HERITAGE REPRODUCTION IN THE AGE OF HIGH-RESOLUTION SCANNING: A CRITICAL EVALUATION OF DIGITAL INFILLING METHODS FOR HISTORIC PRESERVATION.

ANDRE PAUL JAUREGUI

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Heritage Reproduction in the Age of High-Resolution Scanning:
“Imitation is not just the sincerest form of flattery, it’s the sincerest form of learning”.

George Bernard Shaw
A special thanks to Columbia University and the outstanding faculty members in the historic preservation department for their unyielding encouragement, including my advisor Adam Lowe, who has taken time out of his busy schedule to assist me in this pursuit. Also, my dear Colleague Halley Ramos who has been a source of true friendship and support during these unprecedented last two years.

This thesis is dedicated to my mother, Maria Dina Jauregui, the strongest person I know.
Heritage Reproduction in the Age of High-Resolution Scanning:

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Abstract

High-definition digital scanning has established itself as a useful tool for documenting cultural heritage in the twenty-first century. Proponents of surveying technology are hailing the use of digital fact-based 3D models as valuable tools for recording, analyzing and safeguarding items of cultural importance. Methods for digitally filling holes have not yet been considered through the lens of historic preservation.

No modeling technique is error-free and understanding how heritage professionals are addressing lacunae is vital for understanding digital heritage objects resulting from 3D scanning hardware. Frameworks exist for working with scanned data, but they define general principles for a broad range of applications and do not provide any guidelines or strategies of how to comply with them practically.

This thesis is a comparative evaluation of current practices of in-filling digital lacunae that attempts to establish which methods are best suited to the following historic preservation practices: documentation, Interpretation graphics, Long-term monitoring, digital restoration, physical fabrication.

Keywords: Cultural Heritage, 3D Documentation, Digital Preservation, Surface Reconstruction, Hole filling, Polygonal Mesh, Visualization, Post-Processing, Restoration algorithms.
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Outline

I
Outlines concept ideas, overviews general objectives and formulates central research questions related to the thesis including the methodology and approach.

II
The chapter reviews the fundamental backgrounds of 3D modeling for cultural heritage while discussing the complex issues and limitations associated with heritage modeling.

III
This section presents a literature review of theories of authenticity related to object reproductions. It also provides a summary of preservation theory and discourse surrounding digital replication and relevant emerging issues.

IV
Chapter six presents existing methods for addressing lacuna (hole filling) in 3D models. The chapter discusses technology for documenting, modeling, and processing digital fact-based models.

V
This section is a survey of thirty-four lacuna filling methods each graphed on a radar chart.

VI
Evaluates thirty-four approaches based on a comparative analysis of preservation-related attributes. Similar works are noted, and parallels are shown using an information graphic tool.

VII
Concludes the main findings, answering all research questions. Finishes by providing recommendations for hole filling of 3D models of cultural heritage.

VIII
Concludes the main findings, answering all research questions. Finishes by providing recommendations for hole filling of 3D models of cultural heritage.
Methodology

The methodology used in this work begins with a historical analysis of the history of 3D modeling for cultural heritage followed by supporting the review of academic materials addressing the issues within the practice of lacuna filling. A literature review of theories concerning the authenticity of reproductions, historical preservation practices concerning lacunae filling theory. A graphic tool compares thirty-four algorithmic digital hole filling methods for polygonal meshes through both objective and subjective comparative analysis.

The methods used in each case study are assessed using preservation-minded qualitative analysis to analyze their variations, limitations, and strengths. Selected literature, relevant documents, data derived from previous research and existing preservation-minded frameworks were examined to provide insights on the subject and contextualize analysis. This research culminates in a set of proposed guidelines and a new graphical tool for evaluation methods that take into account best practices for addressing lacunae in digital historical models.
Research

Questions

I
How have models been used as tools for historic preservation?

II
Are there existing methods of hole filling that are more beneficial than others for use on recorded historical data?

III
What standards are needed for digital hole filling in the field?

IV
What are the best method to fill holes in fact based models used for Historic preservation purposes?

Goals

I
Determine the current methods available for filling holes in fact based models used in the field of historic preservation.

II
Determine criteria to evaluate existing hole filling methods and their attributes.

III
Provide preservation-minded recommendations for addressing holes in digital models used for fact-based models.

IV
Situate 3D modeling and digital hole filling methods as complex and valuable aspects of historic preservation practice.
1 Limits of Heritage Reproduction in the Age of High-Resolution Scanning

1.1 INTRODUCTION

This thesis is a comparative evaluation of current practices of in-filling digital lacunae that attempts to establish which methods are best suited to the following historic preservation practices: documentation, Interpretation graphics, Long-term monitoring, digital restoration, physical fabrication. Recent advances in digital scanning techniques have resulted in exciting new opportunities for recording historical building components. Experts and amateurs alike are utilizing 3D scanning technology to document objects in the physical world more than ever before [1]. In addition to individual users, large institutions such as museums, universities and visual industries have been quick to incorporate scanning technology into their use. The largest of these areas has been in the fields of visual graphics computer science, and digital archeology. The introduction of rapid prototyping methods such as 3D printing has provided heritage specialists with the ability to 3D print architectural detailing to replace damaged or missing building elements. As this practice becomes more common, the development of policies that address the manipulation of factual data will need to be developed [2].

When working with 3D models generated by scans of historical data, and reviewing the literature, there is an overall lack of resources available for preservationists seeking to fill missing information in 3D models. As a response to this deficiency, this thesis is an investigation into the application of hole filling methods for use in the field.

Few tools for 3D scanning, photogrammetry, and manufacturing take the necessities of cultural heritage into account. As no specialized education exists, fabricators tend to bring their intuition and experiences from other fields into the process, which leads to a myriad of highly creative and


unusual approaches, with no standard guiding principles. Guidelines for the collection of heritage object data, production of good quality replicas and recommendations for non-invasive approaches exist but fail to address critical issues of hole filling. Current 3D modeling software has adopted the polygonal mesh as a primary mode of digital representation [3]. Multiple surveys have assessed the value of new tools promoting their various outputs. The procedures for filling holes within these polygonal meshes, however, has not been a topic of research. New standards for addressing lacunae need to include procedures to help users prepare digital 3D models for research, documentation and preservation purposes. These standards will in turn provide a framework for evaluating effective post-processing of 3D objects.

1.2 Target Audience

The thesis is targeted at both, researchers and practitioners with interest in 3D cultural heritage documentation and hole filling methods for fact based-Models. Instead of listing the existing methods based on their application to one specific case study, the paper presents the lacunae repair problem from a general application perspective that is helpful for both developers of 3D models and researchers that make use of meshes in their activity. In particular, researchers from historic preservation and fields specializing in cultural heritage constitute one of the primary targets of this thesis, since they quite often work with polygon meshes and (often implicitly) make assumptions about their integrity. Furthermore, an analysis of authenticity in the state-of-the-art and a brief history of 3D models is presented to give context to hole filling practices. Thus, also researchers in other fields can take advantage of this work.

1.3 Limits and Lacunae in Digital Reproductions

Currently, methods for hole filling, or missing data, are developing within fields outside historic preservation such as visual graphics and computer science. Software developers and visual graphics

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experts are less concerned with the theoretical interpretation inherent in working with historical artifacts, as it a subject typically not in their purview. As such, most methods for addressing missing data have failed to consider the externalities of existing digital hole filling methods.

From 3D scanning to 3D printing, new methods of 3D modeling are being used to record historical sites [4]. Increased precision in digital documentation, however, has not always meant an increase in the accuracy of digitally scanned architecture. As a result, digital scans can lead to an inadequate interpretation of historical information. Accurately identifying material attributes is fundamental for the study and analysis of historical objects. Furthermore, lacunae found in digitally models is often overlooked and the correction of holes is relegated to automatic processes built into software tools that take the decision-making process out of the hands of the preservationist, typically without the full knowledge and awareness of the various methods at their disposal [5]. Additionally, a paradigm has emerged that prioritizes digital heritage as a cultural “product” which fetishizes “sellable” representations over research and preservation aims. This further obscures the authenticity of historical objects.

The recent introduction of digital file standards by ASTM International [6] as well as the 2017 ReACH Conference outline a concerted effort toward guidelines and standards for the dissemination of digital data relating to heritage modeling [7]. Saying that, the formulation of best practices for 3D cultural heritage documentation is still a subject of

**Existing Standards**

**Fig. 2**

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<td>Definition of basic objectives for 3D methods and practical approaches.</td>
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<tr>
<td>ReACH</td>
<td>ReACH (Reproduction of Art and Cultural Heritage) is a global initiative spearheaded by the Victoria and Albert Museum in partnership with the Peri Foundation which explores how we can collectively re-think our approach to the reproduction, storage and sharing of works of art and cultural heritage in the twenty-first century.</td>
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6. STM’s 3D imaging standards provide the proper procedures to specify and evaluate the performance of Three-Dimensional (3D) Imaging Systems. 3D imaging systems include, but are not limited to laser scanners (also known as LADAR or laser radars) and optical range cameras (also known as flash LADAR or 3D range cameras). These 3D Imaging Standards will be valuable to manufacturers, federal agencies, design professionals, professional societies, trade associations, and academia. “3D Imaging Standards.” ASTM International, 2017, www.astm.org/Standards/3d-imaging-standards.html. E2807-11, E2641 - 09 (2017), E2544-11a

debate and there are still no universally accepted standards or guidelines for the manufacturing of cultural heritage reproductions and practical lacunae filling. Charters exist that refer to the practice generally but fail to assist in the complex decision-making processes involved with 3D models [Fig. 2].

Digital issues arising from 3D documentation techniques have been a topic of discussion since the 1990’s. At the 1990 CAA conference, Ryan first discussed the topic of utilizing meta-data (digital labels) that can serve to “validate” models that have undergone significant manipulation for reconstruction or repair [8]. The further popularization of the term “reconstruction” as it pertains to digital asset production occurred with the writing of Forte, Siliotti [9] who suggested that:

“...virtual archaeology can be defined as digital reconstructive archaeology, computational epistemology applied to the reconstruction of three-dimensional archaeological ecosystems.”

The effective application of 3D technology for heritage research has been the focus of much research, the bulk of which centers around the topic of tool selection, institutional uses and software development. Attempts to promote 3D model reliability as a tool for research first took place in the field of archeology. This example was partially due to the encroachment of what Robert Hewison termed the ‘heritage industry,’ [10] that transformed heritage projects into vehicles for industrial sponsorship that often resulted in a lack of reliable data sources in favor of “realism” and sellable visualizations for entertainment and advertisement.

3D modeling as a research tool has only began to codify in the last decade, mostly due to hardware advances as performance capabilities of digital hardware have increased across

Figure 3: 3D model of a marble bust of Arsinoe IV queen of Egypt, Ben Kreunen, Photogrammetry, 55 x 20mp images Reality Capture: 11M poly mesh Instant Meshes: 325K poly mesh 3DS Max (Pro optimizer): thirty-fourK poly mesh, 4K bump map, Reality Capture: 4K texture map.


the board. Although current 3D workflows still suffer from several restrictions, accuracy in recent reproductions has demonstrated that new scanning and fabrication technology is capable of achieving excellent results in the production of high-resolution facsimiles and virtual multimedia appearing in popular culture and museums around the world [11].

Along with hardware advances, the increase in digital modeling, and by default digital lacunae, is also due, in part, to the proliferation of commercial digital scanning devices paired with the development of photogrammetry algorithms that are increasing 3D scanning usage globally. The cost and complexity of 3D imaging tools once thought to be impractical, have now allowed for the widespread use by many heritage institutions. Consumer grade cameras are now capable of 3D documentation leading to both virtual and physical replications that aid in the research, documentation, replication, and sharing of heritage objects [12].

1.4 Objectives

The significant contribution to the field of historic preservation is the development of a comparative evaluation of current practices of in-filling digital lacunae to establish which methods are best suited for historic preservation practices. As well to argue that preservationists need to take ownership of the technologies they are using to safeguard the physical objects, recorded data and history they aim to preserve.

This research outlines the various digital lacunae methods available to preservationist involved in processing scanned objects of cultural heritage by evaluating the limits of hole-filling methods for fact-based polygonal modeling. Findings suggest that a gap exists within modeling cultural heritage objects between users of technology and access to effective standards for treatment of digitally recorded historical objects that is resulting in a myriad of poor quality reproductions [13]. Therefore, scanned objects are inaccurate and misleading. Comparative analysis will form a basis for discussing strengths, limitations, and attributes that the author hopes to use as groundwork to argue for standards that can efficiently deal with practical hole filling of digital models. The primary goals are to determine the current methods available for filling holes in fact based models that can be used for the field of historic preservation, Identify hole types and determine criteria to evaluate existing digital hole filling methods, provide preservation-minded recommendations for addressing holes in digital models used for fact-based modeling and to situate 3D modeling and digital hole filling methods as complex and valuable aspects of historic preservation practice.

With new awareness and understanding of hole filling methods currently being used for historical reproductions, practitioners can make better decisions on how to best address lacunae filling for achieving specific goals. This research hopes to encourage new perspectives around the value of 3D digital data and treatment of 3D cultural objects. This research should be of interest and importance.


to the layman preservation community/industry operators/suppliers and consumers who seek assistance with understanding the interpretative effects of fact based 3D models.

The four primary research questions that will be addressed in are; How have models been used as tools for historic preservation? Are there existing methods of hole filling that are more beneficial than others for use on recorded historical data? What standards are needed for digital hole filling in the field? and what are the best methods to fill holes in fact based models used for Historic preservation purposes?

1.5 Methodology

To address the research questions, the current role fact-based 3D models play in the field of historic preservation is presented by describing the history of 3D modeling for cultural heritage. This is followed by issues within the practice of lacuna filling, a literature review of the authenticity of reproductions and existing frameworks revolving around similar works, and finally, a critical assessment of thirty-four digital lacuna case studies within heritage modeling practice.

The methods used in each case study are assessed using preservation-minded qualitative analysis to understand their variations, limitations, and strengths. Selected literature, relevant documents, data derived from previous research and existing preservation-minded frameworks were examined to provide insights on the subject and contextualize analysis. This research culminates in a set of recommendations that take into account best practices for addressing lacunae in digital historical

![Diagram](image-url)
2 3D MODELLING FOR CULTURAL HERITAGE

2.1 MODELS FOR PRESERVATION

To understand digital lacunae one must first understand the role models play in the field of historic preservation. Fact-based digital models in their contemporary digital form (as a product of geometric-based computer vision) developed in the 1960’s are only the most recent display of architectural modeling traditions dating back to ancient times [14]. Understanding digital lacunae necessitates an understanding of this history. In this chapter, the author gives a concise overview of the developments of 3D modeling and the field of geometry-based computer vision. First, a definition of model and geometry-based computer vision is presented along with a brief history of its application on cultural heritage modeling. Second, the author outlines the complexities of 3D modeling as an area of research.

Figure 5: Model Granary from the Tomb of Meketre Period: Middle Kingdom Dynasty: Dynasty 12 Reign: reign of Amenemhat I, early Date: ca. 1981–1975 B.C. Geography: Egypt, Upper Egypt; Thebes, Southern Asasif, Tomb of Meketre (TT 280, MMA 1101), serdab, MMA 1920 Medium: Wood, plaster, paint, linen, grain.

2.2 The Model as a Tool

Modeling built forms for preservation stems from the long tradition of documentation and reproduction that dates back to the Roman copies of Greek statuary and to the famous cast courts of the 19th century, Fig.6 [15]. However, similar to old modes of modeling, not all digital modeling is as accurate as it is precise. Of the various definitions of the word ‘model,’ the French ‘maquette’ is the term that most correctly points to the concept of a model as it pertains to the field of architecture. A maquette it is tied to the action of demonstration, Monstrum, the Latin derivation of demonstrating, means divine, portent or warn. At its root then, to demonstrate indicates the bringing forth of a prodigal actor or the prophecy of something tangible coming into being. The proximity of the demonstration and notions of the divine are historically closely related to religious ideas of God and perfection. This act of representation has no doubt served as one of architecture’s primary modus operandi as a robust method to predict the future and to warn of problems ahead [16].

Three-dimensional models have played a vital role in the practice of designing and constructing buildings throughout history. Remarkably the earliest documented architectural scale models were for the purposes of architectural preservation. Pharaoh Imhotep thought to be the world’s first architect, used funerary models to preserve architectural designs for construction in the afterlife, Fig.5, [17]. Although the methodology of modeling has evolved from its historical roots the fundamental principles remain the same models act as mediators between the intellectual and physical world by demonstrating the physical, visual record of a potential future or a representation of the past. Today, 3D models are defined as mathematical representations of objects or the surfaces of objects (either inanimate or living) in three dimensions via the use of software [18]. 3D models can be viewed as two-dimensional images through a process called 3D rendering or computer simulation. 3D models can also be physically created using machines [19]. 3D scanning is the act of mapping an object, structure, or area, and describing it in the form of x, y, and z coordinates - a format known as a point cloud. Although there are various methods

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of 3D modeling described extensively in the field of visual graphics, this thesis will only cover the most commonly used method known as polygonal mesh representation. Polygonal meshes are comprised of a wireframe of triangulated data points that are gathered from point clouds generated by 3D scanning hardware, Fig. 7. Common examples of this hardware include cameras/photogrammetry, white-light structured scanners, and LIDAR devices to name just a few.

The needs for modeling in the field of historic preservation differs from those traditionally used in architecture. In architecture, the creation of new forms precedes the need to represent already existing built forms, while in historical preservation this relationship is inverse for in the case of heritage documentation. Historic preservation utilizes modeling, not as an “a priori” maquette but a post factum reclamation of existing materials. The creation of a 3D model is standard practice in today’s architectural discipline and has demonstrated its place in contemporary architectural expression. Preservation fact-based modeling, the subject of this thesis, however, exclusively deals with data that has been gathered by sensor scanning technology and not artificially generated through imagination.

The use of high-resolution scanning means that models have transcended typical human-caused errors inherent in analog modeling, such as plaster casting, and have now crossed the threshold into the realm of machine-caused errors. This has lead to the term fact-based-modeling, which is the process of using scanning hardware to digitally record and construct a 3D model with the intent of generating a digital facsimile. On-site surveying and site documentation are among the most affected aspects engaging the field by the introduction of 3D modeling [20].

This thesis identifies the five primary goals of contemporary 3D heritage modeling as: documentation for analysis, which can be pivotal for preservationists dealing with at-risk heritage sites, by saving data that can later be used to reconstruct or study lost artifacts. II. Interpretational graphics, which are a valuable tool for property managers, community organizers and non-for profit organizations hoping to raise awareness about their causes by generating visual graphics for sharing. In some cases, 3D data is sold to visual artists who can use the 3D models in video game design, virtual reality, exhibition planning or box-office entertainment [21]. III. Long-term monitoring (HBIM), which can be achieved cheaply and efficiently for historical objects using 3D scanning technology. This is especially suitable for sites that are irregular or liable to environmental material degeneration such as those of earthen construction [22]. IV. Digital Restoration, which serves as a valuable document for conservators engaged in restoration, that does not risk affecting the in-situ artifact and allows for iterative digital alterations that can be rendered and assessed before ever touching the actual object. Digital scanning hardware has yielded reproduced


historical objects at resolutions that are nearly imperceptible to the human eye. Regarding lacuna, digital reproductions are beneficial as they have the power to reversibly alter models and provide an experimental environment to test multiple methods without any risk to the historical object [23]. V. Physical Fabrication, which can be achieved through computer-aided construction methods that generate “G-Codes” allow the for the construction of highly accurate facsimiles using additive or subtractive techniques [24].

2.3 Background

3D modeling was born out of the aerospace industry, where designers grappled with maximizing the efficiency of airplane cockpits. Modeling human forms was helpful to layout ergonomic interiors for pilots that required high levels of accuracy and precision for their construction [25].

Designer William Fetter is the first documented engineer to create a computer-generated orthographic projection of the human form in 1960 [26]. He dubbed the graphics output he achieved a “computer graphic,” which ultimately led to the term “computer graphics”.

Although Fetter was a seminal figure in the development of computer graphics, Ivan Sutherland is known as the father of computer graphics. Sutherland authored his Ph.D. thesis in 1963 on the topic, calling it Sketchpad: A Man-machine Graphical Communications System. Sutherland’s work was revolutionary for its time. His software was the first instance where an image was created on a computer display. It effectively laid the groundwork for computer graphics as we know it today [27].

Figure 7: A point cloud created from a combination of terrestrial laser scans and photographs stitched together in RealityCapture, Credit: © Factum Foundation.


Concepts such as memory structures to store objects, the ability to zoom in and out of a display and the ability to create perfect lines, corners, and joints directly led to the development of Computer Aided Drafting (CAD) systems that would eventually become primary tools for architectural drafting. Sutherland’s work showed that computer graphics were capable of creating digital models that used both technical and artistic representations. An important precursor to modern 3D modeling software was the development of the GUI, a graphic navigation system developed by David Canfield Smith [28] introduced the concept of icons. The term Graphical User Interface (GUI) was coined to describe the interaction interface that allows users to interact with electronic devices.

The primary limitations of the digital sketchpad were in its two-dimensional representation; it was still easier to draw on a notepad than on a digital “sketchpad.” This limitation changed with the introduction of 3D images formed using the hidden surface removal algorithms or (HSR), which rendered solid objects for the first time by hiding elements of 3D models positioned behind other objects lending to their appearance as solid. Computer algorithms continued to be developed throughout the 1980’s that further refined the processing and rendering of 3D objects [29]. Models during this time were rudimentary compared to today’s standards and lacked shading and color.

Around the same time as computer graphics was being developed, the study of computer vision also began to take place. Computer vision, beginning in the late 1960’s, differed from computer graphics as it hoped to mimic the human visual system in how it extracted 3D data from the natural world. Computer vision goals were to generate and recognize lines from the material world in digital form. One method created to achieve this was the development of sparse 3D reconstructions of scenes from various images, sparse reconstructions were built upon by the study of photogrammetry. Photogrammetry is the use of photography in surveying and mapping distances between objects; a technique that can be

Figure 8: Sutherland on “Sketchpad”, Buxton, W. et al. (2005) Interaction at Lincoln Laboratory in the 1960’s: Looking forward-Looking back, Conference on Human Factors in Computing Systems - Proceedings.


dated back to as early as 1849 when Aime Laussedat was using photogrammetry on the facade of Hotel des Invalides in Paris [30]. Photogrammetry as a method for model making is valuable for its ease of use and ability to document highly detailed objects quickly and efficiently. The contemporary principles that make photogrammetry possible are similar to what was used in Laussedat’s work at the turn of the 19th century [31].

It became clear to computer scientists attempting to achieve realism in their models that image overlays can supplant complex geometry. In the case of 3D modeling a brick wall, for example, it is much less computationally burdensome to model the wall as one slab and overlay an image of bricks on top it, rather than modeling each brick individually. This shortcut method requires shading to represent details without the massive computing necessary in modeling each brick. Shading computer-generated models was a technique made possible by Henry Gouraud and his Gerard Shading Model, that utilized interpolation methods to calculate and distribute pixel coloring across surfaces, resulting in a shaded model. The limitations of this process were the faceted nature of the modeled objects and star-shaped highlighting [32].

Although this method was expanded upon by Phong Bui-Tuong who further developed the algorithm, his model suffered from prolonged render times. It was not until the invention of the bump-map that shading 3D models addressed the limitations of Gourard’s algorithm. The “bump-map” was a method that simulated the appearance of increased surface geometry with higher image quality [33]. Limitations of bump-mapping is in the rendering of surface-ends that typically terminate the map; this is similar to cutting a photograph through the middle and losing realism due to image fragmentation. To account for this, the technique of displacement mapping was invented, which addresses this issue but at the cost of increases in processor and memory loads. Bump-mapping is a standard practice of 3D modeling today.

Throughout the 1990’s 3D graphic design started to overtake 2D design methods due to advances in hardware, graphics cards and Open GL software. Interest in video games supported the development of 3D model graphics as well as the adoption of 3D modeling in the development of major motion picture that pushed the boundaries of 3D representation. Eventually, the film industry developed techniques to create the first entirely computer-generated movie, Toy Story in 1995 [34]. Digital renderings began to appear in films such as Terminator, Star Wars & Jurassic Park and has increasingly become part of entertainment culture.

2.4 State of the Art

Currently, the use of 3D models relies on several representational methods that are vulnerable to lacunae. Multiple assumptions and arguments embedded within the act of creating a 3D model that can lead to lacunae, which in turn has the power to mislead and manipulate a viewers interpretation of an object if not taken into consideration. Authors of digital content, therefore, need to be aware of the potential externalities involved in representing cultural objects. Five of the most common issues with contemporary reproduction representations are outlined below [35].

1. The absence of human figures; the lack of human figures can leave viewers free to inappropriately claim spaces for themselves similar to the way early European settlers strategically left out Native Americans in their artistic portrayal of the American West.

2. The absence of alternative interpretations; replications are creating a single predetermined path which does not give the viewer insight into what other historical interpretations may be present.

3. The absence of time; viewers are subjected to a single period that has been pre-selected for them at the expense of others, a concept that is not unique to replications but also part of the nature of restoration work.

4. The absence of context in digital models; many replications are taking place in at-risk areas around the globe with little consideration for human lives. One of the faults of reproducing heritage objects is the prioritization of time and funding of reproduction versus initiatives to aid victims in conflict zones.

5. The lack of access to the digital modeling tools; hardware and software needed to scan and generate 3D models are expensive and not everyone has access to them.

These five elements of 3D modeling are essential to consider, particularly when working with cultural heritage models.

2.5 Types of Holes

There is a strong connection between lacunae and the quality of digital reproductions. Defining types of holes is essential to locate and evaluate them in preservation projects. In this paper holes are categorized into five types: Embedded Holes, Experiential Holes, Usage Holes, Enacted Holes and Strategic Holes. Generally holes that occur in mesh surfaces occur during registration as surface reconstruction, Fig. 9.

Embedded Holes

Usage Holes

Missing information about the pattern of organization of the critical actions that take place around the object, and the processes of interacting with it, its environment, and data from its environmental attributes. An analogy would be a model of the Egyptian Pyramids without the city of Giza shown.

Experiential Holes

Experiential holes are missing attributes of an object that contains human perception including the human sensorial perception that can assist in subjective metaphysical interpretations. An example of this would be a model of an Italian castle that does not include the smell of the nearby Tuscan hills.

Usage Holes

Missing information about the pattern of organization of the critical actions that take place around the object, and the processes of interacting with it, its environment, and data from its environmental attributes. An analogy would be a model of the Egyptian Pyramids without the city of Giza shown.

Enacted Holes

Enacted holes occur during the reconstruction process and are externalities of scanning processes or due to operator error. An example of an enacted hole is a church model derived from a scan that is missing the roof because the technician was unable to scan a tall structure. Or a hole occurring due to a reflective surface that a scanner was unable to record.

Strategic Holes

Strategic holes are holes that occur in models for the purpose of external needs or deception. An example of a censured hole is the strategic prioritization of a portion of an object over another due to time/site constraints. Another would be the removal a confederate flag from a scanned confederate monument.

Fig. 10
Embedded holes are part of the physical object, and they exist before the scanning has taken place. An example would be scanning a painting with a tear in it. The damage is an embedded attribute of the object.

Embedded holes are a part of every scanning project as no heritage object contains un-damaged or aged information gaps. The idea of authenticity is often a factor in dealing with missing data embedded in the historical artifact. In most cases the missing information is prioritized, authenticity and replications is a topic covered in the literature review section of this thesis. The scan of Set I’s tomb by Madrid based Factum Foundation used scanning data to replicate the ancient Egyptian surface details of the monument Fig.7, [36]. Holes in the historic fabric can cause issues when considering how to post-process the data; decisions were made for the tomb project to use the existing holes to exhibit the transformation that has occurred over time.

**Experiential Holes**

Experiential holes are missing attributes of an object that contains human perception including the human sensorial perception that can assist in subjective metaphysical interpretations. An example of this would be a model of an Italian castle that does not include elements of the Tuscan landscape behind it or local people. The presence of human figures to accompany a digital model is a typical missing element in 3D representations. The lack of human figures and relationship to nearby local communities can leave viewers free to inappropriately claim spaces for themselves similar to the way early European settlers strategically left out Native Americans in their artistic portrayal of the American West. This seemingly insignificant aspect of digital representations can result in misinterpretations of cultural context. In the case of the CAD Model of an Inca temple dated Circa AD 800 pictured here in Figure 11 scanned by J. von Schwerin et al. the absence of human figures, as well as nearby landscapes, is apparent [37]. The temple model was created in the 3D Studio Max software program and contains specific details such as color, material shading indicating the use of image mapping. Their workflow was to use the reality-


based, laser scan model of the existing remains of the ruined structure and photogrammetric models of various sculpture elements from the collapsed façade to develop the components of the reconstruction. The model was not made with the aim of creating a photo-realistic reproduction, so it is unfair to judge it based on its use for detailed analytical evaluation. It was designed to illustrate the general, hypothetical form of the structure with the locations and relationships of the motifs and themes adorning its walls but the missing context is notable for our purposes such as jungle environments, its relationship in the landscape and high details of texture are missing.

Usage Holes

Missing information about the pattern of organization of the critical actions that take place around the object, and the processes of interacting with it, its environment, and data from its environmental attributes. An analogy would be a model of the Egyptian Pyramids without the city of Giza shown.

In the case of the Bagan temple recorded by CyArk the local community is not presented in the modeling or rendering of the scanned data, any use of the ancient structure is not apparent, and the model fails to show any information that can lead viewers to consider aspects of the model other than its facade. Bagan is a vast ancient city located in Myanmar. From the 9th to 13th centuries, the city was the capital of the Pagan Kingdom [38]. The site contains over 10,000 Buddhist temples, pagodas, and monasteries constructed between the 11th and 13th centuries, 2,200 temples and pagodas exist today, but the from the model one might view the temple as a stand-alone site.

Figure 12: Bagan temple, Myanmar, Photogrammetric scan. Recorded BARTON, J. (2010) Surveying | CyArk, CYARK

Enacted Holes

Enacted holes occur during the reconstruction process and are externalities of scanning processes or due to operator error. An example of an enacted hole is a church model derived from a scan that is missing the roof because the technician was unable to scan a tall structure. Or a hole occurring due to a reflective surface that a scanner was unable to record. A typical scanning defect is presented in Matteo Dellepiane et al.’s work, Fig.13, 14. The column capital was not covered by the scanner. Various regions of the column capital couldn’t be adequately sampled since they were hidden either to the emitter or the sensor of the triangulation-based scanning device [39]. Laser scanners, photogrammetry methods and other sensor and proximity-based sensors all suffer from the problem of hidden elements and sightline limitations.

Strategic Holes

Strategic holes are holes that occur in models out of constraints or for the purpose of censorship. An example of a censured hole is the strategic prioritization of a portion of an object over another due to time/site constraints. Another would be the removal a confederate flag from a scanned confederate monument.

Due to time constraints, the scanning of the ceiling at the Rio Maggiore in Venice was limited. Technicians then had to make the decision to leave out perimeter details of the ceiling as a form of strategic planning. This missing information resulted in missing data that can be is seen in Fig. 15 by the jagged edges of the model.

Figure 15: Arrows indicate strategic data loss of 16th Century Ceiling Scan, Cini Foundation, San Giorgio Maggiore. Credit: Andre Jauregui 2017.
3 Literature Review

3.1 HOLE FILLING FOR PRESERVATION: AUTHENTICITY, THEORY & EMERGING ISSUES

Understanding the role of authenticity is critical in developing guidelines for evaluating and assessing models. 3D models are challenging traditional notions of authenticity, whether through recent polygonal mesh representations or 19th century plaster casts. Definitions of authenticity and its power to effect representations of culture are being debated. New 3D modeling tools, as with the birth of any new technology, are bringing to the fore historical debates and instigating new issues never before raised. The following chapter will briefly highlight some of the existing discourse concerning the relationship of authenticity and reproduction.

3.2 Authenticity of Reproduction

Because of the introduction of new methods or representation it is now more critical than ever to understand the value that reproductions may or may not have in the greater heritage discourse. All architecture replicas, whether they be in the form of wooden models, plaster castings, digital mockups or twenty-first century facsimiles face a similar host of theoretical difficulties that revolve around notions of historic value, authenticity and originality. Conversations concerning the value of heritage reproductions specifically, have concerned philosophers, historians and theorists for centuries, giving rise to a range of view from dystopian to utopian perspectives. By examining the role of authenticity in reconstructions, we can begin to grasp issues that can occur within a preservation-minded framework for lacuna filling in 3D models.
Authenticity is defined as the quality of an object to be truthful or genuine. The ambiguity of the term and the problems inherent in its semantics are evident when used as an instrument to assess historical value of cultural objects. Understanding what it means for an object to be authentic has been problematic since antiquity [40].

The dilemma of the ship of Theseus recounted in Plutarch’s Lives highlights a primary issue of authenticity for heritage reproductions. The myth tells the tale of a famous ship that served to transport the founder of Athen [41]. After suffering degradation, it had been continuously retrofitted with new wooden planks over a period of time, ultimately being reconstructed entirely of new material. The question then, is can this ship be considered the authentic ship of Theseus? Plutarch’s initial questions, later expounded upon by Thomas Hobbes, asked what would be the “true” ship of Theseus, the new rematerialized ship or the lost ship of old planks (if they were to be re-gathered and formed into a facsimile)?

Aristotle reasoned that the “formal cause” of the ship was separate from its “materiality” and therefore the “new” retrofitted ship is the more authentic ship. However, the Aristotelian historical value is based on the premise that an object’s cause (simply put, its reason for existence) is the sole determiner of its identity. This is problematic because an object or replication, in this case a ship or facsimile, may hold multiple reasons for existing. Therefore indirect proof arguments stipulate that if both a facsimile and original exist for the same reason, and one is destroyed in a fire, then by Aristotle’s logic the survivor would be completely equal to the destroyed object (even if the survivor was the reproduction and not the original). This demonstrates that an object’s formal cause of existing cannot be its sole determiner of identity, the object’s materiality must also be considered [42].

Materiality is only useful if it has an aura a characteristic that if moved out of its context of origin will vanish, argues Walter Benjamin. The most cited work of this logic is his 1935 essay, “The Work of Art in the Age of Mechanical Reproduction” where he states that even a flawless reproduction will always lack several key elements. The primary element is it’s “unique existence in a particular time and place.”[43]. This contextual uniqueness is valuable to Benjamin because it bears the mark of history in the form of decay. This decay validates an object and imbues it with a mystical aura. He defines aura as “a strange tissue of space and time [derived from]ritual and tradition,” and understanding that was perhaps heavily influenced by German existential phenomenology theorist Ludwig Klages [44].

Benjamin’s notion of aura parallels victorian philosopher John Ruskin’s notion of the “golden stain of time” addressed in his extended essay “The Seven Lamps of Architecture” [45], in which he states “buildings should respect the culture from which they have developed.” (page number)

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Benjamin similarly values the subservience relationship between objects and their ritualistic traditions and sees technological reproductions as the scalpel cutting a crucial relationship between a vital past. He is opposed to the idea that a reproduction can hold significant value, pitting reproductions against their original analogs. More importantly, however, he asserts that reproductions can harm the objects they copy. For him, surrogates have the power to degrade sensitive auric, iconic and ritualistic qualities of a work. Benjamin claims that “Traces of [history] can be detected only by the chemical or physical analysis (which cannot be perform on a reproduction)”; a statement that may be at odds with the goals of contemporary practitioners. Producers of facsimiles argue that advanced technology, particularly high-resolution fabrication, makes unique characteristic analysis a strength of current reproductions.

Although contemporary replications have been chiseling away at the problem of recreating chemical aspects of recreations notably smell and color, Benjamin give us two reasons why “authenticity eludes technological reproductions” [43], because (1) technological reproductions are more independent of the original than a manual reproduction and (2) technological reproductions have the ability to place a copy of an original in a geographic place that the original can never attain and as a result will devalue the “here” and “now” of the work. Benjamin claims this new contextualization attacks authenticity and erodes the value it derives from tradition. Replications for Benjamin can be summarized by his statement that reproductions “substitute a mass existence for a unique one”. and will lead to a massive upheaval in the domain of objects handed down from the past.

Benjamin values an object on its “reproducibility,” claiming that the ancient Greeks would have dismissed easily reproducible objects, such as film, because film can be edited and rearranged infinitely and therefore represents the exact opposite of his highest ideal. For him, the ideal work is the work of a single brush stroke because it represents a form of expression that once created is difficult to edit and reproduce. He justifies his claim by making another claim that the ancient Greeks held the highest appreciation for sculpture because it was an unreproducible art form and represented a work of eternal value.

Walter Benjamin is not alone in his claims that regard reproduction as a form of dangerous destabilization. Contemporary French sociologist Jean Baudrillard has similar views on the destabilizing effects of reproductions, based on the belief that exact replications will prompt a total break-down of material relationships. In the opening chapter of “Simulacra and Simulation” Baudrillard employs a useful analogy to explain the differences between fakes of the past and new forms of simulation [46]. He describes the difference between a “fake” and a “simulation” by using the analogy of two hospitalized patients; one is faking an illness and the other simulating one. He reasons that the difference between a patient who is “faking,copying” an illness is that he is merely pretending

to be ill while, on the other hand, a patient who is “simulating/reproducing” an illness is different in that he “actually feels” the symptoms. Baudrillard’s perspective is relevant to the discussion of heritage reproduction because his philosophy blurs the hard line between simulation and original, by claiming that future reproductions will inhabit the role of the real object; a role that historically has been solely owned by the original. Baudrillard argues that new forms of media are dissolving traditional notions of what is real, resulting in the ultimate reduction of information into a semiotic self-referring existence. He believes that high-resolution reproductions/simulations are correlated to a progressive merging of the material/immaterial relationship and will resolve in a total imperceptibility of differences between the replication and materiality of the future.

Others disagree that the aura, as defined by Benjamin, is threatened by reproduction. Benjamin’s argument that reproductions threaten historical authority by separating the defining nature of an object’s history, may not make sense when reproductions are created through digitizing or new facsimile methods. Fiona Cameron, for example, argues that reproduction involves a curatorial process of decision making, which in and of itself has the power to represent historical value and meaning. She notes that “the past is at the service of the object reclaimed through its counterpart.” For her, “surrogates illustrate, reiterate, and pass on a set of social relations constructed for the real while endorsing their ascribed value” [47]. In “Theorizing Digital Cultural Heritage”, Fiona Cameron argues in her essay “Beyond the Cult of the Replicant” that we must challenge what she calls the “illusion of the immaterial”.

Her focus is primarily on questioning and challenging the “superiority” placed on originals over copies. Addressing this topic through the lens of discourse in the field of digital art and used multimedia in the museum, she argues that the roles and uses of replicated digital objects must be understood as part of a greater heritage complex with a broader institutionalized culture of practices and ideas. She cites the western tradition of elevating material remains of the past over copies as a means to cope with and challenge societal fears of obsolescence. Earlier reproductive technologies such as line engravings and photography were destabilizers of traditional concepts of the authentic. Cameron posits originals and copies as discursive objects and manifestations of implicit western cultural rules where copies and originals are kept at a distance to support institutional claims of authority. She notes that reproductions are looked down upon as inauthentic, inferior, surrogate and valueless due to 19th-century empiricist/evolutionist ways of thinking that use materiality as a basis of authenticating. Value, therefore, is based on assumptions used as evidence of older history. From her perspective, this way of thinking framed history through an almost purely material lens, as materiality and methods for manufacturing of original objects were considered a perfect communication of the past.

Cameron reasons that although materialistic epistemology worked well for the pre-internet age, today this is no longer the case. Postmodernism and post-structuralism deflated the idea of “irreducible facts” and reinterpreted materiality as disparate and polysemic, meaning the concept of real authenticity can be viewed as a social construct and not an objective truth. This effectively let the beast out of the cage resulting in a full-scale offensive on strict ideological limitations previously placed on replicas. Historical objects are no longer viewed as absolute and a new emphasis on polysemy and interaction has occurred as well as increased democratization of access that should be played upon and encouraged not viewed as a terrorist.

If advanced forms of heritage reproduction have declared war on authenticity then facsimile creators, such as Adam Lowe and his fleet of technical magicians, are Admirals leading the armada. Adam Lowe, a trained artist, and perhaps the world’s foremost expert on facsimile creation has been involved with projects ranging from high-resolution recreations of renaissance paintings to full-scale recreations of Thutmosis III’s tomb in Egypt. In “The migration of the aura or how to explore the original through its facsimiles”. Bruno Latour & Adam Lowe discuss the new role of authenticity as it relates to what they call “evolving originalities” [48]. The opening pages of their paper begin with an anecdote of a woman who is puzzled to learn that the restored painting by Holbein titled “Ambassadors” is a disappointment. She contemplates why it resembles a cheap copy, stating “it is an original only in name, the real original has been irreversibly lost,” it has been substituted by “what most people like in a copy: bright colors, shining surfaces.” [48,pg. 2]

This story is meant to show us that originality is a farce; the time, alteration, and natural aging of all objects means that restoring them will always be a subjective decision. The painting witnessed in the story has been ruined because it has been altered by conservators that made poor decisions to restore the work to an idealized state; in this case, an ideal state that has no actual historical relation to what the artist created, but is instead based on a hybrid of commercial merchandising and community desires. With their opening arguments, we can again spot the Aristotelian justification for value assessments based on function, used in the Ship of Theseus paradox, part of Latour and Lowe’s justification for replication being that an object’s reason for existing (formal cause) should be used to determine its value.

The story has another important notion the authors highlight throughout the paper. Namely, institutions that house heritage objects have the power to make irreversible decisions that may not always be in line with what we would consider good historic preservation practices. They feel that issues of originality can be addressed and reframed through heritage replications, specifically in the form of non-contact facsimiles that can reduce these incidences.

Lowe and Latour remark that the importance and value placed on “originals” are directly correlated to “copies,” and that the mere presence of reproductions in the world reifies the fallacy of the original object. They advocate for heritage objects to be viewed not assingularly static snapshots divorced from their reproductions. In their words, “[facsimiles need] to behave like hydrographers intent on deploying the whole catchment area of a river, not only focusing on an original spring. A given work of art should be compared not to any isolated locus but to a river’s catchment, complete with its estuaries, its many tributaries, its dramatic rapids, its many meandering turns and, of course, also, its several hidden sources” [48, pg. 4].

Latour and Lowe, believe that objects can grow in originality through the application of physical reproductions. Moreover, unique to previous texts, they believe that without reproductions the very existence of the original is at stake. Interestingly they question beliefs that govern the way people view heritage reproductions and why it is that they differ from those of other forms of artistic reproduction such as dancing or theater. No one complains about a play’s authenticity upon viewing a reproduction of King Lear. Theater audiences instead choose to value the play’s revival as a form of expression and cultural importance. Furthermore, there are endless revisions of the play that take place with seemingly unceasing glosses and variations from the original. The result is a judgment on merit and less on mimetic comparisons with an unattainable original, a standard that is not equally applied to objects of cultural heritage.

Outlined in “The migration of the aura or how to explore the original through its facsimiles” are three essential ways of enhancing originality that reproductions can enhance originality: re-contextualization, access, and enhanced surface features (all of which are non-contact methods). Lastly, they discuss Benjamin’s essay on mechanical reproduction as an intellectual oversimplification and posit that the technology is not the issue. Rather, the accuracy of reproductions is the primary concern.

Another author is concerned with the tradition of replication throughout history as well as analyzing a technological form of reproduction that was similarly considered the most advanced of its time. Mari Lending’s “Plaster Monuments” [49] is a thorough and less dystopic survey of the philosophies, problems, and successes of architectural replication throughout history. Her account of 19th century casts is at odds with the philosophical discourse of both Benjamin and Baudrillard. Unlike Benjamin and Baudrillard who regard replication as a danger to authenticity, Lending, focusing primarily on the historical use of plaster reproductions, argues that reproductions are not only valuable objects for documentation, they even warrant the label “monument” in their own right. Her focus is relevant to the greater discussion of architectural reproduction and parallels the same issues faced with other forms of reproduction including high-resolution scanning methods, facsimile production, and VR/AR applications [50].


Lending demonstrates that plaster castings are a form of replication that is part of a fluctuating historical tradition and have been employed successfully as an effective means to document and perpetuate historical narratives and reify cultural identities. Toward the end of the 19th century, cast reproductions were primarily viewed as alternatives to luxurious tours of Europe, trips that were only available to those in the upper echelons of society. Also, Lending’s book is valuable because it highlights the regional differences of reproduction philosophy and methodologies, demonstrating that not all reproduction methods are created equal. Cultural differences have the power to influence methods of reproductions and ideas of authenticity.

Illustrating this point, Lending cites the French and American approaches to architectural casting. American institutions with their powerful benefactors, such as the Metropolitan Museum and Andrew Carnegie, claimed that cast reproductions could entirely replace the need to visit the original objects. This claim was in part fueled by 19th century American institutions’ lack of historical objects in comparison to their European counterparts. Across the Atlantic, British institutions were more concerned with the chronological organization and educational benefits reproductions could offer. The belief that the chronological arrangement of architectural elements could only be achieved through cast reproductions arranged in multiple adjacent views, a situation unattainable with in-situ architecture.

By contrast, the French claimed preservation and documentation as their primary goal. They asserting that casts had the total scientific value of the original even going so far as to claim that cast replications were more exact than their original counterparts’, due to their proximity to perfection. Unlike in the United States, Parisian cast replicas depicted buildings still in use. Parisian museums were working toward communicating ideas and representing casts as chronological tools to conceive a full-scale indoor history of architecture rather than producing facsimiles of decayed or antiquated objects.

Lastly, Lending reflects on the political power of cast reproductions. New agendas changed historical replications’ meaning and usage throughout the 19th century from being instruments of education, documentation, and markers of cultural acquisition to tools for political dissonance. She points to the destruction of replicas as a political instrument of change, i.e., the 1968 destruction of beaux arts castings by students. The tactic of destroying i the casts indicates they acted as great historical containers and were so effective in their roles that their destruction attempted to neutralize their communicative strength. Therefore Lending shows us that the authenticity of cast copies has historically been viewed as a vehicle for achieving a range of goals ranging from the documentation, communication, and political activism. In other words, copies have power.

Debated authenticity in architectural reproductions is causing legal and ethical issues as well, as outlined in Erin Thompson’s “Legal and Ethical Considerations for Digital Recreations of Cultural Heritage”. Thompson’s paper on digital reproductions effectively outlines several primary issues facing reproductions in the digital space. [51] Thompson notes that the law offers little

recourse to those seeking to protest digitization copies of cultural objects, while offering protections for those who have done the digitization. Due primarily to the fact that technology has outpaced the courts, currently authentic heritage objects are not protected by copyright and are in the public domain. Whether reproductions are viewed as great destablizers of material reality or essential elements for guaranteeing the survival of tradition they seem to act as powerful instruments for challenging notions of what is valuable in an object.

3.3 Historic Preservation: Past Methods of Hole Filling

Filling in missing information in historical objects was not always considered significant. Unlike how we view past artifacts today, before the 1500’s, purposes that were considered historically substantial were not regarded as irreplaceable materials. Artists freely manipulated and replaced ancient works as they saw fit without the fear of being accused of adulterating essential materials. With the onset of the Renaissance, reproductions became more common, and the general public began to notice differences between readily available wooden replicas and the originals they copied. Alterations of works of art during this period were becoming a subject of concern. The treatise of architecture titled Tutte l’opere d’architettura, et prospective (1537–75) by Sebastiano Serlio is accredited with beginning the tradition of documenting conditions to identify attempts at filling in missing data and located alterations [52]. This introduced suspicion into how one filled in missing information and provided the groundwork for oversight of historical fabric manipulation. The shift from the practice of freely altering historical objects meant that objects were becoming relics that were required respect and careful treatment.

Sebastiano Serlio was a pioneering author that laid the groundwork for contemporary archives of historic architecture and ancient objects. His treatment of holes can be described as the first documentary approach, and it provided baseline documentation in the form of measured drawings to inform and educate preservationists with a tool for comparing new filling information methods with pre-intervention data.

In addition to Sebastiano’s introduction of baseline documentation, others such as Leo von Klenze (b.1784) dealt with missing data by emphasizing the use of context to assist in the historical presentation objects [53]. Klenze advocated for displaying historic artifacts in rooms that were designed in the same period as the historic object. Klenze was also detrimental in the restoration of the Acropolis that serves as an example, for better or for worse, of how period hierarchy can be employed when filling in missing information. Klenze chose a specific period of significance and removed all other evidence outside of the “time of Pericles,” removing historical elements such as Ottoman architecture and historic churches. Klenze was a pioneer for his treatment of context to inform


 hole filling and restoration. A kleinze approach to missing data could be described as filling the hole as close to a particular period as possible while emphasizing the removal of any other time-periods except for one specific epoch.

The politics of filling in missing information has always been a tricky subject, the issue of whether to depoliticize or use objects for political gain is apparent in the works of figures such as Henri Grégoire and Alfonso Rubbiani. Preservationists have demonstrated how the treatment of historical objects can be deployed as a political tool since the French revolution. Henri Grégoire b.1750 was one such advocate that saw the dangers of this politicization historical objects. During the French revolution, Grégoire was a fierce advocate for the de-politicization of historical objects for the sake of their survival [54]. His work is the basis for many of the international frameworks that exist today for the protection of cultural heritage.

Alfonso Rubbiani sought to reify political strengths of objects by filling data gaps using architectural language to act as a symbol of ideologies preferring the power of persuasion over archeological exactitude. Rubbiani (b.1848) wanted to reinforce Italian national identity through interpretative measures, during his lifetime he was a prolific organizer of significant restoration projects in Bologna Italy [55]. His approach was employed in the restoration of the Palazzo di Re Enzo (1244-46, restored 1905), the Palazzo dei Notai (restored 1908), the Palazzo Comunale were he uses medieval elements freely to fill missing historical information.

Hole filling methods can be instigated and influenced by cultural factors as well, and one method is to fill holes purely for entertainment value. A historical example of this is noted in the restoration of the Notre-Dame de Paris due to the book (The Hunchback of Notre Dame, 1831) that spurred a restoration with pre-renaissance goals in mind, although the Notre-Dame underwent restoration with historical accuracy in mind, not all 3D models are [56]. Hollywood employs hole filling methods in the creating imaginary worlds that can lead to newfound interest and support for historical objects even if this is not their intention.

In the approach of Eugène Emmanuel Viollet-le-Duc (b.1814) artistic intervention was also considered. "Missing information must be infilled by a restorer and not an archeologist" argued Viollet-le-Duc [57]. Meaning that consideration must be made for artistic interventions. In his commonly quoted work, Viollet-le-Duc wrestled with the idea of completeness and what can be defined today as a structural rationalist approach. Viollet-le-Duc was interested in the merging of science and creative art as a means to make historical objects fit for contemporary uses and emphasized material fidelity and the need to maintain additions of the past. He promoted make necessary improvements if deemed useful to enhance an object historical significance. Filling missing information for him should be employed with artistic tact and influenced by ideas of completeness.

While Viollete-le-Duc was placing the architect and restorer at the top of a hierarchical pyramid, William Morris was (b. 1834) was distrustful of this and instead opted for a private society to act as jurors to oversee all restoration work [58]. He believed that historical objects, specifically art and architecture, belonged to the public and therefore they must act as its stewards. His work is the foundation of the contemporary preservation society.

Another less engaging approach for filling missing information is not to fill it at all. John Ruskin (b.1819) thought of restoration of historical objects as a vicious attack against historical objects [59]. He ascribed value to the original laborer’s hands and referred to defects in architecture caused by age as a “golden stain of time” that maturity and absence yield. Restoration and Hole filling, are viewed as erasing valuable elements of an original object. In today’s context it may be possible to interpret holes in digital models as a form of time-staining occurring from our tools that will be recognized in the future as a marker of our epoch.

Methods for filling holes can also be made up of hybrid approaches that borrow for multiple ideologies. Camillo Boito b.1836 synthesized John Ruskin’s approach with elements of Viollet-le-Duc, his work is the basis for the Athens Charter (1931) and the Venice Charter (1964) that are the standard for preservation intervention today [60]. His approach is unique in that it distinguishes between layers of intervention and places responsibility on the preservationist to challenge their preconceived notions and prejudices. The need for professional practitioners to have authority and responsibility in restoration practice was also the goal of George Gilbert Scott (b.1811), who wanted to avoid malpractice by novice interventionists. [61]

Scott’s establishment of guidelines for professional practice argued for experimental approaches that utilized guides to assist in making intervention decisions based on a case by case basis. Sigurd Curman b.1879 wanted to apply scientific approaches to cultural object methods [62]. Curman was an influential non-architecturally trained scientist. Instead of viewing preservation as an architecturally specialized field his he viewed it as a scientific endeavor. He engaged missing data by promoting the use of modern methods that show the intervention is of a different time than that of the historical object. If one applies his views to hole filling in 3D models, then holes should be made to be unmistakably apparent.

Noticeable hole filling techniques are not in line with other methods that prioritize notions of beauty, but beauty is a dangerous tool to be used for attributing significance to historical objects argued Aloïs Riegl (b.1858). Riegel, an art historian, is...

known for his work in pioneering selection criterion for historic preservation [63]. He established methods for saving historic buildings absent from considerations of their beauty. For him, beauty is an unstable and changing attribute that should be left out of the question altogether. Filling data holes based on notions of beauty would be akin to ignoring other aspects of the object. If Reigel were alive today, he might claim that only prioritizing objects of beauty and their information is not an adequate methodology for 3D modeling or hole filling. Elements that have been considered in more recent culture is the emergence of sites of collective trauma. An approach to dealing with emotionally sensitive sites can be seen in the 9/11 memorial in Manhattan where elements such as the hole left by the implosion of the towers as an exhibit and a form of collective mourning. Filling or leaving absent holes in cultural objects can serve as a powerful emotional stimulus. In the case of the 9/11 memorial representation of reverence, loss, and perseverance. A sign of respect for the past and a sign of a positive future ahead.

However, preservationists have not been shy to say that preservation is not just for the past and the future. Lewis Mumford b.1895 argued for methods that serve the present above all else [64]. His work in the “death of a monument” articulates his reasoning that pretending to restore things based on our perceived notion of what the dead or unborn want is egotistical and foolish. His approach is utilitarian in that he thought of historic architecture as a hardline of either dead or living. Along these line filling in missing data, one should only consider our needs and not the needs of a past or present. Methods for filling holes in historical objects are varying in scope and strictness and stringency, Cesare Brandi (b.1906)’s Methodology is notable because he is less concerned with rigid rules or ideology and more concerned with the image of an object. Brandi wants to replace missing data based only on information that is known. A hole in Brandi’s eyes should be left open unless we know exactly what was there. Additionally, he argued for a subtle differentiation between original material and new [65].

Lastly, James Marston Fitch (1909) in his work Preservation vs. Historicism: Postmodernism and the Theme Park, Argues that lacuna should be addressed based on three criterion; By “Using the best of modern science and technology, the art conservator undertakes that 1) nothing of the original fabric is to be removed; 2) nothing new is to be added which cannot be justified by rigorous archival and laboratory research which 3) cannot be subsequently removed without damage to the original fabric” [66]. His method is in many ways built upon subsequent approaches and when applied to 3D Models is a good starting point for purveyors of scanning technology to base their project objectives.


3.4 Questions and Emerging Issues of Digitizing Cultural Heritage

Practitioners are left with many choices when choosing to use 3D models. When deciding what method should be employed to manipulate 3D models, there are several factors one should take into consideration. Accurately assessing and managing models should be based on output goals. The discussion of authenticity and how technology affects the perception of authenticity is a tricky one, but practitioners with set goals such as those outlined in this paper can be valuable. Judgments are made on how others have addressed the question of what a copy does to an original and how authenticity effects copying and effects sharing.

Perceptions of cultural heritage change in response to the stream of images generated by an increasingly digital and interactive world. Given the introduction of 3D movies, high-definition video games, virtual reality (VR), augmented reality content, and the rapid ubiquity of streamed media content, it should come as no surprise that a banalization of traditional methods of engagement with objects of historical significance is one result of contemporary culture.

In response to this, a new paradigm of sharing and preserving historical objects has spurred the development of experimental preservation tactics that question established discourses of cultural heritage. Due to this influx of digital resources, projects that attempt to preserve cultural heritage must now include within their digital domain surrogates, in addition to the physical objects that were the previous scope of concern.

Even with digital abilities, the question arises: what objects are worthy of conservation? Significant objects embody values that signify evolving social relationships, engagement, and political negotiations (the broader problem of determining what is important and to whom is a question that lands outside the scope of this thesis). For this exploration, it is enough to venture that the complex relationships humans form with historic objects are one aspect of making culture, and, taken together, these relationships shape our collective culture. Engaging with cultural artifacts gives a brief glimpse into an unknowable past. Therefore, the role of the historical object is to provide us with a trace of this past while existing within our present.

New forms of mediated experiences—like interactive, virtual, and social media—are causing notions of the already complex idea of “the authentic” to be examined anew. It is not hard to imagine that experiencing da Vinci’s Mona Lisa in a VR environment without the hassle of travel, would be a far better option for many. Furthermore, if this virtual Mona Lisa were to is restored to its original state, would the replication serve as a more authentic representation of the painting than the artifact as it exists today? And, would the existence of this digital replica devalue the original, or enhance it? This example, at its core, asks: How can an object remain authentic in the digital space? And, how might sharing play a role in reifying or diminishing an object’s importance as a legitimate mode of historical representation?

As was previously mentioned with Roman copies of Greek works, the practice of replicating and archiving objects of cultural heritage has a long history. Statue replications were seen as objects to be shared, revered, and recreated in marble. The Romans also cast the faces of the dead to preserve their expressions; these “death masks” were a form of replication that demonstrated how reproductions are an effective means to document
and perpetuate historical narratives and reify cultural identities. We have seen that in the 19th century, the plaster castings (in its own time the most advanced technology available) in Mari Lending’s book revealed that replications could act as valuable objects in their own right. Since then, we’ve advanced beyond plaster and wax castings as a method to record heritage.

Today, technological advancements in 3D scanning and additive manufacturing techniques are advancing rapidly to disrupt existing legal and ethical frameworks, reproductions in the digital space face several challenges, much like plaster casts challenged the authority of the original in prior eras. The law as it stands offers little recourse to those seeking to protest digitization copies of cultural objects and many protections for those who have done the digitization, primarily because technology has outpaced the courts. Several issues of social justice must be addressed when purveyors of this technology transfer information from distant parts of the world. Access to technology, ownership rights and the political ramifications of publicising dangerous sites are factors that need to be addressed as 3D modeling continues. Heritage objects are not protected by copyright and in digital forms, are part of the public domain making them susceptible to reproduction on a large scale.

After ISIS destroyed the Monumental Arch of Palmyra in 2015, a physical replication was fabricated and shared around the globe with little consideration for its complex site context, Fig.16. The Arch was recreated digitally to stand in symbolic solidarity against terrorism, though the model of the arch was an inauthentic replication because it lacked any actual scanned data or traceable artifacts of the artifact such as height, weight, contextual surface details, etc. It was an ersatz art piece devoid of its historical contextual significance and may have even placed the remaining historic objects in Syria in further danger by hyper-politicizing the UNESCO world heritage site. It is no surprise that bad copies lead to bad interpretations, but when digital surrogates benefit their new environments and fail to aid their culture of origin or potentially damages the actual original objects, questions of cultural appropriation or even cultural imperialism must be raised.

Another facet of sharing 3D heritage data is the lack of contextuality mentioned by Benjamin, that is inherent in the practice—one can only model or scan so much. Modern practices of archiving cultural heritage embrace technology as a means to preserve archival content for use by the general public. However, digital recording and sharing have a tendency to flatten tactile 3D objects by manipulating data through multiple hardware and software filters that compress an object’s complex context into 2D images or low quality 3D renderings. Generally, sharing of replicated
cultural heritage can communicate authenticity, but over time the message of this communication can become degraded over time or become tangled with the interpretation of copies over the original. Surely one’s impression of the seeing the Mona Lisa is, by now, shaped by seeing the image of the painting played out throughout the cultures of the world.

Crowdsourcing data is one method that challenges this loss of context. Crowdsourcing allows to collectively generate metadata, whose secondary value continues to keep physical objects as central figures, even as digital paradigm gains traction. Metadata is essential in retrieving contextual meaning from digitally archived images, and there is no reason not to apply this method in the process of digitally sharing historically-relevant objects. The “Living Archives,” funded by the Swedish Research Council at Malmö University, has, as an example been researching how metadata can be generated through social media as a collaborative process to keep information current and contextually relevant.

In this example, the more input is gathered, the more reliable the information becomes. Opening up archival contents, generating metadata relevant to the public, and providing linkages to open government and historical data allows the sharing of cultural heritage to be contextually relevant. Though it is still susceptible to the same and kind of biases and appropriations are seen on open-source sites like Wikipedia, this type of metadata sharing is a way to generate information that is reliable, and provided by a globalized public.

3D models often showcase objects of cultural heritage decoupled from their contextual significance, as of the danger of visual modes of communication taking precedence over other forms of information. Without context, the virtual models stand as scans/objects in a storage archive at best, or a messy pile of digital detritus at worst, potentially creating faux cultures/histories. Meaning, how these models are used and interpreted are subject to human intention, much like any piece of technology. As participants in an increasingly globalized society, individuals must consider objects of heritage together with their context, physical and cultural. And when this is not possible, we must remain transparent about the manipulation of digital artifacts to be clear about non-historical interventions and to promote historically-minded practices.

Sharing our historical data responsibly is vital to sustaining cultural transmission and plays a role in both reifying and diminishing historical importance, each in a healthy way. Sharing cultural heritage is not only a form of digital archiving but should also serve, we argue, as a reliable method of preservation. Although it is still unclear whether sharing digital heritage damages or benefits the objects they represent, it is clear that sharing historical data responsibly is vital in establishing reliable and enduring interpretations of the world’s historic objects. And understanding the role of authenticity is paramount in developing a better understanding of hole-filling technology as there is a lot at stake.

67. The official title of the project is Living Archives: Enhancing the role of the public archive by performing memory, open data access and participatory design. The project addresses the challenges facing the digitized society through (1) the phenomena of public cultural heritage archives that increasingly are being digitized, and (2) the practices of archiving that are dramatically being transformed because of networked technologies. https://www.mah.se/Forskning/Sok-pagaende-forskning/Living-Archives/
4 HOLE FILLING METHODS

4.1 INTRODUCTION

Currently, there are thirty-four methods for filling holes in 3D models that are published and peer reviewed; peer-reviewed journals have been chosen since they provide credible descriptions of methods that have been tested and described in detail. For Based on their primary attributes, they are classified into five categories: Polygonal, Parametric, Volumetric, Image-based & context-based methods, Fig. 17 [68]. In order to accurately assess benefits of each method preservation goals must be outlined. The following section presents these methods and gives a brief description of each. Recommendations for specific methods will be presented based on five primary historic preservation applications and compared using graphics analysis.

The first step in determining how to fill a hole is the identification of the hole boundary. This identification is a vital step to be considered for cultural heritage models as the operator must decide whether the approach will be focused “locally” or “globally.” Local approaches focus on the vicinity of the hole whereas global approaches apply the algorithm to the entire surface of the model. Most methods based on polygonal representation are local and the manipulation of the model occurs only in the vicinity of the missing data.

Characteristics of hole filling methods based on polygonal representation methods: Polygonal representation methods work by identifying the perimeter of the hole and then joining the edges together. These joined edges serve to form “cycles” which recognize the perimeter of the cycle as the boundary of the hole.

5 Hole Filling Methods

4.2 Parametric Methods

Non-polygonal techniques deal with missing geometry by using parametric representations. A parametric model differs from a polygonal mesh system in that geometry is comprised of distributions that can be described using a finite number of parameters. Characteristics of hole filling methods based on Parametric representation methods [69].

Parametric methods use NURBS surfaces to assist in identifying and filling holes in models. Parametric methods work similarly to polygonal methods except they are capable of working with much larger data sets and are relatively fast. These methods can be dangerous for the preservationist because they often occur during the generation of the model from the point cloud so that the filling is done automatically.

4.3 Methods based on distance functions and volumetric representations

Polygonal methods focus on local approaches to mend holes, volumetric approaches by contrast focus on global approaches, and view objects as a volume [70]. Complete re-meshing of the input is a result, and volumetric representations typically rely on non-polygonal intermediate data structures.

The characteristics of methods based on distance functions and volumetric representations are that volumetric approaches use voxels. Voxels are defined in computer-based modeling or graphics simulation as each element in an array of elements of volume that constitute a notional three-dimensional space. They are especially understood as each element in an array of discrete elements that comprise a representation of a three-dimensional object (PLACE SOURCE).

4.4 Image-based methods

Image-based methods are not as conventional as polygonal or parametric methods as they are often more complicated. 2D image-based methods rely on images to detect and fill holes [70]. During scanning, photographs of the object can be taken.


that inform the hole filling operators to compute efficient filling. In several cases, this method works best for geometric authenticity over surface detail filling.

The primary characteristics of image-based methods include several stages of reprocessing. An unfortunate side effect of this methodology is that the addition of 2D images can actually introduce more holes in the form of noise.

4.5 Context-based methods

Context-based methods work by using machine learning to analyze surroundings. It coarsely fills a hole, then refines the coarse patching by fitting a new surface pattern over it. A downside of this approach is that a hole must have a solid boundary for it to work.

The defining characteristics of Context-based methods are that when identifying a hole, the system learns through the actual and practical experience and begins to make a priori assumptions and calculations about holes. It identifies surface patterns that are repeated and uses them to fill the holes. [71]

4.6 Evaluation Rubric

Each method contains a set of attributes that can be used to assess the value of each approach for a particular aim. This paper will use the seven following attributes to label each method: Object, Hole size, Distortion, RAW points needed, Process time, Manual control, pre-processing and post-processing. The following terms are presented with a brief definition.

Object
This refers to the kind of object which the method applies to: free-form shapes; and polyhedral shapes.

Hole Size
The size is measured in relation to the total area of the object. Thus, we distinguish between large (>3%) and small (<3%).

Distortion
Distortion analyzes whether the method introduces distortions around the hole’s boundary or on the whole surface of the object.

RAW-Points needed
Either RAW-Points are needed or not. This depends on particular demands in the data acquisition stage. For example, some methods need repetition of patterns in the piece to be dealt with; others require color information to be included in the data.

Process Time
Process time is characterized as either acceptable or high. This classification has been made from a qualitative point of view after the observation of the results presented in each method. To offer quantitative values of time, when information is provided, the relation between the time taken to fill the mesh and the number of vertices of the input mesh is taken into consideration for rating.

Manual
This refers to whether there is user intervention or not. Users can take part in algorithm execution. In some papers the intervention of the user is suggested.

Required Pre-Processing
Some approaches require a data preprocessing stage to be carried out before applying the specific hole-filling algorithm. For example, cleaning or deletion of wrongly oriented triangles or to reduce the occurrence of self-intersections, Steiner points are added to the mesh. The assessment here is either “Yes” or “No.”

Required Post-Processing
Sometimes post-processing tasks are necessary to fill a hole appropriately. This is evaluated with a “Yes” or “No.”

Definitions of Processing Methods:
Mesh smoothing is the process of reducing noise in scanned surfaces by generalizing signal processing techniques. Refinement is the method of adapting the accuracy of a solution within certain sensitive or turbulent regions of simulation. Mesh repairing refers to the need for further repair elements not filled using the method.

It must be pointed out that the graphics shown in this analysis depend on many factors and differ significantly depending on project-specific variation (resolution of the input mesh, pre-processing step, the complexity of the algorithm, etc.). They should, therefore, be taken as illustrative.

4.7 Application Needs for Hole Filling methods for 3D Objects of Cultural Heritage
Historic preservation includes several field-specific aims that each have their own unique attribute needs. This paper classifies these five aims as analysis, interpretation, monitoring, digital restoration, and reconstruction. based on the needs of each aim by providing an ideal case for each method for comparison using a five-point graph.

A radar chart uses a radial (circular) display with several different quantitative axes emerging like spokes on a wheel to create a unique shape of quantitative values, Fig. 18. Each axis represents a quantity for a different categorical value for the subject. The various axes identify the number of passes, number of methods, and the efficacy of each % etc.

The idea is that by plotting a value along each axis and then connecting up the resulting points a shape forms. First, identify what category each axis represents. Then assess how the methods are related to one another as you read around the wheel. The ‘zero’ of each axis is the center of the wheel. The further towards the edge of the spoke a point reaches, the higher the quantity. Then look at the whole shape: which features stand out? Are some categories more pronounced than others? Which groups are lacking?
The limitations of radar charts are that they can sometimes yield shapes that are inconsistent with the data. It is important to pay more attention to the position of shape along the axis than the connecting lines between axes. Sometimes categories may not have a real sequential link, but sometimes they may, in the case of some attributes the radar chart can be misleading since the result may be binary therefore yielding an ineffective shape.

**Analysis**

Analysis aims include the needs of academic research and prioritize attributes that enhance the quality of the model and focus on the need to preserve as much detail as possible. Hole filling should be precise and not contain significant distortion. Models used for analysis and research should be carefully manipulated. The geometric / topological authenticity should be maintained to the highest possible quality standards. Manual editing is also a priority as it gives researchers the ability to control what aspects of the model are affected by the hole filling method. Lastly, any hole filled in a model depicting historical objects should consider the appearance of the hole. Entirely untraceable interventions can be problematic for research purposes.

**ANALYSIS**

![Radar Chart](image)

**Geo-Authenticity:** The need to retain the overall form, 5 is the most true to the original form.

**Topo-Authenticity:** The ability to retain fine surface details, 5 is the most true to the original form.

**Manual Editing:** The ability to provide manual (non-global) filling, 5 represents the highest required.

**Interoperability:** The need to move a file to other software programs, 5 represents the highest need.

**Apperency:** The ability to notice the patch, 1 - unrecognizable, 5 - Highly Noticeable.
Interpretation

Interpretational needs prioritize geometric topology over topological authenticity as the 3D models are typically used for visual graphics, entertainment, rendering, and other non-analytical means. Models used for interpretation need to have high interoperability. Apparancy is vital for visual graphics artists that are attempting to hide holes as efficiently as possible. Manual editing is also critical.

Monitoring

3D models used for monitoring, prioritize authenticity and appearance. Interoperability is less critical as monitoring conditions rely on keeping as many factors the same as possible. It is unlikely that the models will need to have the ability to move between different software.

**Geo-Authenticity**: The need to retain the overall form, 5 is the most true to the original form.

**Topo-Authenticity**: The ability to retain fine surface details, 5 is the most true to the original form.

**Manual Editing**: The ability to provide manual (non-global) filling, 5 represents the highest required.

**Interoperability**: The need to move a file to other software programs, 5 represents the highest need.

**Apparancy**: Is the ability to notice the patch, 1 - unrecognizable, 5 - Highly Noticeable.
Digital Restoration

Digital restoration needs include medium levels of topological authenticity and geometric authenticity. This does not mean that these factors are not crucial for this aim. Rather, highlights that relative to the needs of analysis, the quality of a hole-filling for digital restoration techniques is not as essential as that of analysis. Interoperability is vital for transferring information into other software to further process restoration needs such as color and texture.

Reconstruction

Reconstruction pertains to fabrication and physical reconstruction needs for use in replacement of historical elements or the creation of facsimiles. Although, interoperability needs are high as well as manual editing, geometric authenticity and topological authenticity, authenticity is required only to the level of machining error. Apperency is also low as recreations typically don’t wish to show errors in hole-filling methods.

**DIGITAL RESTORATION**

**Reconstruction**

**Apperency**

Interoperability

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**HISTORIC PRESERVATION THESIS**


Geo-Authenticity: The need to retain the overall form, 5 is the most true to the original form.
Topo-Authenticity: The ability to retain fine surface details, 5 is the most true to the original form.
Manual Editing: The ability to provide manual (non-global) filling, 5 represents the highest required.
Interoperability: The need to move a file to other software programs, 5 represents the highest need.
Apperency: Is the ability to notice the patch, 1 - unrecognizable, 5 - Highly Noticeable.
4.7 Evaluation System for Defining Attributes of Lacuna-Filling Methods

After reviewing thirty-four hole-filling methods, the intention is to establish a rubric for evaluating the success of filling approaches. Comprising several attributes that are important from a preservation standpoint, each method is categorized by their base technique and evaluated on a scale of one to five based on their attributes. There are five base techniques used for filling holes in polygonal mesh models; Polygonal, Parametric, Volumetric, Image-based and context based. The bulk of the methods, which are isis polygonal and volumetric as they are the most widely used. Since approaches do not always follow similar patterns a five-point graphic using as a tool for comparing each method and its respective attributes is used as a tool. By overlaying the graphs, readers can visually compare the strengths of each approach for themselves. Additionally, a diagram that presents ideal attributes for applications in heritage fields is presented (Figure X). The five applications present are analysis, interpretation, monitoring, digital restoration, and reconstruction.

Authors of the methods do not follow a set pattern when they present their approaches and experimental results, nor have they typically focused on heritage related goals. Many of the methods presented are highly technical. By reading the process in which the algorithms work, the author was able to provide an analysis that assesses each technique based on the results presented in each approach and their underlying methodology. Additionally, some authors give
complete information (including software to test the approach), while those who only provide visual evidence of the results and do not quantitatively evaluate the method can be evaluated using supplemental data such as information including surveys conducted on the methods. Although, it is difficult to establish comparisons among the techniques referenced in this paper, the general attributes are important as research continues to address lacuna filling in models in the contexts of cultural heritage analysis.

It is important to mention, several methods are combined for conciseness such as those in the “shape methods” category, and several are not regarded as purely hole-filling methods. The authors of the methods, publishing dates, and contributors are noted for reference in each category.

The author of this paper is not trained in computer science and therefore relies heavily on additional surveys conducted for each method to assist in the categorization and analysis of each method.

**Geometric Authenticity**

The need to retain the overall form; a score of 1 denotes a hole that is least similar to the original form while a score of 5 denotes a hole that is most similar to the original scanned object. For this study, authenticity is defined by a balance between the accuracy and precision of a fact-based 3D reconstruction.

**Topological-Authenticity**

The ability to retain fine surface details; a score of 1 denotes a hole that is least similar to the original form while a score of 5 denotes a hole that is the most similar to the original scanned object. For this study, authenticity is defined as the balance between accuracy and precision of a fact-based 3D reconstruction.

**Manual Editing**

The ability to provide manual editing abilities for the hole-filling process; a score of 1 denotes a hole-filling method that is entirely automated while a score of 5 denotes a hole-filling method that is primarily user-guided and locally based.

**Interoperability**

The ability for a file to be moved to other software programs; a score of 1 denotes a hole that is least similar to the original form while a score of 5 denotes a hole that is most similar to the original scanned object. For this study, authenticity is defined as the balance between accuracy and precision of a fact-based 3D reconstruction.

**Apparancy**

Defined as the quality or state of being apparent. The ability to notice the patch; a score of 1 denotes a hole that is unrecognizable to its surroundings while a score of 5 denotes a hole that is most visibly apparent compared to the original model.

**4.8 High-Resolution Digital Scanning Technology**

To understand issues of data processing, it is first necessary to understand the methodologies used to capture digital data. The primary goal of this paper is to understand and evaluate techniques in the processing of holes in data and is by no means a complete survey of the various surveying technology available for use in cultural heritage work.

When surveying historic objects, each object has unique considerations that must be considered before a method of scanning should be selected. Among these characteristics are the physical condition of the object, the time allotted to undergo scanning, the level of accuracy needed and the
The geographic location of the site (as some equipment may be unrealistic to move).

The importance of cultural heritage documentation is recognized globally. 3D data is now a critical component to recording culturally significant objects. The value of digitally documenting objects from architecture to art has generated many projects using scanning technology to generate reality-based 3D models. (SOURCES Levoy et al. 2000; Beraldin et al. 2002; Stumpfel et al. 2003; Guidi et al. 2004; Gruen et al. 2004; Ikeuchi et al. 2007; El-Hakim et al. 2008; Guidi et al. 2009a; Remondino et al. 2009a).

A technique is defined as a scientific procedure to accomplish a specific task while a methodology is a combination of techniques. Reality-based techniques such as photogrammetry and laser scanning use hardware and software to reconstruct real-data of existing objects into 3D models. Methodologies for this purpose are based on passive sensors and image data, active sensors, range based systems, or a combination of several of these.

The choice of what method to use is based on a variety of factors that include the level of required accuracy, an object’s size, location constraints, hardware portability, hardware complexity, surface features, user training, budgets and output goals. The image-based approach has taken precedent due to recent developments in automated image matching (PLACE SOURCE Goesele et al. 2006; Remondino et al. 2008; Hiep et al. 2009; Hirschmueller 2008)). Usability has increased for non-experts. Lacunae areis present in every scanning technology making some more suitable for specific tasks than others. Lacunae areis caused by accuracy limitations, portability issues, high cost for quality sensors, site time constraints, and flexibility. Therefore, most documenting projects rely on integrated methods to achieve their goals. The following is a brief description of the technology currently being used to survey cultural objects for the creation of fact-based 3D models.

**Hardware**

**3D Range Sensors**

Range sensors rely on calculating the distance of points from a sensor to build 3D information in the form of point clouds. Common hardware in this category is triangular-based laser scanners and stripe-projection systems. They are typically high in cost, hard to transport and fail to capture surface attributes in great detail. Range sensors are primarily used for scanning large objects. The need for error removal is high since the instrument must be relocated successively to properly document a site and the angle of recording can cause large holes in the data (SOURCE Salvi et al. 2007) or least squares method procedures (SOURCE Gruen and Akca 2005). Terrestrial range sensors (LiDAR) work similarly.

**Image-based Scanners**

By far the most promising technology available today, and widely used for cultural heritage applications are image-based methods capable of recording high levels of detail. Photogrammetry and computer vision are preferred due to their ease of use, transportability, and cost. Aerial vehicles have demonstrated their effectiveness and accurate feature extraction of hard to reach areas and large sites. Similar to range sensors, image-based hardware produces a sparse point cloud for a generation of 3D geometry. (PLACE SOURCE (Böhler 2005;6 Remondino et al. 2005; Grussenmeyer et al. 2008)

**Multi-sensor Approach**
Multisensor methods allow for the data from multiple sources to be combined. This multi sensor approach can be in the form of data overlapping or data replacements through merging. In some cases, overlays can be used to identify changes or hidden characteristics in heritage studies. Multilayered approaches are used at both large and small scales. Many experimental approaches are in this category, notably the Lucida Scanner which is capable of recording the surface of paintings and objects with remarkable accuracy.
# Survey of Methods

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## Polygional Methods

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### Geometric Authenticity

- **Interoperability**
- **Manual Editing**

### Topological Authenticity

- **Apperency**
### Polygional Methods

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Polygional Methods

4

Alan Brunton 2009
Polygonal Method

Wuhrer, S., Shu, C., Bose, P. and Demaine, E.

Object        Freeform
Hole Size      Large
Distortion     No
RAW Point Needed No
Process Time   Acceptable
Manual         No

Req. Pre-Process Additional Points

Req. Post-Process Refinement


Geometric Authenticity

Topological Authenticity

Apperency

Manual Editing

Interoperability

Fig. 5. Head model 1. (a) Hole in the head of a human model; (b) Unfolded mesh; (c)- (e): Final embedded mesh obtained by minimizing $E_{SSE}$; (f): Final embedded mesh obtained by minimizing $E_{SSE}$. (g): Final embedded mesh obtained by minimizing $E_{SSE}$. (h): Final embedded mesh obtained by minimizing $E_{SSE}$.

Fig. 6. Head model 2. (a) Hole in the head of a human model; (b) Unfolded mesh; (c)- (e): Final embedded mesh obtained by minimizing $E_{SSE}$; (f): Final embedded mesh obtained by minimizing $E_{SSE}$. (g): Final embedded mesh obtained by minimizing $E_{SSE}$. (h): Final embedded mesh obtained by minimizing $E_{SSE}$.
Polygional Methods

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Polygional Methods

6
Lung-Chun Wang, Yen-Chu Hung  2012
Polygional Method

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Distortion  No
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Req. Pre-Process  No
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Fig. 9. Result of the rabbit model after hole filling: (a) Rabbit-hole model, (b) & (c) hole filling result.

---

Fig. 10. Skull model hole filling results. (a) Skull-hole model, (b) hole filling result.
Polygional Methods

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Geometric Authenticity

Topological Authenticity

Apperency

Interoperability

Manual Editing

(a) (b) (c) (d)
### Polygional Methods

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Polygional Methods

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Fig. 5. More results of feature curves reconstruction. (a) Octa-flower. (b) Twirl. (c) Twist. (d) Part of the Fandisk.
Polygional Methods

Ngo and Lee
Polygonal Method

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Polygional Methods

Parametric Methods

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HISTORIC PRESERVATION THESIS


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HISTORIC PRESERVATION THESIS
Parametric Methods

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Dey, T., Giesen, J. and Hudson, J. (2001). Delaunay based shape reconstruction from large data, Proceedings of the IEEE 2001 Symposium on Parallel and Large-Data Visualization and Graphics (PVG’01), San Diego, CA, USA, pp. 19–27

Parametric Methods

Parametric Methods

### RBF with Point Clouds

**2001, 2001**

**Contributers:** Dinh and Turk, Carr

**Object:** Point Loud

**Hole Size:** Small

**Distortion:** Yes

**RAW Point Needed:** Yes

**Process Time:** Variable

**Manual:** No

**Req. Pre-Process:** No

**Req. Post-Process:** Yes

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Parametric Methods
## Volumetric Methods

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(a) Input model.

(b) Cell solidities indicated by colored dots.
Volumetric Methods

<table>
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Contributors: Marschner, S., Garr, M. and Levoy, M.

Object: Freeform

Hole Size: Small

Distortion: No

RAW Point Needed: No

Process Time: High

Manual: No

Req. Pre-Process: No

Req. Post-Process: No

Volumetric Methods

Sagawa and Ikeuchi 2008
Signed Distance & Volumetric Method

Contributers n/a
Object Freeform
Hole Size Large
Distortion No
RAW Point Needed No
Process Time Acceptable
Manual No
Req. Pre-Process No
Req. Post-Process Smoothing


Figure 12.14. The models after flipping the signs of the SDF of the Buddha: (a) a 2D slice of the SDF; (b),(c) the results of volume rendering; (d),(f),(h) the mesh model rendered with triangles; (e),(g) the wire-frame representations; (i) the red surfaces are created by the voxels that do not converge without changing $\alpha$ and $\beta$. 
Volumetric Methods


### Volumetric Methods

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**Contributors**
- n/a

**Figure 9:** A scanned angel model contained numerous holes that take up a large portion of the surface. The active reached a minimum depth of 23 to 24 with some of the vertices surrounding the hole, though only 339,000 real nodes were scanned. The hole-filling process took about 13h.

**Figure 10:** (a) An algorithm filled this skull model, even though a large percentage of the surface area was missing. (b) The result produces an initial result. (c, d) This is smoothed to produce a more pleasing solution.

---

**Figure 1:** The well-known bunny model is filled with an active diffusion field. The hole-filling process took a little longer than a minute.

**Figure 2:** The result produces an initial result. (c, d) This is smoothed to produce a more pleasing solution.

---

Volumetric Methods

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**Object**: Freeform

**Hole Size**: Large

**Distortion**: Yes

**RAW Point Needed**: No

**Process Time**: Variable

**Manual**: No

**Req. Pre-Process**: No

**Req. Post-Process**: Smoothing, Repairing


![Diagram of geometric vs. topological authenticity](image)

Fig. 4. (a) Original bunny model (top view) 66,451 faces. (b) Results of patchy court using one scanning direction (top view) 191,230 faces. (c) Results of patchy court using 13 scanning directions (top view) 191,230 faces. (d) bunny model (top view) 66,451 faces. (e) Results of patchy court using one scanning direction (top view) 194,629 faces. (f) Results of patchy court using 13 scanning directions (bottom view) 191,230 faces.
### Volumetric Methods

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Volumetric Methods

Bischoff 2005
Signed Distance & Volumetric Method

Contributers Pavic, D. and Kobbelt,
Object Freeform, Polyhedral
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Distortion No
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### Volumetric Methods

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**Kumar and Shih (2012)**

**Signed Distance & Volumetric Method**

**Contributors**

A., Ito, Y., Ross, D. and Soni, B.

**Object**

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**Hole Size**

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**Distortion**

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**RAW Point Needed**

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Variable

**Manual**

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**Fig. 8.** Chinese Lio. (a) Front and back of original model. (b) Front and back of model after mesh repair based on surface approach. (c) Front and back of model after mesh repair based on hybrid approach.


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**Geometric Authenticity**

**Topological Authenticity**

**Appearance**

**Interoperability**

**Manual Editing**
## Volumetric Methods

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Fig. 7. Comparison of three different algorithms. (a) The input data, where the red points are removed to test hole filling. (b) The result of the MRF algorithm. (c) The result of the Poisson algorithm and (d) the MPU result.
Volumetric Methods
## Image Based Methods

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### Image Based Methods

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#### Figure 9. Completion of tower of Pisa

#### Figure 10. Extension of natural surface textures

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### Geometric Authenticity

- **Apperency**
- **Manual Editing**
- **Interoperability**

### Topological Authenticity
# Image Based Methods

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### Geometric Authenticity and Topological Authenticity

- **Interoperability**
- **Manuscript Editing**
- **Apperency**
- **Manual Editing**

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HISTORIC PRESERVATION THESIS

COLUMBIA GSAPP
Image Based Methods

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Contributers: Gill Barequet, Micha

Object: Freeform

Hole Size: Large

Distortion: No

RAW Point Needed: Yes

Process Time: Variable

Manual: No

Req. Pre-Process: No

Req. Post-Process: No


Geometric Authenticity

Topological Authenticity

Apperency

Manual Editing

Interoperability
Image Based Methods
Context Based

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<td><strong>Req. Pre-Process</strong></td>
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![Figure 9: The back area of the sculpture "Youth" by Michelangelo as reconstructed from the original scans (a). Context-based completion of the point-sampled surface (b).](image)

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![Diagram of Geometric Authenticity, Topological Authenticity, Apperency, Manual Editing, and Interoperability](image)
Context Based

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Context Based Methods

Geometric Authenticity

Topological Authenticity

Interoperability

Apperency

Manual Editing


Contributers

1. Alexa, M. and Cohen-Or, D.

2. Vichitvejpaisal and Kanongchaiyos

3. Tal, A. and Grinspun, E.

**COMPARISON CHART**

**POLYGONAL METHODS**

**VOLUMETRIC METHODS**

**PARAMETRIC METHODS**

**IMAGE BASED METHODS**

**CONTEXT BASED METHODS**

**ANALYSIS**

**INTERPRETATION**

**MONITORING**

**RESTORATION**

**RECONSTRUCTION**

---

Red Indicates Methods **

Grey Indicates Ideal Attributes **

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6 Evaluation Findings

6.1 Recommendations

Monitoring conditions of historical objects can be cheaply and efficiently achieved using 3D scanning technology. This is especially suitable for sites that are irregular or liable to environmental material degeneration such as those of earthen construction. For conservators engaged in restoration, the model serves as a valuable document for manipulation that does not risk affecting the in-situ artifact and allows for iterative digital alterations that can be rendered and assessed before ever touching the actual object. That have yielded reproduced historical objects at the resolutions that are nearly imperceptible to the human eye. Regarding lacuna, digital reproductions are beneficial as they have the power reversibly alter models and provide an experimental environment to test multiple methods without any risk to the historical object. Lastly, digital models have demonstrated their ability to be physically reconstructed. Computer-aided construction methods can generate “G-Codes” that can construct highly accurate facsimiles using additive or subtractive techniques.

3D model hole-filling methods differ in many aspects ranging from distortion, process type and hole variation and these differences benefit or hinder aims of historic preservation goals if not considered before filling lacunae. A pattern exists in hole filling research that does not consider hole-filling for use on 3D fact-based models.

Hole-filling issues are not trivial and have no all-encompassing solution. After outlining and discussing the various digital lacunae filling methods for 3D models, the resulting graphs have demonstrated that although there exists both benefits and limits to every approach, there are visible identifiable patterns in each method. Polygonal and volume-based methods are robust and work well in both geometric and volumetric
approaches. The Parametric approaches tend to be weaker when analysing topological geometry. Image assisted methods along with contextual methods are more experimental and rely on sophisticated computations that encompasses more cumbersome processing time. This information can provide a guide for the avoidance of specific methods that reduce the level of authenticity of heritage models.

The method evaluation has yielded qualitative ratings for dealing with processing large or small holes, approaches which are suitable for holes located in edges of polyhedral and polymetric shapes, the presence of significant distortion, the need for extra processing and the ability for the user to manually edit the model. Hole-filling methods for fact-based modeling must be chosen based on desired output goals. The comparative analysis has formed a basis for discussing the strengths, limitations, and attributes of various methods and goals for use in cultural heritage modeling.

Comparative graphics have been included (fig.5) so that the readers themselves can evaluate the effectiveness and versatility of each approach. These graphs have been generated based on the rating system presented in chapter [X] after a careful review of each method. Sources are provided for the reader to analyze for themselves.

Additionally, to emphasize the main strengths and limitations that characterize hole-filling strategies, the individual graphs for each method have been overlaid onto ideal needs from each goal category. This paper classifies the five aims listed as analysis, interpretation, monitoring, digital restoration, and reconstruction based on the needs of each objective by providing an ideal case for each method for comparison using a five-point graph. These provide insight into the practices that are more successful. Outlined in red are the top two methods for each. As the hole-filling problem has no general solution, in many cases there is more than one possible successful method to be considered. The identified methods should serve only as a recommendation for best practices.

6.2 METHODS FOR DOCUMENTATION

Analysis
Polygonal / Volumetric

Analysis aims include the needs of academic research and prioritize attributes that enhance the quality of the model to preserve as much detail as possible. Hole filling should be precise and not contain significant distortion. Models used for analysis and research should be manipulated carefully, and the geometric authenticity / topological authenticity should be maintained to the highest possible ability. Manual editing is also a priority as it gives researchers the ability to control what aspects of the model are affected by the hole-filling method. Lastly, any hole filled in a model depicting historical objects should consider the appearance of the hole. Entirely untraceable interventions can be problematic for research purposes.

For this reason, both the polygonal and volumetric methods for hole filling are more suitable. Polygonal and volumetric methods have been a topic of extensive research, therefore, tend to be more developed and provide the most robust methods for dealing with holes. In addition to this,
they are exceptionally adept at filling holes of various sizes and shapes. Alan Brunton’s method, in particular, stands out for its ability to unfold models [83]. He has demonstrated in his method the ability to work well on human figures. For analysis purposes, volumetric methods also work nicely with reconstructing topologically geared models with high accuracy. In the cases of Wang’s method (2012) the ability to work on complex geometry is demonstrated and its efficiency to fill holes for historical analysis seems to be a good fit. Jean-Philippe’s method (2006) is beneficial for filling holes that lay on curves, as most historically documented objects are not orthogonal it can be considered a benefit for purposes of historic analysis. Davis’-method (2001) has also proved to be highly effective on statuary scans, and the results appear to have no distortion on surrounding areas, a vital aspect of analytical modeling.

6.3 METHODS FOR INTERPRETATION GRAPHICS

Interpretation

Polygional/Parametric/Context

Interpretational models prioritize geometric topology over topological authenticity for use in non-academic purposes such as visual graphics, entertainment, 2D rendering, and other non-analytical means. Models used for interpretation need to have high interoperability. Apparancy is vital for visual graphics artist that are attempting to hide holes as efficiently as possible. Manual editing is critical to provide additional editing tools for visual artists.

Robust polygional methods are again successful here as they fill holes in various sizes and shapes remarkably well, however they are more computationally heavy than parametric methods. Parametric methods are successful at processing massive amount’s of data efficiently. Parametric methods are also well suited for interactive goals as they tend to use NURBS curves to approximate surface detail, a move that can serve to fill holes at the cost of topographic authenticity efficiently. RBF methods by Dinh and Turk (2001) are highly effective at rendering from sparse point clouds, which is a good fit for representational methods, such as video game design that focus on overall object geometry over high-resolution topological geometry.

Context methods are included here due to their prioritization of aesthetic reconstruction over factual reconstruction. The holes filled with these methods are useful in goals not concerned with analysis. Vichitvejpaisal’s method (2014) demonstrates the power of context-based methods to infill a statue’s beard. The output of this methodology works well for rendering goals for not research-based methods. Also, Harary’s method (2014) uses algorithms to reconstruct an eye in a digital model, but the result is subpar for highly detailed reconstructions.

6.4 METHODS FOR LONG TERM MONITORING

Monitoring

Polygional / Context-Based

3D models used for monitoring prioritize authenticity and appearance. Interoperability is less critical as monitoring conditions rely on keeping as many factors the same as possible, it is unlikely that the models will need to have the ability to move from
different software.

Polygonal methods are adept at robust hole-filling outputs, and context-based methods are rated high in this case as filling holes for monitoring models should be closely related to the surrounding areas.

Polygonal methods are efficient at detailed surfaces with crevices, Zhao’s methods (2007) demonstrated quality results in this area. Leipa’s method (2003), is the basis for meshmixer, a widely used repairing software, which is noted as providing hole-filling without distortion of freeform objects of varying sizes. This is a good fit for monitoring needs. Infill can assist in monitoring building decay. Hole-filling methods that do not take into account topological context can cause false interpretation of holes as deterioration.

6.5 METHODS FOR DIGITAL RESTORATION

Digital Restoration
Polygonal / Volumetric

Digital restoration needs include medium levels of topological authenticity and geometric authenticity. This does not mean that these factors are not crucial for this aim, but it is to say that compared to the needs of analysis the quality of a hole filling for digital restoration technique is not as essential as that of analysis. Interoperability is vital for transferring information into other software to further processing for restoration such as color and texture mapping. Therefore, analysis methods should consider the need for data quality early on.

Digital reconstructions benefit from the polygonal category., Mmethods that stand out are the Kumar method (2012) and Bischoff’s method 2005. Kumar’s method uses voxels to represent internal geometry of the model to inform the patch, while Bischoff’s method is beneficial because the reconstruction yields non-manifold surfaces that are good for imaging purposes.

6.6 METHODS FOR PHYSICAL RECONSTRUCTION

Reconstruction
Polygonal / Volumetric

Reconstruction pertains to fabrication and physical reconstruction. Typical uses are the replacement of historical elements or creation of facsimiles. Interoperability needs are high as well as manual editing, geometric authenticity and topological authenticity but authenticity is required only to the level of machining error. Apparency requirements are also low as physical recreations typically don’t wish to show errors in hole-filling methods.

Polygonal methods are valuable in this area; Robust polygonal methods are again successful here as they fill a hole in very complex geometry. Oliveria methods (2007) is particularly good at filling holes in rounded objects and shapes, and Wang method (2012) is perhaps the best method surveyed for filling very complicated geometry remarkably well. Volumetric methods are useful for reconstruction methods as well, as they are well suited for filling scanning data. Of note in the Volumetric category are Ju (2004) and Paulsen (2014). Both work with minimal distortion but at high processing time.

Since no proper groundwork exists for hole-filling standards in the field of Historic Preservation, this
data hopes to argue for standards that can efficiently deal with practical hole-filling of digital models and act as groundwork for further research. Findings suggest that a gap exists within modeling cultural heritage objects between users of technology and access to adequate standards for treatment of digitally recorded historical objects that is resulting in a myriad of poor quality reproductions. [83]. With new awareness and understanding of hole filling methods currently being used for historical reproductions practitioners can use these findings to make better decisions on how to best address lacunae filling toward specific goals.
7 Conclusion

7.1 In Conclusion

In conclusion, this thesis has contributed a comparative evaluation of current practices of in-filling digital lacunae and has established which methods are best suited to the following historic preservation practices: documentation, Interpretation graphics, Long-term monitoring, digital restoration, physical fabrication. Additionally, it has demonstrated that that modeling has been used as a useful tool for achieving preservation goals throughout history, from the Egyptian funerary models of Imhotep to the British cast courts of the 19th century. 3D models are only the latest manifestation of preservation model usage that has been debated by preservation theorists from John Ruskin to James Marston Fitch and part of an even broader philosophical debate around the relationship of replication and authenticity. The complicated history of 3D technologies revealed that inventors of 3D methods have created novel approaches, but at their core these models are not so different from historical precedents as one might initially think.

The current methods available for filling holes in fact based models used in the field of historic preservation are categorized into five methods based on their approach: Polygonal, Parametric, Volumetric, Image-based and context-based method. In addition to these methods, the role of the model in preservation, theories of historical approaches of hole filling methods in the field have been discussed and the relationship between copies and authenticity are presented as a supplement to the approaches mentioned. Of these approaches, ten have been recommended for specific preservation applications.

In this thesis, I determined that lacuna can be placed into five overarching categories: embedded, experiential, usage, enacted, strategic. Embedded
holes have been identified as part of the physical object, and exist before the scanning has taken place. Experiential holes are missing attributes of an object that contains human perception including the human sensorial perception that can assist in subjective metaphysical interpretations. Usage holes are holes that contain missing information about the pattern of organization of the critical actions that take place around the object, and the processes of interacting with it, its environment, and data from its environmental attributes. Enacted holes occur during the reconstruction process and are externalities of scanning processes or due to operator error. Strategic holes are holes that occur in models for due to externalities. Holes in 3D polygonal meshes are considered primarily as an enacted hole, due to hardware and processing defects, but can and also classify as any of the other four categories.

Criteria to evaluate existing hole filling method have been presented based on a comparative analysis radar graphic approach based on each methods attributes. An ideal case has been developed for each application to assist in the comparison.

The findings suggest that for analysis applications the polygonal / volumetric work best. Polygonal and volumetric methods have been a topic of extensive research, therefore, tend to be more developed and provide the most robust methods for dealing with holes. In addition to this, they are exceptionally adept at filling holes of various sizes and shapes. Alan Brunton’s method, in particular, stands out for its ability to unfold models [83]. He has demonstrated in his method the ability to work well on human figures. For analysis purposes, volumetric methods also work nicely with reconstructing topologically geared models with high accuracy. In the cases of Wang’s method (2012) the ability to work on complex geometry is demonstrated and its efficiency to fill holes for historical analysis seems to be a good fit. Jean-Philippe’s method (2006) is beneficial for filling holes that lay on curves, as most historically documented objects are not orthogonal it can be considered a benefit for purposes of historic analysis. Davis’-method (2001) has also proved to be highly effective on statuary scans, and the results appear to have no distortion on surrounding areas, a vital aspect of analytical modeling.

For interpretational applications polygonal/parametric/context methods are more suitable. Robust polygonal methods are successful to fill holes of various sizes and shapes remarkably well. RBF methods by Dinh and Turk (2001) are highly effective at rendering from sparse point clouds, which is a good fit for representational methods, such as video game design that focus on overall object geometry over high-resolution topological geometry. Vichitvejpaisal’s method (2014) demonstrates the power of context-based methods to infill a statue’s beard. The output of this methodology works well for rendering goals for not research-based methods.

For Monitoring applications the polygonal / context-based are recommended Polygonal methods are efficient at detailed surfaces with crevices, Zhao’s methods (2007) demonstrated quality results in this area. Leipa’s method (2003), is the basis for meshmixer, a widely used repairing software, which is noted as providing hole-filling without distortion of freeform objects of varying sizes. This is a good fit for monitoring needs. Infill can assist in monitoring building decay. Hole-filling methods that do not take into account topological context can cause false interpretation of holes as deterioration.

Digital Restoration methods should consider using Polygonal / Volumetric approaches. Digital restoration needs include medium levels of topological authenticity and geometric authenticity. Digital reconstructions benefit from the polygonal
category., Methods that stand out are the Kumar method (2012) and Bischoff’s method 2005. Kumar’s method uses voxels to represent internal geometry of the model to inform the patch, while Bischoff’s method is beneficial because the reconstruction yields non-manifold surfaces that are good for imaging purposes.

Models needed for reconstruction purposes are recommended to use Polygonal / Volumetric methods. Polygonal methods are valuable in this area; Robust polygonal methods are again successful here as they fill a hole in very complex geometry. Oliveria methods (2007) is particularly good at filling holes in rounded objects and shapes, and Wang method (2012) is perhaps the best method surveyed for filling very complicated geometry remarkably well. Volumetric methods are useful for reconstruction methods as well, as they are well suited for filling scanning data. Of note in the Volumetric category are Ju (2004) and Paulsen (2014). Both work with minimal distortion but at high processing time.

This thesis has demonstrated that 3D modeling and digital hole filling methods are complex and valuable aspects of historic preservation practice. Modeling built forms for preservation stems from the long tradition of documentation and reproduction dating back to the Roman copies of Greek statuary to the cast courts of the 19th century [12]. Three-dimensional models have played a vital role in the practice of designing and constructing buildings throughout history even demonstrating that earliest documented architectural scale models were for the purposes of architectural preservation. Although the methodology of modeling has evolved from its historical roots the fundamental principles remain the same Models act as mediators between the intellectual and physical world by demonstrating the physical, visual record of a potential future or a representation of the past.

The creation of a 3D model is standard practice in today’s architectural disciplines. 3D modeling and digital hole filling methods are complex and valuable aspects of historic preservation practice. Today, historic preservation utilizes modeling, not as an “a priori” maquette but a post factum reclamation of existing materials. The creation of a 3D model is standard practice in today’s architectural disciplines. 3D modeling and digital hole filling methods are complex and valuable aspects of historic preservation practice. Currently, the use of 3D models relies on several representational methods that are vulnerable to lacunae. Five of the most common issues with contemporary reproduction representations have been outlined as important aspects of perception [30]. (SOURCE THOMPSON):

The absence of human figures; the lack of human figures can leave viewers free to inappropriately claim spaces for themselves similar to the way early European settlers strategically left out Native Americans in their artistic portrayal of the American West. The absence of alternative interpretations; replications are creating a single predetermined path which does not give the viewer insight into what other historical interpretations may be present. The absence of time; viewers are subjected to a single period that has been pre-selected for them at the expense of others, a concept that is not unique to replications but also part of the nature of restoration work. The absence of context in digital models; many
replications are taking place in at-risk areas around the globe with little consideration for human lives. One of the faults of reproducing heritage objects is the prioritization of time and funding of reproduction versus initiatives to aid victims in conflict zones. The lack of access to the digital modeling tools; hardware and software needed to scan and generate 3D models are expensive and not everyone has access to them.

3D modeling and digital hole filling methods are complex and valuable aspects of historic preservation practice because of the strong connection between lacunae and the quality of digital reproductions. The thesis categorized holes into five types: Embedded Holes, Experiential Holes, Usage Holes, Enacted Holes and Strategic Holes, and demonstrated five case studies for each hole type. Including digitals scanning projects of Set I Tomb, an Ancient Incan and Bagan Temple, the holes common in the scanning of an ancient Corinthian Capital and the process of strategic hole placement having taken place at the Rio Maggiore in Venice. All this to say demonstrate that 3D modeling and digital hole filling methods are deeply embedded in preservation practice today.

7.2 Research Questions Answered

How have models been used as tools for historic preservation?

This thesis has demonstrated that models have been used as a tool for on-site surveying and site documentation are among the most affected aspects engaging the field by the introduction of 3D modeling [20]. The five primary goals of contemporary 3D heritage modeling are:

I. Documentation for analysis, which can be pivotal for preservationists dealing with at-risk heritage sites, in saving data that can later be used to reconstruct or study lost artifacts.

II. Interpretational graphics, which are a valuable tool for property managers, community organizers and non-for-profit organizations hoping to raise awareness about their causes by generating visual graphics for sharing. In some cases, 3D data is sold to visual artists who can use the 3D models in video game design, virtual reality, exhibition planning or box-office entertainment [21].

III. Long-term monitoring, which can be achieved cheaply and efficiently for historical objects using 3D scanning technology. This is especially suitable for sites that are irregular or liable to environmental material degeneration such as those of earthen construction.

IV. Digital Restoration, which serves as a valuable document for conservators engaged in restoration, that does not risk affecting the in-situ artifact and allows for iterative digital alterations that can be rendered and assessed before ever touching the actual object. Digital scanning hardware has yielded reproduced historical objects at the resolutions that are nearly imperceptible to the human eye. Regarding lacuna, digital reproductions are beneficial as they have the power to reversibly alter models and provide an experimental environment to test multiple methods without any risk to the historical object.

V. Physical Fabrication, which can be achieved through computer-aided construction methods that generate “G-Codes” allow the for the construction
of highly accurate facsimiles using additive or subtractive techniques.

Modeling methods for historic preservation are not new. Documentation and reproduction date to the Roman copies of Greek statuary and to the cast courts of the 19th century [12]. Methods were tied to notions of the divine and related to religious ideas of God and perfection. [13] This act of representation has served as one of architecture’s primary modus operandi as a robust method to predict the future and to warn of problems ahead in construction and renovation [14].

Three-dimensional models have played a vital role in architectural, the earliest documented architectural scale models were for the purposes of architectural preservation. Pharaoh Imhotep thought to be the world’s first architect, used funerary models to preserve architectural designs for construction in the afterlife. [15] Although the methodology of modeling has evolved from its historical roots the fundamental principles remain the same Models act as mediators between the intellectual and physical world by demonstrating the physical, visual record of a potential future or a representation of the past. Today, 3D models are defined as mathematical representations of objects or the surfaces of objects (either inanimate or living) in three dimensions via the use of software [16]. 3D models can be viewed as two-dimensional images through a process called 3D rendering or computer simulation. 3D models can also be physically created using machines. [17]

The needs for modeling in the field of historic preservation differs from those traditionally used in architecture. In architecture, the creation of new forms precedes the need to represent already existing built forms, while in historical preservation this relationship is inverse for in the case of heritage documentation [19]. The creation of a 3D model is standard practice in today’s architectural discipline and has demonstrated its place in contemporary architectural expression.

Are there existing methods of hole filling that are more beneficial than others for use on in Historic Preservation applications?

There are existing methods of hole filling that are more beneficial than others for use on recorded historical data. Based on applications analysis applications the polygonal and volumetric work best. Polygonal and volumetric methods have been a topic of extensive research, therefore, tend to be more developed and provide the most robust methods for dealing with holes. In addition to this, they are exceptionally adept at filling holes of various sizes and shapes. Alan Brunton’s method, in particular, stands out for its ability to unfold models [83] . He has demonstrated in his method the ability to work well on human figures. For analysis purposes, volumetric methods also work nicely with reconstructing topologically geared models with high accuracy., In the cases of Wang’s method (2012) the ability to work on complex geometry is demonstrated and its efficiency to fill holes for historical analysis seems to be a good fit. Jean-Philippe’s method (2006) is beneficial for filling holes that lay on curves, as most historically documented objects are not orthogonal it can be considered a benefit for purposes of historic analysis. Davis’-method (2001) has also proved to be highly effective on statuary scans, and the results appear to have no distortion on surrounding

Heritage areas, a vital aspect of analytical modeling.

For interpretational applications polygonal, parametric and context methods are more suitable. Robust polygonal methods are successful to fill holes of various sizes and shapes remarkably well. RBF methods by Dinh and Turk (2001) are highly effective at rendering from sparse point clouds, which is a good fit for representational methods, such as video game design that focus on overall object geometry over high-resolution topological geometry. Vichitvejpaisal’s method (2014) demonstrates the power of context-based methods to infill a statue’s beard. Monitoring applications should utilize polygonal / context-based methods. Polygonal methods are efficient at detailed surfaces with crevices, Zhao’s methods (2007) demonstrated quality results in this area. Leipa’s method (2003), is the basis for meshmixer, a widely used repairing software, which is noted as providing hole-filling without distortion of freeform objects of varying sizes. This is a good fit for monitoring needs. Infill can assist in monitoring building decay. Hole-filling methods that do not take into account topological context can cause false interpretation of holes as deterioration.

For applications requiring digital restoration models preservationists should consider using polygonal and volumetric approaches. Digital restoration needs include medium levels of topological authenticity and geometric authenticity. Digital reconstructions benefit from the polygonal category. Methods that stand out are the Kumar method (2012) and Bischoff’s method 2005. Reconstruction models required for fabrication purposes are recommended to use polygonal and volumetric methods. Polygonal methods are valuable in this area; Robust polygonal methods are again successful here as they fill a hole in very complex geometry. Oliveria methods (2007) is particularly good at filling holes in rounded objects and shapes, and Wang method (2012) is perhaps the best method surveyed for filling very complicated geometry remarkably well. Volumetric methods are useful for reconstruction methods as well, as they are well suited for filling scanning data. Of note in the Volumetric category are Ju (2004) and Paulsen (2014). Both work with minimal distortion but at high processing time.

**What guidelines are needed for digital hole filling in the field?**

This thesis demonstrates that guidelines are needed to evaluate hole filling methods by emphasizing differences of each method and discussing the the varying degrees of success for each approach. Guidelines are needed that can provide practical advice to assist individuals in choosing 3D modeling methods that are the most suitable for their needs. This thesis hopes to be a starting point for further work.

**What are the best method to fill holes in fact based models used for Historic preservation purposes?**

Findings suggest that polygonal methods are best for working at all scales, keeping distortion to a minimum, and working efficiently with raw points but bad at working with both freeform and polyhedral shapes making them useful for large-scale building scans. Parametric methods are effective at dealing with distortion, point clouds, but not useful for objects of varying hole sizes.
Volumetric techniques work best on oddly shaped holes, and highly curvature objects such as sculpture and ornamental purposes. Image-based methods are useful for filling holes with minimal distortion. Context based, have yielded the best results overall, but cannot work efficiently with multiple objects sized objects, complexity, not readily available.

Using the guidelines provided by the comparative analysis, I proposed an innovative evaluation method for the complicated case of filling holes in fact based 3d Model based on preservation-minded approaches. Additionally, Not only does this proposal demonstrate the ways that hole filling methods can be used as a preservation strategy to complete fill holes in heritage data in an authentic manner, but the thesis also demonstrates the critical role 3D models play in contemporary practice. In conclusion, the thesis contributes an in-depth investigation and guidelines for filling digital heritage models in the field of Historic Preservation.

By the comparative evaluation of current practices of in-filling digital lacunae this thesis has established which methods are best suited to the following historic preservation practices: documentation, Interpretation graphics, Long-term monitoring, digital restoration, physical fabrication. Through the lens of historic preservation, this data has determined that some methods are better than others at producing successful results. It can also be concluded that no modeling technique is all-encompassing, and professionals are addressing lacunae in heritage objects with many different complex ways. Surveying technology and the digital fact-based 3D model are valuable for recording, analyzing and safeguarding objects of cultural importance but purveyors of this must be careful when choosing methods to achieve their goals. The advancement of these methodologies will continue to play an essential role in the processing of historical 3D models. As stakeholders in historic preservation continue to focus their attention on digital technologies for advancing the field, innovations in high-resolution recording, processing, and reproduction capabilities will give preservationists more control on how 3D models can serve cultural heritage for the better.

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Andre Paul Jauregui

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Submitted in partial fulfilment of the requirements for the degree
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Graduate School of Architecture, Planning and Preservation
Columbia University
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Advisor
Adam Lowe
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Andre Paul Jauregui