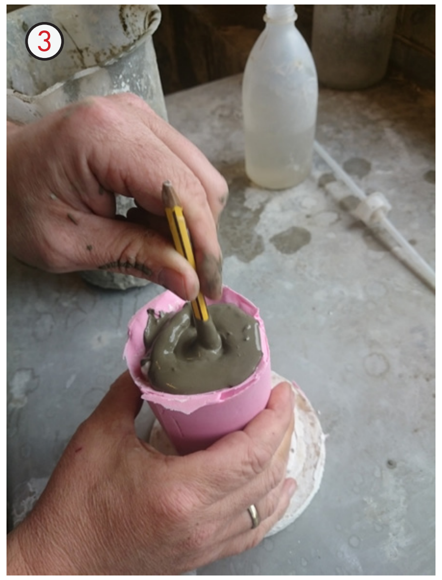
A test gypsum sample was cast in the mold, unfortunately the mold proved to be too stiff and the cast was damaged.

Alternative Method



Due to the nature of the geometry, the first method proved unsuccessful. Therefore, the brushed silicone was removed from the gypsum and a cylindrical silicone cushion was cast around it (using Mold Max 30 Part B).

A mixture of i.tech Ultracem 52.5 cement was poured into the new mold, mixed with water with a ratio of 2:1 (two parts cement).



The mixture was gently shaken and mixed inside the mold to prevent bubbles forming inside the mold.

The casted cement broke upon removal. It was postulated that this occurred because the cement mixture did not have enough time to cure.

The cement was casted again but this time was left to cure for two days. A screw was added to the narrower part as a precaution.

The cast was removed successfully in one piece but had a cavity at the bottom, possibly due to insufficient shaking and mixing during pouring.

Final Production

Since the use of FDM (Fused Deposition Modeling) 3D printing technology was selected as the primary mode of production, the print could now be manufactured in two parts due to the larger build volume provided by the Ultimaker 2+ Extended printer.

This time, a tolerance of 0.3 mm was used for the cylindrical inserts. A higher value was used so that small adjustments could be made if necessary during the glueing process. Like earlier, an extruded platform was modeled on top of the fragment to create a pouring cavity during the production of the mold.

Printing Specifications

The final print was manufactured with a layer height of **0.15 mm** and a fill density of **20%** with a print speed of **50 mm/s** using a standard white **PLA** filament.

The printing took considerable time however, with the top fragment taking up to 20 hours and the bottom fragment around 12 hours.

Mold Reinforcement

An enclosing box was modeled to save material while pouring the silicone shell. The box was milled out of MDF and would be clamped together during the manufacturing process.

The box consisted of two pieces with simplified cavities that conformed to the basic shape of the fragment to be manufactured but with an offset of 2 cm. This would essentially be the thickness of the second silicone shell.

Post Processing

Since the 3D printed 'master' was going to be produced in two pieces, there was going to be a joining cavity that could potentially be transferred to the mold. In view of this, there were two options, either to sand it out on the 3D print itself or to sand it on the casted cement. The latter option was chosen since any damage to the master could potentially delay the process considerably, whereas the cast could just be casted again.

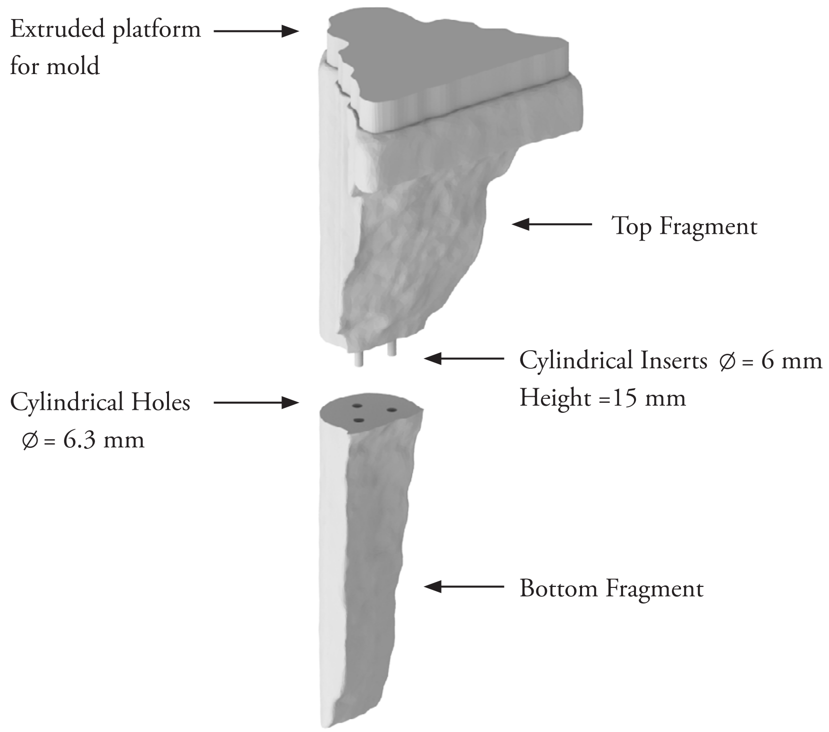


Figure 153. Two part model for Ultimaker 2+ Extended Printer. Source: Author

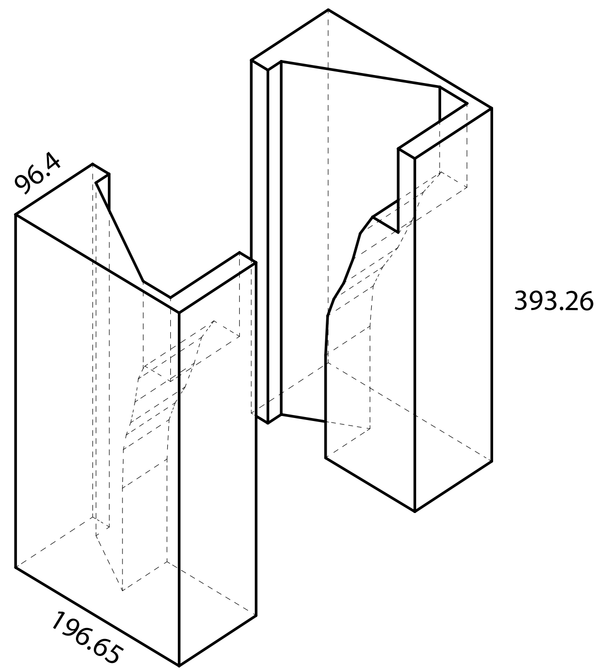
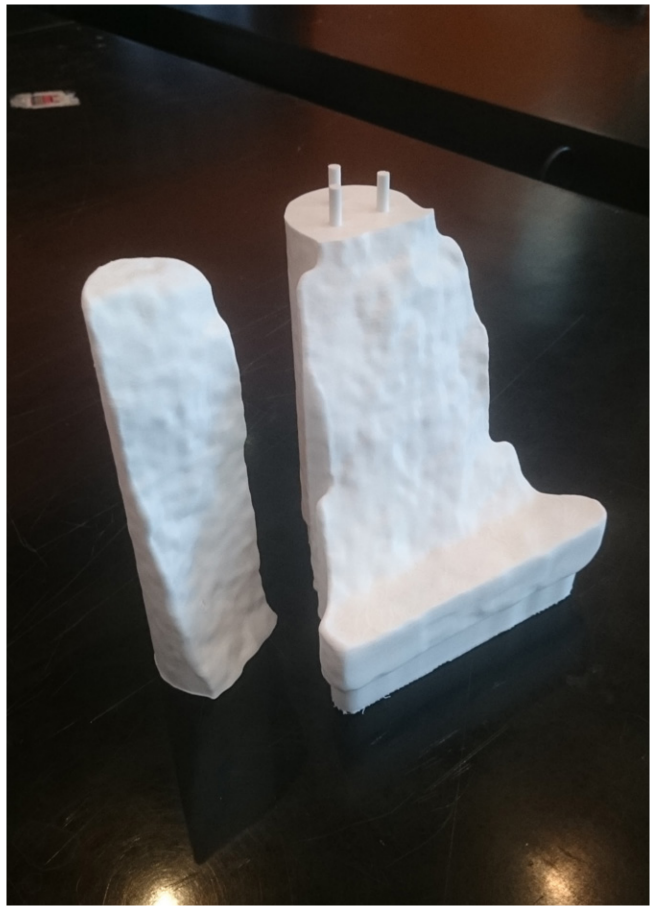


Figure 154. MDF Mold Reinforcement (All Dimensions in mm)

Generation and Alignment of Pattern



The two printed fragment parts did not need an adhesive to be joined together and would fit together readily.

Interestingly, because the manufactured fragment fit the stone column so accurately, it did not require any adhesion or force to be kept in place.

Transference of Pattern (Mold Production)

1. Although the two components fit together readily, PVA white glue was still used as a temporary measure in case the silicone leaked inside the cavity between the two pieces.

2. A thin layer of Vaseline was applied to all the exposed surfaces as a release agent against the silicone. This also ensures the smooth removal of the pattern from the mold.

3. The ‘pattern’ was held down using wet clay and the first layer of silicone (using Mold Max Stroke Part B) was applied to the surface.

4. Progress after first layer. Some excess silicone flowed to the bottom of the pattern, this excess silicone can be cut off once the layers have cured.

5. Progress after second layer. A second layer was brushed on after waiting for 30 minutes so that the viscosity of the silicone was increased and the brushing action would not cause the first layer to come off.

6. Progress after third layer. The surface was slightly textured to improve adhesion with the silicone to be poured later.

7. The silicone overflow was sliced off using a paper cutting knife to ensure that there is room for a layer for clay to hold the pattern down.

8. The pattern was then held down using wet clay and a thin layer of Vaseline was applied to the clay as a release agent. No release agent was applied to the silicone surface since it had to bind with the poured silicone layer.

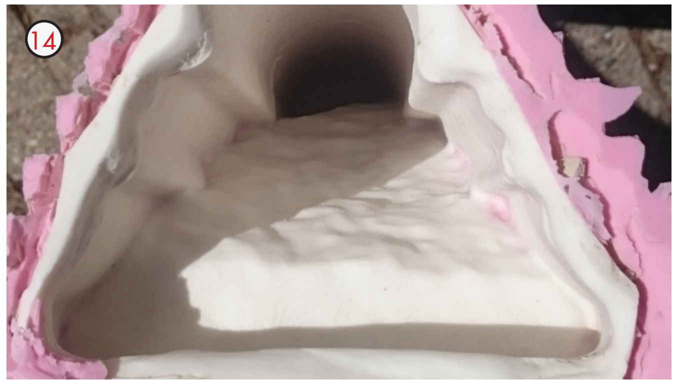
9. An MDF mold reinforcement was CNC milled with an average offset of 2 cm to aid in the pouring of the secondary silicone layer. This MDF container would also help strengthen the mold to prevent any deformations during the casting process.

10. The pattern was placed approximately in the middle of the mold reinforcement and the setup was clamped shut using four bar clamps.

11. The silicone (with Mold Max 30 Part B) was slowly poured around the pattern to ensure that there are no gaps left behind. Care was also take to ensure that the pattern did not move during pouring.

12. The newly poured silicone was then left to cure inside the mold reinforcement for 24 hours.

13. The setup was disassembled for inspection after the silicone had cured. In this instance, the inner surface of the mold reinforcement had been contoured to save time but that caused difficulties during disassembly, despite the use of a release agent. Therefore, it is recommended to mill a smooth surface or to use a different material.



14. The setup was disassembled for inspection after the silicone had cured. In this instance, the inner surface of the mold reinforcement had been contoured to save time but that caused difficulties during disassembly, despite the use of a release agent. Therefore, it is recommended to mill a smooth surface or to use a different material.

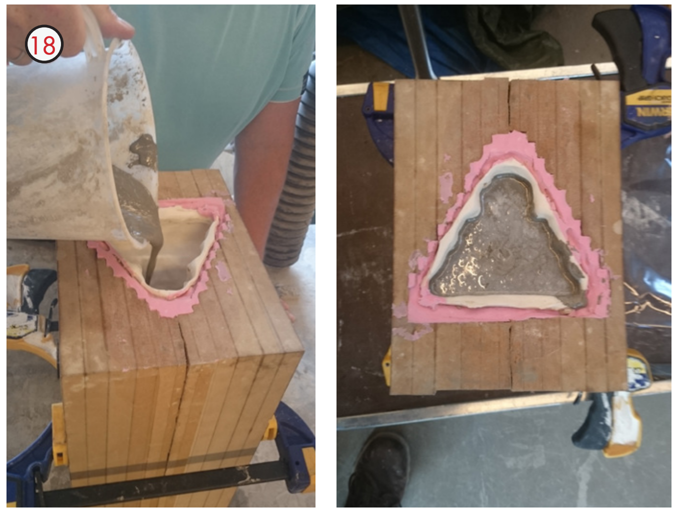
15. A layer of Smooth On Universal Mold Release was applied and left to dry overnight. Another layer was applied 15 minutes before the casting process as instructed by the manufacturers.

NOTE: Respiratory protection is required if the spray is being applied in an unventilated area.

16. The mold setup was placed on a vibrating table to prepare for the casting process. The vibrating table helped ensure that no bubbles were trapped inside mold. Bubbles can potentially cause loss of detail and larger bubbles can result in improper casting.

17. The first cement sample was casted with a water-cement (i.tech Ultracem 52.5) ratio of 0.5 and the addition of white pigment (Titanium Dioxide) to lighten the color of the cement.

A second sample followed the same ratio but with the addition of a bag of fine sand and aggregate (CEN Normsand DIN EN 196-1) in a mixer to increase strength and durability.



18. Each sample was casted in two sessions, with 600g cement and 300g water. The first sample was mixed with no aggregate or sand and 10g of white pigment, the second sample used more pigment (20g) and 1350g (1 bag) of fine aggregate and sand.

After pouring halfway, each sample was vibrated for 30 seconds for compaction, filled till the end marker and compacted again.

19. The sample was removed after curing for 72 hours. A slight incision had to be made on the mold to extract the cast, the incision would leave minimum marks on any subsequent castings due to the cohesive properties of silicone.

20. The transferred markings from the PLA pattern were then sanded away from the casted material using a medium grit sandpaper.

A visual comparison of the first cast (right) with the PLA pattern (left).

Fitting of first cast, the seam caused by the smoothing of the edges is visible.

Top of the first column segment with the first cast, displaying the mirroring of the geometry. Small bubbles that escaped from the inside of the cast are also visible.

Fitting of the second cast, the lightening caused by the doubling of the pigment amount is visible.

Figure 186. First Cast

Photographed by Marcel Bilow

CW Ratio 0.5 - No Sand or Aggregate
10g White Pigment

Figure 187. Second Cast

Photographed by Marcel Bilow

CW Ratio 0.5 - Fine aggregate and sand

20g White Pigment

10.1.11 Cost Comparison (Estimation)

The costs of projects can vary because of the economics of scale. Larger projects may have one time costs divided over multiple cases, lowering the overall cost per case.

In consultation with Hendrik-Jan Tolboom, some figures were arrived at to estimate the costs that would be incurred for the patching of the test case. It was determined that the majority of the costs would be labor costs, material costs for traditional methods would be considerably lower.

The calculations were made assuming a specialized stonemason per hour cost from 25 to 40 Euros (figures provided by Tolboom) in the Netherlands and postulating 3 days of work with an 8 hour work day.

The digital fabrication method would require at least 5 days since some days would need to be dedicated to scanning and manufacturing of patterns. However a dedicated 3D modeller may be required to model the meshes and the laser scanning may need to be outsourced to a scanning firm. A pay-scale of a 3D artist in the United States can be considered, which amounts to 15 to 25 Euros per hour ("Payscale," 2016). An advantage of using digital fabrication is that the availability of skills is not geographically limited, so the pay-scale can vary considerably. The material costs would be higher for the digital fabrication method because of the newness of the technology but these costs may come down over time. Since the digital fabrication method required the use of silicone molding due to the hybridization of the technique, these costs will also be added.

Table 6. Costs	**Lower Estimate**	**Upper Estimate**
Traditional Method (Labor Costs)	25€ x 8 (hours) x 3 (days) = 600€	40€ x 8 (hours) x 3 (days) = 960€
Material Costs	100€	200€
Production Costs	Negligible	Negligible
Total Est. Costs	**700 - 1160€**	
Digital Fabrication (Labor Costs)	15€ x 8 (hours) x 3 (days) = 360€	25 x 8 (hours) x 3 (days) = 600€
Material Costs	20€ (PLA) + 102€ (Silicone) + 20€ (MDF) + 30€ (Cement and Misc)	100€ (PLA-SLA) + 102€ (Silicone) + 20€ (MDF) + 30€ (Cement and Misc)
Production Costs	Negligible (in-house)	60€ (3D Printing) + 20€ (Milling)
Total Est. Costs	**532 - 932€**	

Conclusion

While there is a difference in costs between the techniques, due to the assumptions in the calculations and variation in labor costs throughout the world, the comparison is inconclusive. It has to be noted however, that 3D modeling is not limited geographically and there is a possibility of outsourcing to reduce costs. Due to these uncertainties, it can be concluded that cost comparison should not be the primary motivator behind pursuing digital fabrication since it provides many other advantages.

10.1.12 Restoration Matrix (Table 7)

	Safety	Durability	Costs	Historical Accuracy
Reversibility	-	Binder should be resistant to acid/erosion.	Costs are not as important for this aspect as other construction activities.	If the used epoxy is reversible then the restoration can be reversed if better techniques are available for higher historical accuracy.
Compatibility	-	The **thermal expansion and contraction rates** of the new and old material should be the same to prevent cracking.	-	-
Original materials	The original stone would be heavier than any casted material therefore requiring stronger bonding.	Original stone would be more durable than casted material	Having a craftsman carve the missing pieces can incur more costs (especially with Dutchman method)	Using the original material would ensure partial historical accuracy.
Minimum intervention	**No steel binding rods** (only epoxy) could cause safety issues.	-	Costs can be reduced as the existing stone does not have to be altered.	The column would be more historically accurate as more of the original material would survive.
Traditional techniques	Steel rods can be used in addition to epoxy for a stronger bond.	-	Traditional techniques can be potentially more expensive than digital fabrication.	Carving by hand would be more historically accurate as a process but not necessarily the end result.
Maintenance	-	The elements should be regularly checked for failure of the binding material.	Maintenance costs can be derived from the funds saved via Digital Fabrication.	-
Digital Fabrication	Generating complementary fracture surfaces can increase **surface adhesion**.	The same stone, Belgian Blue Limestone can be **CNC milled directly** for higher durability.	Costs can be lower than hiring a traditional craftsman if the **workflow is streamlined**.	It is possible to create an **exact replica** of an existing ornament, something that is not achievable if a new one is carved by hand.

10.2 BOERDERIJ DE HAMWONING

Location	Rotterdamseweg 155, Delft
Material	Unknown Wood
Function	Ornamental Relief
Target	Angel Relief
Intervention	Replacing missing geometry
Style	Renaissance Mannerism
Date	~1608 CE

This wooden relief was one of the more challenging candidates selected for intervention not only due to the kind of damage that it had sustained but also because of the location of the angel relief that was to be scanned. The angel was 3.6 m above ground and surrounded by water from a stream on both sides.

Condition

Initial inspection of wooden fragments found near the site revealed that there was extensive rot present in the core of the wood. This was determined by the weight of the pieces which were quite light weight, suggesting that the rot had eaten away most of the lignin or cellulose in the wood. Further tests would be needed to determine whether it was white, brown or soft rot causing the damage and whether any sources of moisture would have to be cut off before the restoration could begin.

Restoration Approach

There were two ways to approach interpolating the missing geometry on the angel. The first method involves mirroring the angel and making use of subtractive boolean operations to extract the missing geometry. The second method involves overlaying the undamaged angel relief on to the damaged relief and then making use of boolean operations to extract the missing geometry.

Both of these methods depended upon first generating a closed manifold mesh after scanning both of the reliefs however.

The missing geometry would then have to be manufactured using multi-axis

Figure 188. The Gateway to the Boerderij. Source: Unknown


Figure 189. Damaged Relief


Figure 190. Intact Relief


Figure 191. Wood samples with evidence of rot

CNC milling machines. This would require the generation of tooling paths and the accurate milling of the fracture surface. Realistically, if there was indeed rot present inside the wood then a section of the wood would have to be removed to create a clean surface for the new fragment to adhere to. This would be akin to using the Dutchman method except the missing component would be manufactured using digital fabrication technology instead of by a craftsman.

Additionally, there is a layer of thick white paint on the surface of both the reliefs. Ideally this would have to be removed before laser scanning can begin but since the structure is part of a listed building this is not possible.

3D Scanning

Like the Belgian limestone column fragment, this site was also scanned using the Z+F Imager phase difference scanner.

One of the challenges involved in laser scanning this particular case was getting close enough to the relief to get usable details in the scans. This was achieved by renting a 'kamersteiger' or indoor scaffolding to raise the laser scanner mounted on the tripod by 1.85 meters. The scaffolding was rented from a local hardware rental store called Boers and was transported in a Mercedes Sprinter van.


Figure 192. Interpolation using the symmetricity of the relief. Source: Author


Figure 193. Interpolation using the existing geometry from the undamaged relief.

Before the scanning began, four reference spheres (two visible in the picture below) mounted on tripods were placed at regular intervals around the scan target. These spheres, like the printed reference targets used for the column, help orient the scanner in space and aid in stitching the point cloud together from multiple scans. The spheres would also help cancel out any micro-movements that could occur due to the shaking of the tripod and scaffolding due to wind and other external factors. A total of five 360 scans were performed on 'normal quality' and high resolution, taking a 3.5 minutes each.

Interestingly, since each scan instance covers a spherical 360 volume around the scanner, a large chunk of the Rotterdamseweg was also scanned including all adjacent buildings and persons standing around the scanner. This generated a relatively large point cloud file collection of 3.5 Gigabytes out of which the unnecessary data had to be cropped out.


Figure 194. Impression of geometry to be manufactured.

Figure 195. The scan target and apparatus. Source: Author

Figure 196.

Figure 197.

Figure 198.

Figure 199.

Figure 200 .

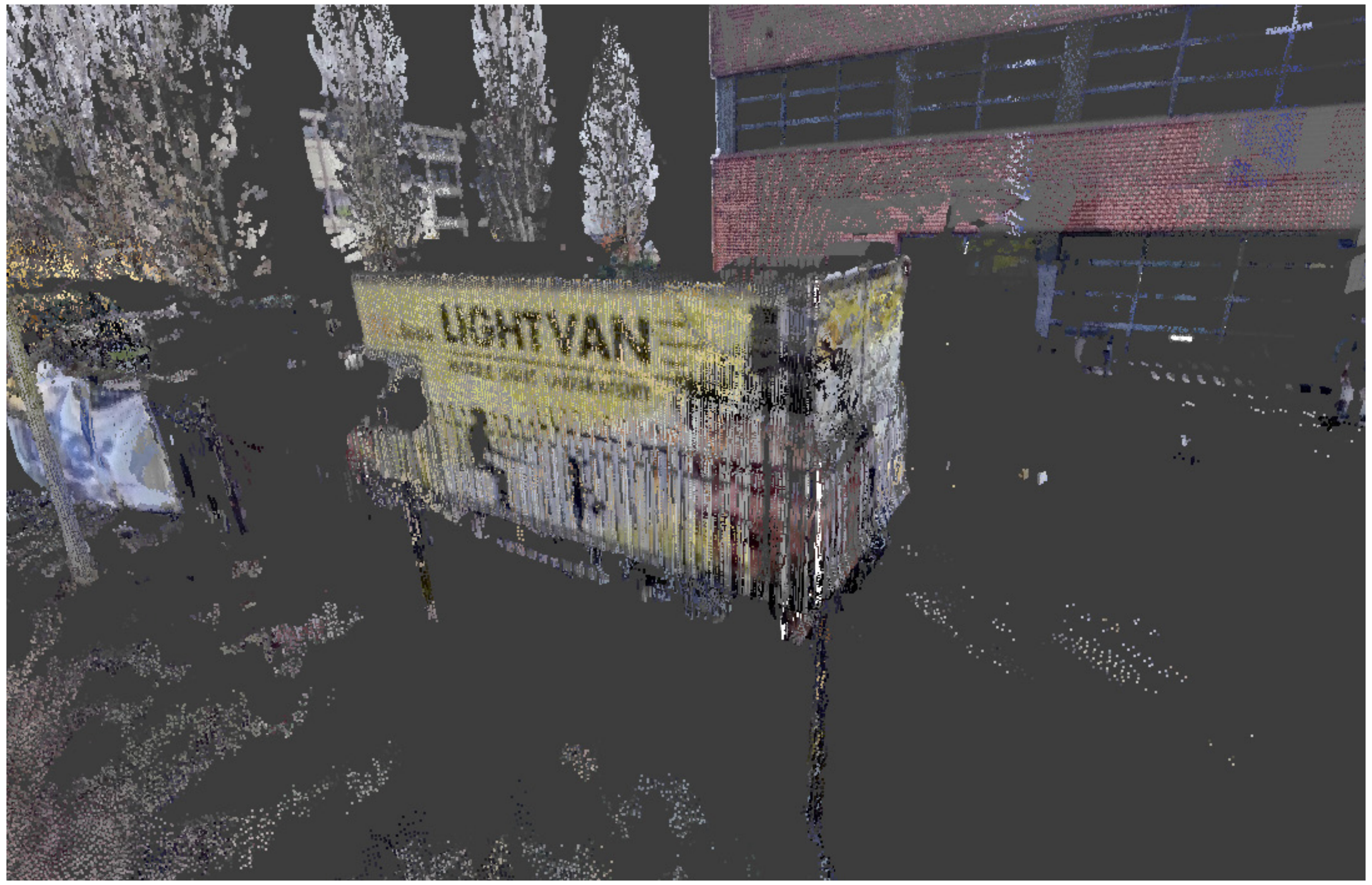


Figure 201. Scanned Context

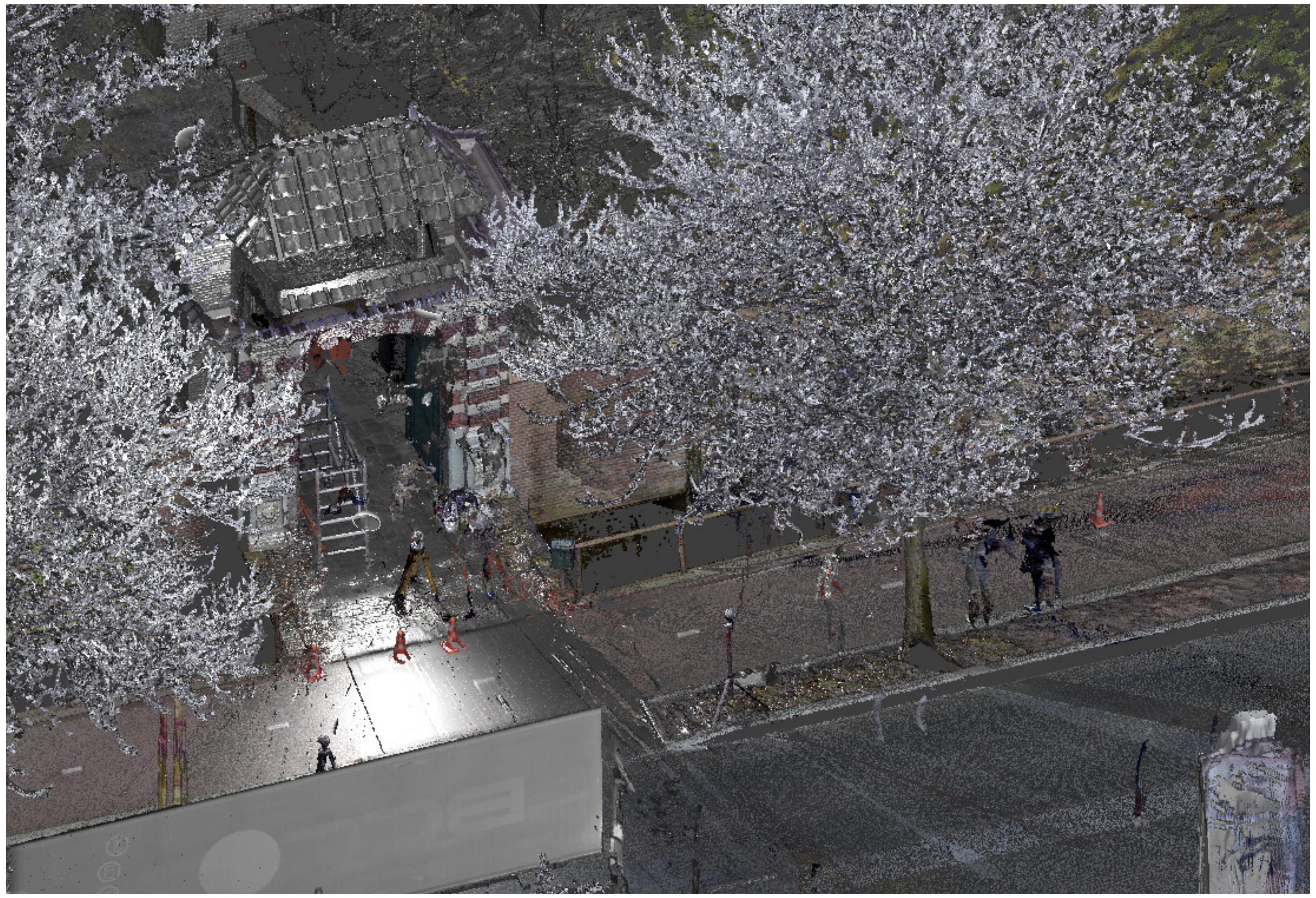
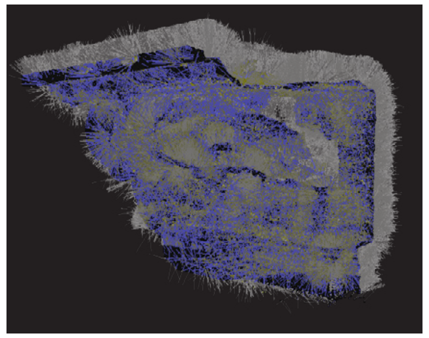


Figure 202. Scanned Context

MESHING

The point cloud collection was imported into Autodesk Recap and were merged together. This revealed a mesh cloud of a large section of the street. The wooden angels (the objects of relevance) were then cropped and the point cloud exported in .pts format.

This second point cloud was imported into Meshlab and the standard meshing workflow was followed. The normals were computed from Filters > Point set > Compute normals for point set and then a Poisson mesh was generated from Filters > Remeshing, Simplification and Reconstruction > Surface Reconstruction Poisson. The image below shows the properly realigned normals.



For the mesh calculation the Octree Depth was set at 10, the Solver Divide at 7 and Samples per node at 15.

MANUFACTURING

Further research into the restoration of this candidate were suspended until the conclusion of the first test case.

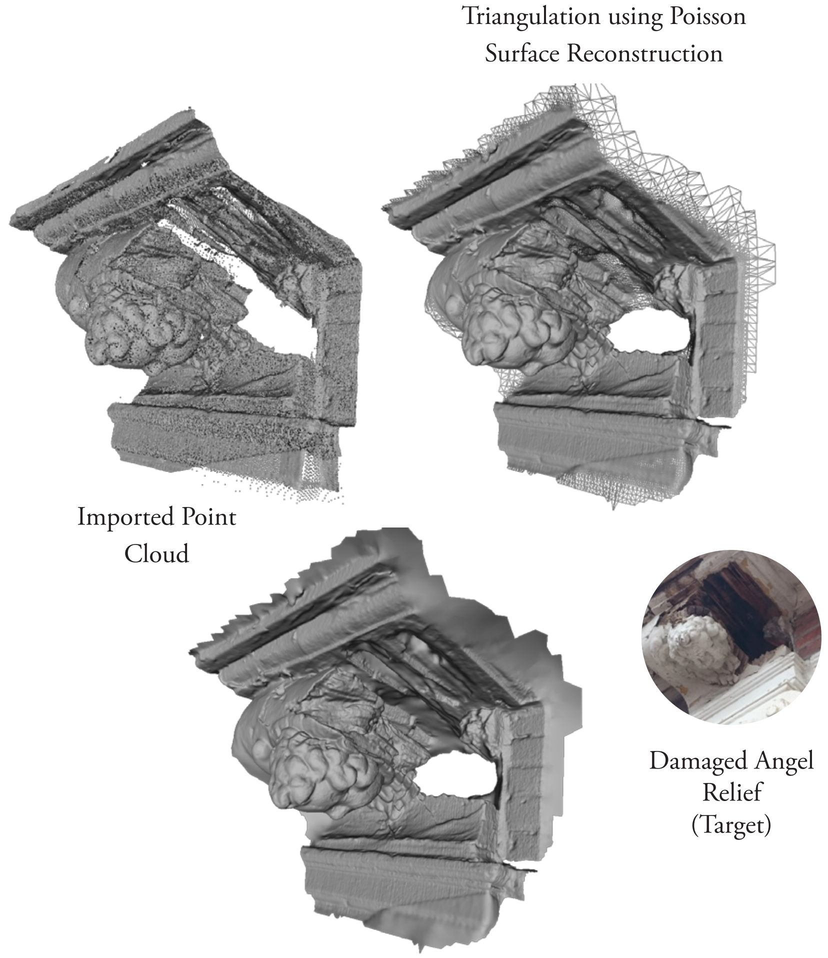


Figure 203. Damaged relief scans and meshing

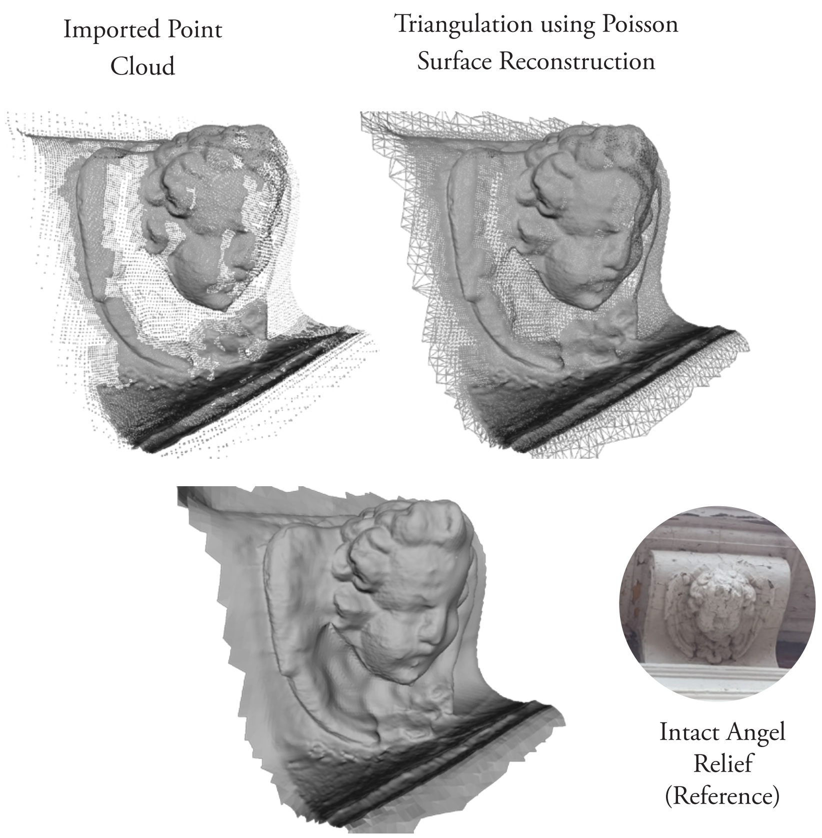


Figure 204. Intact relief scans and meshing

Restoration Matrix (Table 8)

	Safety	Durability	Costs	Digital Fabrication
Reversibility	Chosen binder should not fail.	Binder should be resistant to acid/erosion.	Costs are not as important as other construction activities.	Binder should be compatible with both the fabrication material and technique.
Compatibility	-	A balance should be found between type of wood that matches the materiality of the original and is durable.	If the most compatible wood is the most expensive then funds should be directed to acquire it.	Most compatible material should be chosen from within the limited options that can be digitally fabricated.
Original materials	Rot should be removed or controlled so that the restoration does not fail unpredictably	The original paint should be stripped and replaced.	Long term costs can be reduced by using durable paint.	The new wood should be able to bind with the old without too many differences in expansion/contraction rates /conductivity.
Minimum intervention	-	Only sections affected by rot should be removed.	Costs should be compared with overall budget.	Digital Fabrication combined with laser scanning provides the perfect opportunity for minimal intervention.
Traditional techniques	-	Materials chosen for fabrication should have the same or more durability compared to traditional techniques.	Comparison of digital fabrication techniques with woodworking techniques.	The chosen technique should be able to recreate the intricacies and subtle textures that traditional techniques can provide.
Maintenance	-	The elements should be regularly checked for rot and moisture should be controlled.	Maintenance costs can be derived from the funds saved via Digital Fabrication.	The original scanned files can be used if any other mechanical or fungal damage occurs to the structure.

11. CONCLUSIONS

Answers to Research Questions

'What are the influencing factors in the use and selection of LIDAR and Digital Fabrication for the patching of ornamental heritage?'

The aforementioned research questions can be answered by the aid of the following sub-questions:

i. Is digital fabrication for patching applications more economical than traditional techniques?

Although a comparison was made with traditional techniques, the comparison was not very conclusive since the bulk of the costs for both new and old techniques consists of labor costs. The only difference being manual labor versus digital labor. While the costs for traditional techniques were calculated to be higher than digital fabrication, this was mainly due to the higher labor costs used for a traditional stonemason in the Netherlands, costs may be drastically lower in other parts of the world.

One fact stands out however, since the digital manipulation of meshes is not geographically constrained because of the nature of digital data, it is easier to find a lower bid from a global pool of talent rather than just a local pool. Despite this, current cost estimates do not give an accurate picture of the economy of digital fabrication since the technology is rapidly improving and possibilities of automation in the future might completely discount the role of the craftsman (for the patching of ornaments, not the production of new designs) except in special circumstances.

ii. What are the possibilities of hybridization of techniques (combination with traditional methods) for patching with Digital Fabrication?

This issue was addressed after viable access to a multi-axis stone milling machine could not be established for the project. It was then decided to use molding and casting as a secondary workflow. The final fragment was then casted with cement inside a silicone mold.

This secondary method presented two disadvantages: the casted material would be different than the original and sharp edges in the fragment had to be smoothed out leaving a seam between the old and new materials. While both of these factors are not entirely 'disadvantages', the difference in materials and seam could be considered features of the restoration depending upon the intentions of the restorer, they are however limitations. The casted material would not have the same strength as solid stone for example, and it may have varying thermal expansion or contraction rates. An advantage that the casting method provided however is that the mold could be reused, making it possible to create multiple prototypes for experimentation. Another advantage is the relatively lower cost of molding and the possibility of performing the entire process in-house without the use of expensive machinery (not including the laser scanner).

iii. Is the use of Digital Fabrication for patching advantageous for reversibility?

One of the more important factors for reversibility is a low level of intervention in the initial restoration. With the aid of digital fabrication it is possible to recreate the entire fracture surface of the broken element and then manufacture only the missing fragments without the removal of any of the original material.

This ensures that if a reversible binder is used, the intervention can be reversed to the original state. A similar 'traditional' (non-digital) method would involve the use of a stereo-pantograph (as being used in the restoration of the Parthenon) to recreate the fracture geometry but its use would be limited to simple fractures unlike the detailed geometry that laser scanning can provide. Therefore, digital fabrication has a significant role to play in increasing reversibility.

iv. In which instances is the use of Digital Fabrication warranted over Traditional Techniques for the patching of ornamental heritage?

While Digital Fabrication provides many advantages over traditional techniques, it requires a different skill-set, perhaps with a small overlap. It cannot be argued that it does not make sense to use Digital Fabrication for non-ornamental repairs since traditional methods provide far simpler and tested solutions.

For ornamental repairs however, it can be easy to get blinded by technology and overuse it. In many cases, the damage to an ornament can be more than skin deep, rot in wood and cracks inside stone are examples which require the trained eyes of restoration experts, material experts in particular, to be diagnosed. Any interventions without addressing these issues first can possibly exacerbate the damage.

The use of Digital Fabrication starts presenting advantages when traditional methods become too complex, when a higher degree of reversibility is required or when traditional techniques required to regenerate a certain type of geometry have been lost or are not available.

v. What is the role of the craftsman in Digital Manipulation and Digital Fabrication? (Subjective)

In this context, a difference between a craftsman and operator has to be established. An operator simply follows a set of instructions without any input of their own and his or her skills may not improve over the course of time since the final quality would be dependent upon the machines being used.

It is true that the processes followed in this project required some 'operator-like' functions, laser-scanning for instance requires the pressing of a few buttons and the scanner does the rest (not discounting the skill of the operator since operating complex machinery requires extensive training) if all instructions are carefully followed. There were instances however, when direct manipulation of geometry was required, during the sculpting of the mesh in Geomagic Freeform for example. This kind of manipulation required a certain degree of dexterity, that can only be improved over time. With the use of haptic feedback interfacing devices, the process becomes quite similar to how a traditional craftsman interacts with material, adding legitimacy to the comparison and the term 'neo-craftsman'.

vi. What are the primary limiting factors when patching using Digital Fabrication and LIDAR technologies as they are today?

From the experimentation it was determined that while current technology is advanced enough to enable the manufacturing of considerably complex geometries, material variation remains the primary limiting factor, this was also confirmed by the various experts that were interviewed. While subtractive manufacturing technologies like multi-axis CNC milling can provide high detail results in a large variety of materials, additive manufacturing technologies have some way to go before the most advanced techniques can become mainstream.

Subtractive manufacturing technologies have two main disadvantages, they produce waste material and require the use of heavy machinery under constant supervision. While these factors did not influence the decision to use additive manufacturing for the production, they can play a role depending upon the nature and scale of the project.

One limitation that envelopes all the discussed technologies is the scale of the ornament being repaired. Every selected technology presents its own scale limitation, multi-axis CNC milling machines have a maximum reach while 3D printers have a maximum build volume. These constraints however can be overcome by manufacturing the pattern in pieces or in the cases when the original material is being used, manually finishing the end result.

One of the reasons that the production of the patching sample was hybridized via the use of silicone molds was that even if multi-axis stone milling machinery was directly available for research, production of multiple samples would require heavy investment of time and resources while the alternative only required the use of domestic 3D printers and silicone molding techniques, with the added advantage that the molds were reusable.

During the scanning, the laser scanning apparatus also presented some limitations, namely the large size of the apparatus making mobility difficult, the inclusion of noise in the scans, and the inability to scan hidden geometry. The former limitation was most apparent during the scanning of the Boerderij Hammenwoning, which required the use of scaffolding and tripods to reach the required height. The size of the scanner became a limitation as it would sway with the wind.

The noise however, which is derived from the errors in the digital processes that occur during scanning, as well as environmental factors also proved to be a limitation factor. While the noise could be controlled during the meshing process as well as by the removal of isolated or extraneous data, these processes resulted in lose of high frequency detail, essentially the loss of data.

Although not a limitation of the technology, the inability to scan hidden geometry obstructed by other features on the ornament or hidden in cavities should be taken into consideration before scanning. These hidden geometries can possibly be manually measured and inserted into the point cloud post-scanning.

While these limitations affected the results of the project, they were not significant enough to disrupt the entire process. These limitations can possibly be minimized as the technology develops further.

vii. What kind of role does software play in the patching via digital fabrication process?

It became apparent quite early in the project that software selection played an important role in the correct manipulation and quality of the final mesh.

Starting from the generation of the mesh from the point clouds, various software packages were selected until an optimum result was achieved using CloudCompare. As mentioned in the text, the optimum software package may vary from geometry to geometry, some packages are better at interpolating meshing with sparse point clouds while other are better at memory management which aids in the generation of complex meshes.

For the manipulation and editing of meshes, the software selection played an important part. One of the primary geometric operations that were required for this project was the Boolean operation. There are several different algorithms that perform such operations using slightly different methods and different software packages may make use of different types of algorithms to achieve the same result. Autodesk 3D Studio Max for example is packaged with two different types of Boolean operations, the 'Boolean Compound Object' and the 'ProBoolean Compound Object', both perform the same function but use different methods. After experimentation with the boolean operations in various software packages like 3D Studio Max, Rhino3D and Geomagic Wrap, it was determined that the most usable results were obtained from Geomagic Wrap (3ds Max failed during complex calculations while Rhino3D provided usable results but after decimation) with minimal loss in geometry. One of the reasons for this could be that while all three are mesh editing packages, Geomagic Wrap is optimized for laser scanned data and also provides tools for noise reduction and cleaning of meshes.

It can be deduced from the aforementioned that the selection of software packages is an important factor in the process of digital manipulation and carries as much weight as all the other tools, hardware or otherwise, available to the 'neo-craftsman'.

Conclusion

In summation, the use of Digital Fabrication is context dependent and not universal.

On many occasions it may be a necessity to use Digital Fabrication as an aid to the restoration process in conjunction with other techniques rather than as the primary technique. It has to be noted that on its own, Digital Fabrication is not an effective tool for the patching of geometry, it has to be used in conjunction with other technologies like laser scanning (LIDAR) or photogrammetry.

It also has to be evaluated whether the damage to an ornament is more than skin deep and whether the use of Digital Fabrication can exacerbate the existing damage (see sub-question iv).

Factors that influence the selection of Digital Fabrication technology can include the complexity of the geometry of the ornament (which can determine whether the use of DF is required or not or which technology would be more applicable), the material of the ornament, whether reversibility is a priority, whether the available traditional techniques are better alternatives, if authenticity is a priority or whether applicable traditional techniques have been lost.

Once a technology has been selected, there can be various parameters that affect the end result. These include the level of noise in the scans, the flexibility provided by the selected software packages, the resolution of the selected manufacturing technology, whether there is hybridization with other technologies and the scale of the fragment to be manufactured.

One factor that does not play a very significant role however is economics, since a majority of the cost of such restorations comes down to labor costs and both traditional and new techniques require the use of labor in one form or another.

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