2-13-2023

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James Hutson

Joseph Weber

Angela Russo

Scientific Research Publishing

Art and Design Review, 2023, 11, 15-41
https://www.scirp.org/journal/adr
ISSN Online: 2332-2004
ISSN Print: 2332-1997

Digital Twins and Cultural Heritage Preservation: A Case Study of Best Practices and Reproducibility in Chiesa dei SS Apostoli e Biagio

James Hutson[1], Joesph Weber[1], Angela Russo[2]

[1]Department of Art History and Visual Culture, College of Arts and Humanities, Lindenwood University, St. Charles, USA
[2]Archaeological Museum of Fiesole, Florence, Italy
Email: JHutson@lindenwood.edu, jweber@lindenwood.edu, angela.russo@ef.com

How to cite this paper: Hutson, J., Weber, J., & Russo, A. (2023). Digital Twins and Cultural Heritage Preservation: A Case Study of Best Practices and Reproducibility in Chiesa dei SS Apostoli e Biagio. *Art and Design Review, 11,* 15-41.
https://doi.org/10.4236/adr.2023.111003

Received: January 16, 2023
Accepted: February 10, 2023
Published: February 13, 2023

Abstract

The use of digital twin technologies to preserve cultural heritage has become increasingly common over the past two decades. Evolving from the use of virtual environments (VE) and digital reconstructions that required multiple phases of workflow and multiple software applications and various hardware to output a useable experience to the immediacy of 3D artificial intelligence (AI) generative content and the latest generation of photogrammetric scanning, non-specialists are now able to more easily create digital twins. At the same time, the destruction of cultural heritage has accelerated due to geopolitical instability, seen in examples such as the invasion of Ukraine by Russia (2022). Even with advances in user-friendly and commercially available technologies, digital art history and the digital humanities are in a race against time to train and equip enough individuals onsite to create digital twins before more irreplaceable cultural artifacts and sites are lost to natural disasters, accelerated by climate change, or through armed conflict. However, there remain no international standards for methodological reproducibility and the techniques used currently by many scholars include specialized training and knowledge. As such, this paper presents a case study that addresses reproducibility and explainability in the digital humanities through a detailed workflow of the creation of a digital twin of Chiesa dei SS Apostoli e Biagio in Florence, Italy. A model is presented that is scalable and leverages widely available, user-friendly 360 cameras and photogrammetry with LiDAR to capture cultural heritage sites with best practices on how to quickly and effectively train non-specialists to create site-specific digital twins of a variety of cultural heritage structures.

Keywords

Digital Twin, Cultural Heritage Preservation, Chiesa dei SS Apostoli e Biagio, Photogrammetry, XR Development Pipeline.

1. Introduction

The pace of immersive reality adoption for cultural heritage preservation and reconstruction has accelerated and has moved from the domain of specialists and technicians to the public, scholars, and non-specialists (Gabellone, 2022). Beginning with examples such as virtual environments (VE) created using CAVE technology as in the Foundation of the Hellenic World (FHW), digital reconstructions of ancient cities began to appear, albeit exteriors without realistic texturing (Tzortzaki, 2001). Such early uses of digital twin technology allow researchers and the public to interact with and study heritage sites and/or artifacts that have since been damaged or lost (Hutson & Olsen, 2021). Other examples of this followed with reconstructions of Athens, the Roman Forum, and whole museums have since been created using digitized photographs uploaded to a virtual environment (VE) (Stanco, Battiato, & Gallo, 2011). Along with reconstructions of lost or damaged sites interiors and 3D models of objects have been digitized as in the example of Brennan and Christiansen (2018) where the sculpture collection in the Uffizi Galleries in Florence, Italy was scanned using 3D scanners and photogrammetry and then imported into the game engine Unity to create an immersive experience. These technologies are now poised to work in tandem to create both historically accurate interior and exterior architectural spaces and/or archeological sites complete with the actual furnishings and accoutrement that have since been dispersed or lost (Bevilacqua et al., 2022).

The utility of such three-dimensional virtual models in digital twins cannot be overestimated with regard to cultural heritage preservation. Digital twins are already used widely in the industry to optimize repair and maintenance schedules for a firm's physical plant (Lei et al., 2021; Jiang et al, 2021; Mihai et al., 2022). As such, these digital assets can also be used to monitor the condition of heritage sites and artifacts in real time. Digital twins can be used to track changes in temperature, humidity, and other environmental factors that may affect the stability of heritage objects (Nieves, Bravo, & Sierra, 2022; Ariesen-Verschuur, Verdouw, & Tekinerdogan, 2022). The ability afforded conservators to identify potential risks and take preventative measures to protect objects and sites should spur rapid adoption. Additionally, as in industry, digital twins may be used in planning and conducting restoration and conservation work. Instead of using current estimations of conservation scheduling, cloud-based digital twins can be used to simulate different restoration and conservation scenarios, allowing conservators to choose the best approach for a particular object or site (Bruno et al, 2022; Ni et al., 2022). Finally, these digital reconstructions provide virtual access to heritage sites and artifacts that may be difficult or impossible for the public to visit in person, making them ideal for educational and curatorial purposes (Alsadik, 2022). Such digital twins also have the potential to open access to understudied, but historically significant sites for researchers with expertise in a field to gain access and provide insight for the broader academic community. There are many reasons for restrictive access, but these can include the fragile nature of materials, sites that are located in remote or hazardous areas, or that are subject to restrictions on physical access due to environmental or geopolitical reasons. In addition to war or countries with restricted access, there is the additional consideration of collective security in the wake of the Just Stop Oil protests that led to the defamation or damaging of works in art museums (Widener, 2022).

Recent advances in technology have led to a more streamlined development pipeline for the creation of digital twins for cultural heritage. Previous 3D scanners and photogrammetry required thousands of individual images to be manually stitched together by technicians, but now, readily available systems such as Matterport, can nearly instantaneously produce an interior rendering, especially of relatively flat surfaces (Mikhail, Bethel, & McGlone, 2001; Karami, Menna, & Remondino, 2022). The latest hand-held scanners, such as Scantech, can then be used to produce high-resolution digital twins of objects, complete with precise colors and textures (Kurtha & Balzanb, 2022). Both systems are now highly portable, user-friendly and affordable. Moreover, the latest generation of hardware and software now enables polygonal rendering and low latency of the latest generation of headsets and game engines, such as Unity and Unreal Engine, and allows for the integration of the architectural elements and spaces, as well as the objects contained within for a more authentic cultural appropriation (Barrile et al., 2022). The next generation of 3D model generation with artificial intelligence (AI) currently being developed even further democratizes the creation of virtual content for cultural heritage with text prompts and 3D generative asset creation (Baduge et al, 2022).

Despite these technological advances, cultural heritage institutions in different countries are adopting different software, hardware, and development pipelines, making reproducibility, transferability, and interoperability a barrier to international and interinstitutional collaborative efforts. For example, there is disagreement over which hardware to develop for as the HoloLens 2 has been widely adopted for augmented reality (AR) projects, such as with Clemens Brünenberg, at Technische Universität Darmstadt for archeological reconstructions (Robinson et al., 2021), but others are developing for other headsets, including the ScientoPy and VOS Viewer (Challenor & Ma, 2019). With the discontinuation of the development of the Hololens by Microsoft, researchers are left to determine a viable solution. Virtual reality (VR) development is just as fraught with disagreement over which to adopt with the Meta Quest 2 still dominating the market of head-mounted displays (HMDs), but the anticipated release of those by Apple and Google have left researchers to speculate on which will be dominant and sustainable. The development of software and VR platforms is further complicating interoperability as different software (e.g. Blender, Maya, 3ds Max) and development pipelines (e.g. GitHub, WebVR, The Wild, Unity, Unreal) lead to situations where each development team must start anew instead of building on work by others in the field (Bozzelli et al., 2019; Marto et al., 2022; Zhu, Fong, & Gan, 2022). Furthermore, there remains no international organization to provide interoperable standards for methodological reproducibility and to ensure the longevity of archived files and information (Jacobsen, 2007; Freire et al., 2013; Amato et al., 2022). Complicating the situation further, scholars often work with technicians that have specialized knowledge and training that preclude widespread adoption of their processes (Geng et al., 2022).

As such, this paper presents a case study that addresses reproducibility and explainability in the digital humanities through a detailed workflow of the creation of a digital twin of the understudied Chiesa dei SS Apostoli e Biagio in Florence, Italy (**Figure 1**) (available here: https://my.matterport.com/show/?m=sNCcHkVWmSb). The study will discuss the technical considerations and procedures that are now accomplishable with minimal training and relate how working with technicians (or closing the scholar-technician gap altogether) can provide greater access to cultural heritage sites, not only for research purposes but also for increased awareness by the public of historical sites and museum collections and the relationship between the two. The workflow model presented is scalable and leverages widely available, user-friendly 360 cameras and photogrammetry with LiDAR to capture cultural

Figure 1. Chiesa dei SS Apostoli e Biagio (façade), Florence, Italy, begun 1075.

heritage sites with best practices on how to quickly and effectively train non-specialists to create site-specific digital twins of a variety of cultural heritage structures. The church used to demonstrate the proposed development pipeline is an excellent example of how institutions may use digital twins to increase awareness of historical structures that, while locally famous, remain largely unknown to international scholars. A brief literature review on cultural heritage preservation will be followed by the significance of the structure under investigation, the Chiesa dei SS Apostoli e Biagio. While deeply ensconced in Florentine culture with ties to the Mona Lisa, Michelangelo, and relics from the Holy Sepulcher in Jerusalem, the church remains largely understudied and undervisited. After a comprehensive review of the structure, its history, and the significance of the tombs, paintings, sculptures, and other interior decorative elements, the process taken by the research team to create a digital twin shell be outlined in detail.

2. Literature Review

Digital Twins and Cultural Heritage Preservation

Digital cultural heritage preservation in digital art history and digital humanities study has only recently come into being. Moreover, with digital twin technology developing only recently and being applied to cultural heritage, scholarship is still in a nascent stage (Hutson & Olsen, 2022a). The recent developments began in 2001 with the digitizing of cultural heritage sites. Both ancient and modern sites were created, though access and use were often restricted to researchers and institutions. Such virtual environments (VE) were first developed using CAVE technology, as seen in the Foundation of the Hellenic World (FHW). Digital reconstructions were possible through the use of technology, beginning Miletus, an Athenian and later a Roman colony on the coast of Asia Minor (Tzortzaki, 2001). The potential was recognized for museums and other cultural heritage institutions almost immediately. For instance, Roussou (2001) published how the technology would be ideally suited for exhibitions in museums' "edutainment." Heading the call, many museums began integrating extended reality (XR) experiences in the first decade of the twenty-first century, including The Museum of Pure Form and The Virtual Museum of Sculpture (Loscos et al., 2004). These experiences were designed for use by the general public, who had no experience using this new technology. And unlike experiences for the scientific and medical communities, which tended to be longer, these were necessarily short to keep visitors moving through exhibition spaces (Carrozzino & Bergamasco, 2010). These site-specific XR experiences quickly gave way to completely virtual museums, such as The Exploratorium, a public science museum, and The CREATE project, an EU funded project that allows users to reconstruct archeological sites (Hutson & Olsen, 2022b). Around the same time, whole museum collections were digitized for viewing using augmented reality (AR) devices or head-mounted displays (HMD). Beginning in

2006, the Center for the Art of East Asia in the Department of Art History, Division of Humanities, at the University of Chicago (CAEA) started digitizing and archiving their collections of East Asian paintings and sculptures. Such examples of cultural heritage institutions expanding access to art-historical resources are driving digital twins today. The digitized collection at CAEA and others move the experience from a physical museum to a completely virtual learning environment (VLE) (Christou, 2010). The development is made possible through the recent availability of user-friendly interfaces and immersive design, coupled with shorter engagement duration, and has led to the design of VLE being currently popular.

However, only in the last decade has the use of VLE to deliver cultural heritage content becomes widely available. Most notably this has been accomplished through the creation of computer-generated museums using 3D models or through digitization efforts of real museum spaces. A watershed moment occurred with the launch of Google's Arts & Culture in 2011, which allowed virtual visits to museums, accessible to anyone with a smartphone. The company seized upon the democratizing potential of the technology with Google Cardboard in 2014, an inexpensive HMD that was quickly adopted for secondary education (Boel et al., 2021). Similar VLEs have been developed to tour real or virtual museums (VM), such as the Rijksmuseum, Amsterdam, and the National Archeological Museum of Marche in Ancona, Gyeongju VR Museum, South Korea (Favro, 2006; Clini et al., 2018). The Louvre also recently (2021) released their digital collection of over 480,000 pieces from its collections and made them available via their proprietary platform. One of the most impactful projects as of late has been overseen by UNESCO (2017-2020) and saw the creation of full virtual tours of World Cultural Heritage Sites (El-Said & Aziz, 2022).

Since the pandemic, the use of digital twins for cultural heritage as greatly expanded and adoption is seen across the globe in many areas. For instance, Bevilacqua et al. (2022) described different examples of VR applied to the cultural heritage, including a digital twin of the First Italian Parliament, which no longer exists. The reconstruction that used digital modeling and a prototype in VR was made available to visitors to Palazzo Carignano, Turin. Another example provided describes the creation of a digital twin of the Charterhouse of Pisa in Calci. The virtual environment created includes a reconstruction in three dimensions of frescoes and the cloister in various historical phases. As with the examples provided by UNSESCO, the creation of such digital twins may be driven by tourism, but has also opened a new avenue for researchers around the globe (Shahzad et al., 2022; Zhao, Guo, & Li, 2022).

While these digital twins provide examples of the processes used by European scholars to recreate and/or reconstitute architecture, another case study presented by Tan et al. (2022) demonstrates processes used in Asia. The study focuses on Xiegong, a unique element of Chinese historic buildings that is representative of the development of Dougong. The sense of urgency in the field of archeology, and relevant to our study, relate to the erosion rate and loss of the physical properties that need to be captured for posterity. Using 3D surveying technology, researchers reproduced a three-dimensional digital twin of the site in order to record and survey heritage buildings. In order to support the process, the researchers developed a methodology that aligns digital twin technology and the chronology of forms. Their approach included oblique photogrammetry, LiDAR, and building information modeling (BIM) to assist in archeological research into Xiegong. Xuanluo Hall in Sichuan, China was used as an example for the study and verified the usefulness of the approach with geometry and semantics. The results of the process confirm the viability of using digital twin technology to assist in archeological research. Other studies confirm the viability of archeological research and preserving deteriorating structures (Rosa, 2022; Wang et al., 2022). Taken together, the processes used by the research teams above in creating digital twins require multiple areas of expertise and collaboration between technicians and scholars in order to create usable prototyptes for digital cultural heritage sites.

Chiesa dei SS Apostoli e Biagio

The Chiesa dei SS Apostoli e Biagio (**Figure 1**), known to the English-speaking community serves as the Church of Santi Apostoli, is located in the heart of historic Florence near the Ponte Vecchio. The church is situated in the Piazza del Limbo, named for a cemetery previously onsite where unbaptized children were buried (Trotta, 1992), and, although being steps from the heavily trafficked path along the Arno River, is rarely visited aside by local parishioners. Likewise, despite the historical and religious significance of the church, there is surprisingly little published on it. The brief treatments of Busignani and Bencini (1979) and Trotta (1992) provide a brief history of the construction of the church, which began in the eleventh century, and descriptions of the artworks in the various side chapels. Baccio d'Agnolo (1462-1543) added a small campanile in the sixteenth century and Benedetto da Rovezzano (1474-1552) added a central Renaissance portal in 1512 with flat pilasters in white and gray marble flanked by the Altoviti coat of arms (rampant wolf) (**Figure 2**) (Wellen, 2022). Finally, the church was restored between 1930 and 1938 (Trotta, 1992). Given that, arguably, the most famous aspect of the church is Vasari's *Immaculate Conception* (1541), the 2001 treatment (AA.VV, 2001) of the church provides a summary of the history of the building and further insight into the restoration of the altarpiece. The most recent and useful treatment of the church was published in 2004 by Bertani & Trotta, which provides additional insight into the history of the construction of the church, information regarding the Altoviti family, who patronized renovations, and the description of the artworks.

The Romanesque church begun in 1075 is dedicated to the Holy Apostles and St. Biagio, a fourth century physician, and bishop of Sebastea, Armenia (now Sivas, eastern Turkey). According to his hagiography, the saint was martyred on February 3, 319 CE, and is popularly venerated saints in both the Catholic and the Orthodox Church (Weatherwax, 2003). The dedication of the church to San

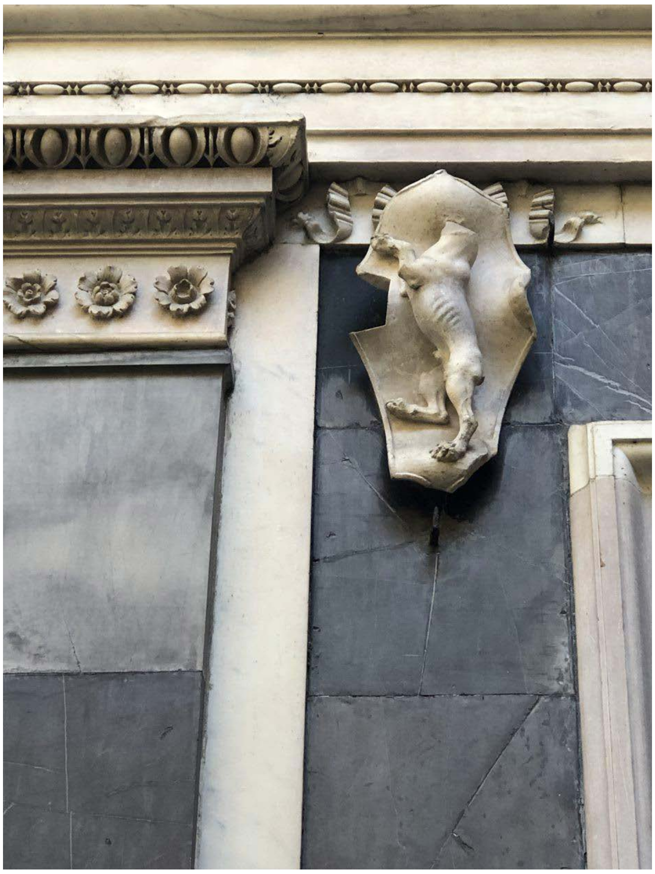

Figure 2. Altoviti Crest, Main Portal, Chiesa dei SS Apostoli e Biagio, Florence, Italy, 1512.

Biagio occurred much later in the eighteenth century when the Grand Dukes of Lorraine suppressed many religious buildings, among them the church dedicated to this saint, not far from SS. Apostles. The latter, therefore, also received the title of the suppressed church and was from that time dedicated to SS. Apostoli and San Biagio (Busignani & Bencini, 1979; Lipp, 2022).

The church can be understood as a microcosm of Florence itself, both historically and culturally. Local legends surrounding the beloved church include ties to the ancient Romans, Charlemagne, the second "Wall" of the city, the Crusades, Michelangelo, and Leonardo da Vinci's *Mona Lisa.* According to legend, the church is one of the oldest in Florence and was founded by Charlemagne in the ninth century (AA.VV, 2001). The assertion is clearly communicated in a carved plaque on the exterior façade (**Figure 3**). The Romanesque façade (**Figure 1**) with irregular masonry is retained on the exterior, as are many of the original architectural elements inspired by ancient Roman buildings on the interior (**Figure 4**). The plan (**Figure 5**) retains elements of Roman basilica design with a nave and two aisles with a semicircular apse. The green marble columns (**Figure 6**), which were quarried from Prato, were spolia from the first century BCE ancient Roman baths near the Piazza del Limbo (Busignani & Bencini, 1979; Maxson, 2023).

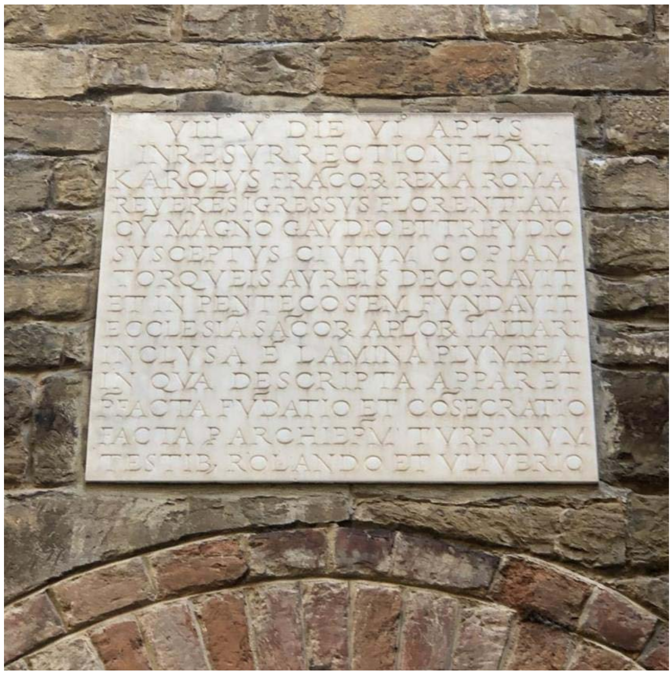

Figure 3. Inscription of dedication of the church by Charlamagne, Chiesa dei SS Apostoli e Biagio (façade above left portal), Florence, Italy, begun 1075.

Figure 4. Chiesa dei SS Apostoli e Biagio (nave), Florence, Italy, begun 1075.

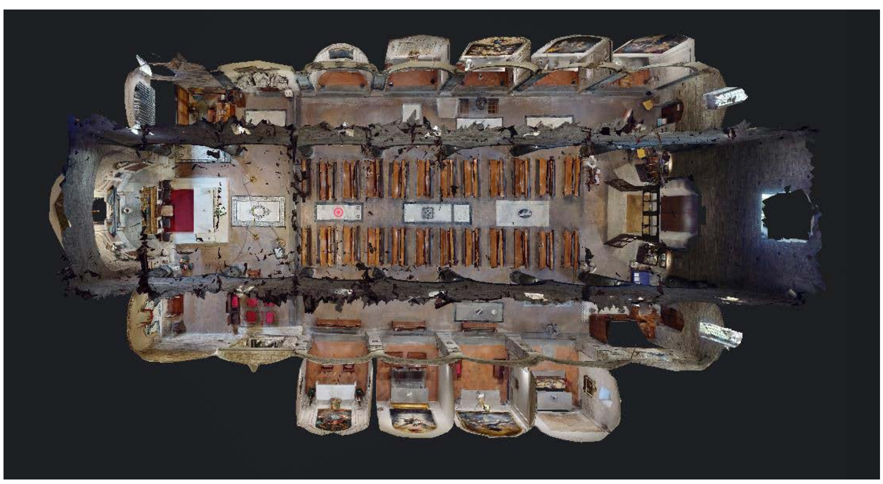

Figure 5. Chiesa dei SS Apostoli e Biagio (overview of plan), Florence, Italy, begun 1075.

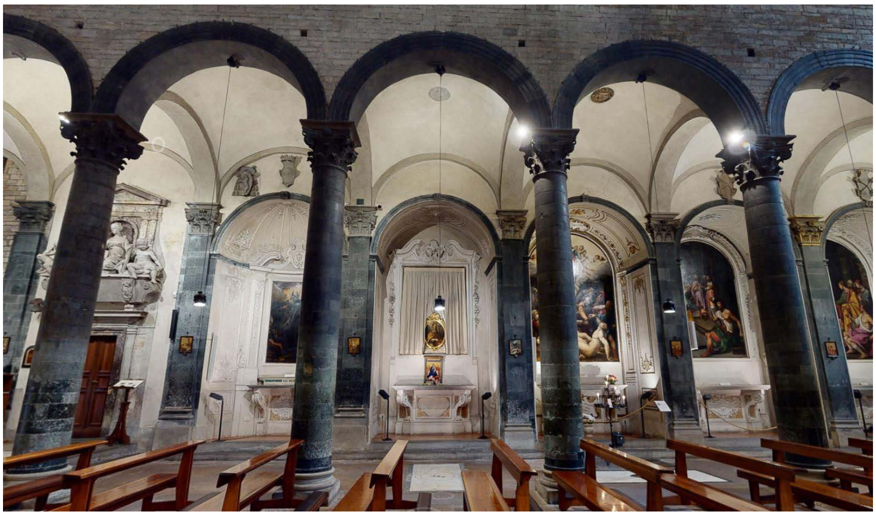

Figure 6. Chiesa dei SS Apostoli e Biagio (detail of colonnade), Florence, Italy, begun 1075.

The church has gone through many phases of construction and remodeling since 1075, when construction began. For instance, the ornately decorated, hand painted trusses of the wooden ceiling (**Figure 7**), reminiscent of early Christian basilicas like Old St. Peter's in Rome, was added in 1333 (Spieser, 2022). Details such as the floor mosaic are maintained from the original from the eleventh century and later restored with contributions from Florentine families like the Acciaioli, Altoviti, and Del Bene (Trotta, 1992). Unfortunately, only fragments remain because tombstones of these families (**Figure 8**) were placed in areas throughout the church, starting in the thirteenth century, and this required destroying much of the original floor decorations. The floor is constructed with *cocciopesto* (mortar with brick, lime and sand) and some elements of the original decoration remain (Lancaster, 2021). In particular, there is a marble-encrusted "tile" (*formella*), with animal representation, found during the restorations of 1930-38 (Bertani & Trotta, 2004). The style of the tile has similarities with those of San Miniato and the Baptistery. The apse area has maintained a Romanesque appearance, with undecorated stones visible (Bossi & Guidobaldi, 2015).

Although remodeled in the fifteenth- and sixteenth centuries, the structure is one of the few in Florence to retain its medieval architectural features and decorations. The primary patrons for the renovations and new construction were the Altoviti, another Italian banking family like the Medici who were papal bankers. Of the family, only Oddo Altoviti (1457-1514) is named in the records associated with the fifteenth-century construction efforts as he was the commissioner of the tomb in the left aisle (**Figure 9**), which he had made for himself and his brother Antonio Altoviti (1454-1507) by the sculptor Benedetto da Rovezzano, who also carved the holy water font (Bertani & Trotta, 2004; Petrucci, 2021). His date of birth would contradict the reported information that an Oddo Altoviti would marry Giovanna Gherardini (whose niece would be Lisa Gherardini, identified as the model for Leonardo da Vinci's *Mona Lisa*) in 1432 (unless there is another

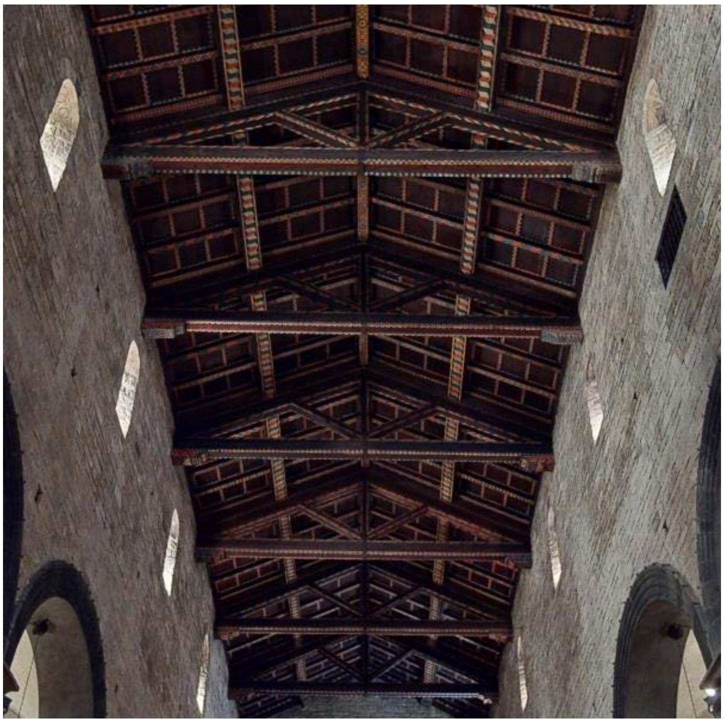

Figure 7. Chiesa dei SS Apostoli e Biagio (detail of wooden ceiling decoration), Florence, Italy, begun 1075.

Figure 8. Altoviti Tomb Slab, Chiesa dei SS Apostoli e Biagio, Florence, Italy, begun 1075.

Figure 9. Benedetto da Rovezzano, Oddo Altoviti Tomb, left aisle, Chiesa dei SS Apostoli e Biagio, Florence, Italy, 1507.

Oddo) (Trotta, 1992; Soranzo, 2022). Antonio's sons, including the famous Bindo, and those of his brother named Stoldo, Bindino and Antonio, were also patrons for the church (Rowland, 2021). For example, Bindo will be the commissioner of the chapel dedicated to the Immaculate Conception with the panel painted by Vasari. Local tradition holds that Michelangelo himself convinced Bindo Altoviti (1491-1557) not to raise the ground level of the church as he had planned and instead to preserve the original Romanesque floor. While Bindo had befriended Michelangelo, the claim cannot be substantiated in the historical records (AA.VV, 2001).

The revitalization of the church included construction of new side chapels in the sixteenth century begun under Oddo Altoviti (1457-1514) in the fifteenth century. The first to be built was the five on the left aisle (**Figure 10**) (now four because the first one was demolished during the restorations of 1929-30). In 1431, there were already two chapels under the patronage of the Altoviti family, the second on the left aisle and the one at the end of the right aisle. These chapels are decorated with altarpieces, including the *Adoration of the Shepherds* flanked by *Saint Andrew* and *Archangel Raphael and Tobias* by Maso di San Friano (1536-1571) (**Figure 11**); the *Archangel Saint Michael and Lucifer* altarpiece

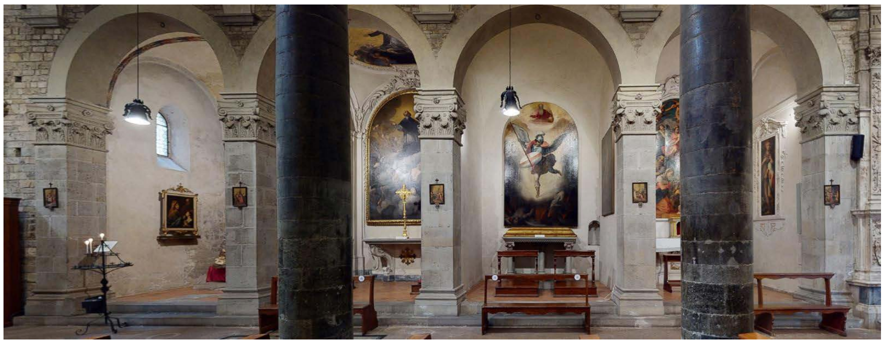

Figure 10. Left Aisle Burial Chapels, Chiesa dei SS Apostoli e Biagio, Florence, Italy, begun 1431.

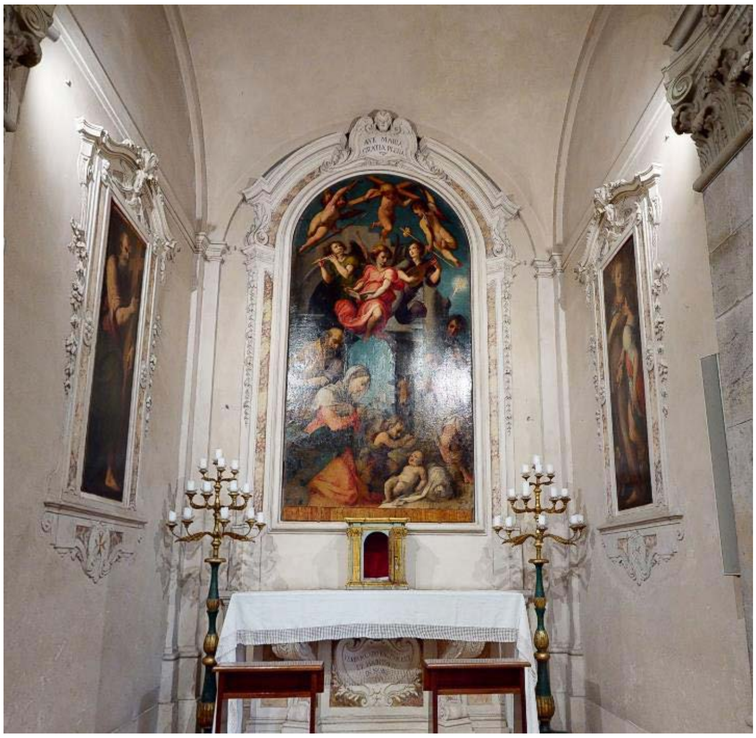

Figure 11. Maso di San Friano, *Adoration of the Shepherds, Saint Andrew, Archangel Raphael and Tobias,* sixteenth century.

by Alessandro del Barbiere (1538/43-1592) (**Figure 12**) also created in the sixteenth century; and the *Madonna and Child* by Paolo Schiavo (1397-1478) (**Figure 13**) from the original façade with fragments of the original fresco flanked by the preserved in sinopia preparatory drawing, early fifteenth century (Brookes, 1965; Bertani & Trotta, 2004; Borghini, 2007).

The same chapel holds an inset niche with a thirteenth-century reliquary created by Florentine goldsmiths out of bronze supported by a gilded copper cup from the fourteenth century (**Figure 14**) that reputedly holds three flints known as the "Stones of the Holy Sepulcher" (*Pietre del Santo Sepolcro*). These two flints were believed to light the lamps of Christ's burial tomb in Jerusalem and are reputed to have been brought back to Florence in 1101 by Pazzino dei Pazzi.

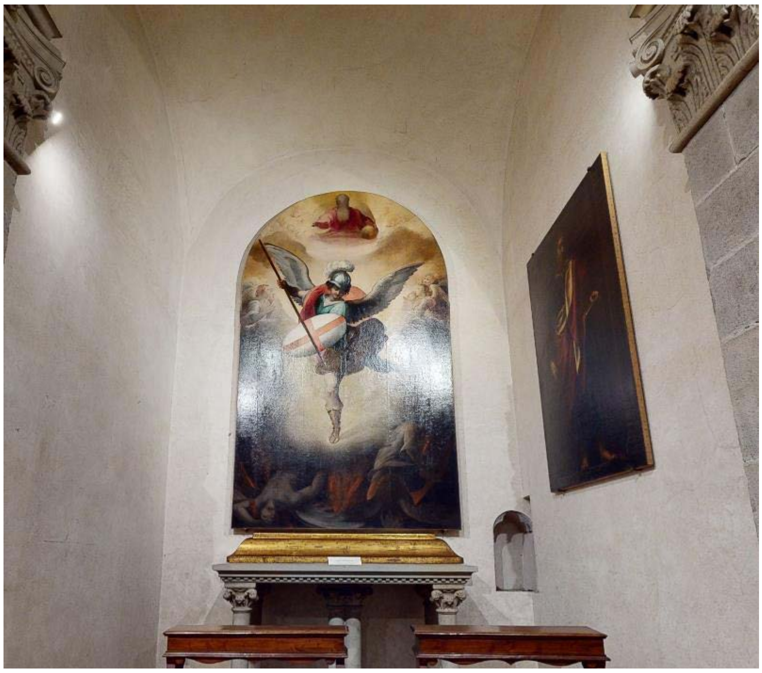

Figure 12. Alessandro del Barbiere, *Archangel Saint Michael and Lucifer,* sixteenth century.

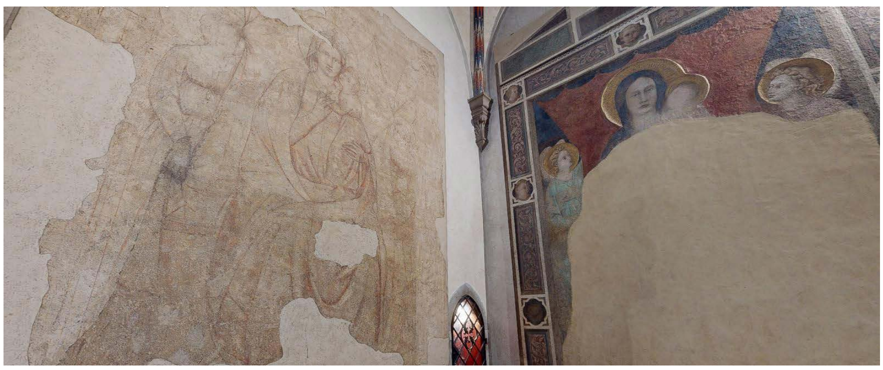

Figure 13. Paolo Schiavo, *Madonna and Child,* fresco and sinopia underdrawings, early fifteenth century.

The crusader was believed to have been among the first Christians to lead the way to the capture of Jeruslaem by scaling the walls of the city in the First Crusade (Addona, 2022). As such, the Pazzi adopted the flaming cup as an element of their coat of arms (Busignani & Bencini, 1979). Annual ecclesiastical celebrations continue to center the Church of Santi Apostoli in Florentine identity and this relic plays an important role. The aptly named "Fire Holder" is linked to the ceremony of *Lo Scoppio del Carro* ("explosion of the cart") and the lighting of fireworks from the *Portafuoco* after Easter Mass in the Florentine Duomo each year. The "holy fire" produced when the flints are struck on Eastertide was carried throughout the city by young men bearing torches until the end of the fifteenth century. At that time, the tradition evolved to modern practice whereby a cart carrying an enormous candle is lit at Santi Apostoli and rolled throughout

Figure 14. Stones of the Holy Sepulcher Reliquary, thirteenth century.

the city to the cathedral where fireworks are then lit in celebration (Langton, 2012).

In contrast, the five chapels on the right of the entrance (**Figure 6**) were built beginning in the 1470s. The chapels are decorated with works from sixteenth century artists, including Giorgio Vasari (1511-1574). His *Allegory of the Immaculate Conception* (1541) (**Figure 15**) is the centerpiece and one of the most celebrated works in the church and represents the Tree of Original Sin of Adam and Eve. Old Testament prophets surround the tree in the lower register and Lucifer is wrapped around the tree as the Virgin is elevated above, supported by angels. Bindo Altoviti commissioned the work for his chapel dedicated to the Immaculate Conception (O'Connor, 2000). The patron was later buried inside the church as well (1570) and his funerary monument (**Figure 16**) above the door of the sacristy was executed by the Ammannati workshop, supervised by Bartolomeo Ammannati (1511-1592). The decorative cenotaph has two coats of arms of the Altoviti family with allegorical figures of Charity framed by a classical temple front with paired ionic flat pilasters surmounted by a pediment (Sorrentino, 2022).

The Bindo Altoviti tomb is directly across the apse from that commissioned for Oddo Altoviti (already mentioned), which is perpendicular to the Eucharistic Tabernacle (ca.1512) (**Figure 17**) by Andrea della Robbia (1435-1525) and Giovanni della Robbia (1469-1529). The ceramicists created the glazed terracotta tabernacle to represent two angels pulling back a curtain to reveal the Annunciation inside a classical, barrel vaulted interior with seraphim in the spandrels and

Figure 15. Giorgio Vasari, *Allegory of the Immaculate Conception*, 1541.

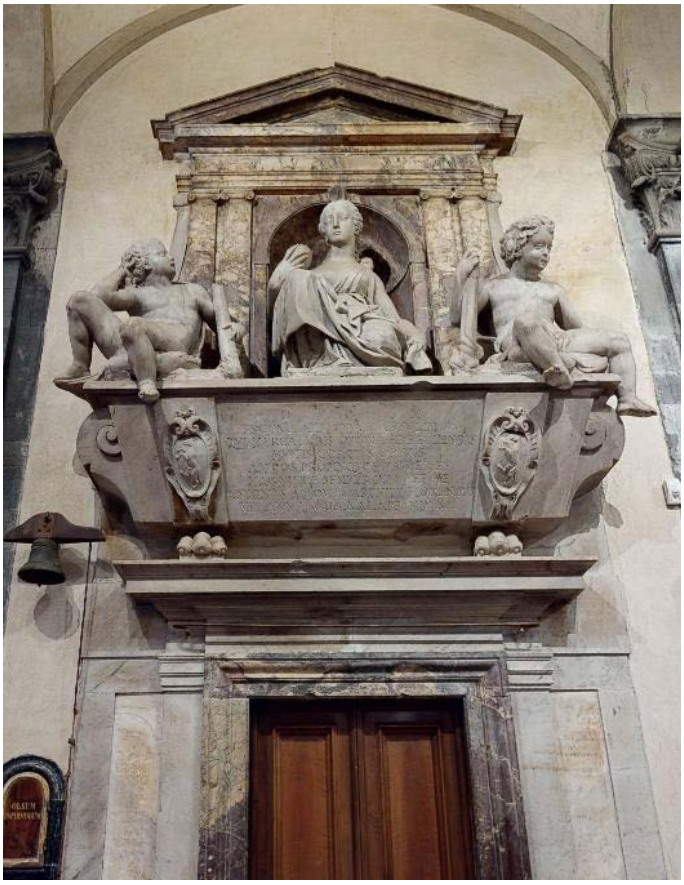

Figure 16. Bartolomeo Ammannati (and workshop), Tomb of Bindo Altoviti, 1570.

Figure 17. Andrea and Giovanni della Robbia, Eucharistic Tabernacle, ca.1512; Florentine School, Tomb of Donato Acciaiuli, 1333.

running horizontally in the entablature surmounted by the Holy Trinity and four flying putti above, who also carry garlands of leaves and fruit (Callahan & Cooper, 2010). Below the tabernacle, the Tomb of Donato Acciaiuli (1429-1478) can be seen in the fragments that remain of the Madonna and Saint John the Evangelist in two relief marble tiles from the Florentine School in 1333 (Ganz, 1982). Next to the tomb in the apse can be found the Funerary Monument of Antonio Altoviti (1521-1573) (**Figure 18**), archbishop of Florence. Giovanni Antonio Dosio created the monument in 1547 with Battista Caccini carving the two busts above the side doors that flank the monument, which depict Charlemagne and Antonio Altoviti (Davis, 1976; Fehl, 1976; Dow, 2014).

The funerary monuments surround the high altarpiece and focal point of the church from the nave. The altarpiece of an *Enthroned Virgin and Saints* (**Figure 19**) was painted by Jacopo di Cione (1325-1390) and Niccolò di Pietro Gerini (1340-1414) in 1382 and was originally located in the convent of the Poor Clares in via dei Malcontenti (Pope-Hennessy, 1949; Spring & Grout, 2002; Davies, 2009). The altarpiece was moved to the church in 1950 and replaced an altarpiece representing Pentecost. The work is situated behind the main altar in white and green marble created in a neo-Romanesque style in 1901 (Bizzarro, 2019). The Madonna and Child are flanked by two angels and Sts. Clare and Catherine of Alexandria. In the four gothic pinnacles atop the scene are Sts. Peter and Paul flanking an Annunciation scene. The panels to either side of the Madonna and Child represent Sts. Lawrence, John the Baptist, Francis and Stephen. The predella depicts the Three Kings in the procession of saints assembling to the right

Figure 18. Giovanni Antonio Dosio, Funerary Monument of Antonio Altoviti; Battista Caccini, Busts of Antonio Altoviti and Charlamagne, 1547.

Figure 19. Jacopo di Cione and Niccolò di Pietro Gerini, *Enthroned Virgin and Saints,* 1382.

and left of a Nativity scene. The altarpiece is but one piece of the historical tapestry that makes up the church. In all, Santi Apostoli is a microcosm of the city of Florence and deserves greater scholarly attention. The prestige of the family and consequently the patronage of the church lasted until 1583 and in 1594 their bank in Rome went bankrupt. Thereafter, the church remained a hidden gem in the heart of the city (Bertani & Trotta, 2004).

Proposed Methodology and detailed workflow

Preproduction

In order to make available a high-quality digital twin of the Church of Santi Apostoli, a team consisting of scholars and technicians from Lindenwood University and local scholars from the Archaeological Museum of Fiesole used the following workflow. All the images in the figures were captured from the scan available here https://my.matterport.com/show/?m=sNCcHkVWmSb. The digital twin can be experienced via mobile phone, desktop computer, or virtual reality (VR) head-mounted display (HMD). The first step to the creation of such a digital twin for cultural heritage preservation, research, and virtual travel begins prior to departure for the location. The rationale for including this preliminary step is to ensure any challenges onsite may be identified and handled prior to being onsite. In the preproduction phase, the production team should perform reconnaissance on the location using existing maps and/or 360 photographs or videos of the location (if they already exist) via Google Maps or similar geospatial records. Familiarizing oneself with the location will improve time on task once on location. Special attention should be paid to light sources, whether the interior is lit by natural or artificial light, and if additional lighting needs to be considered among equipment transported to the location.

For the project, the team used the Matterport system, specifically the Matterport Pro 3D camera. In preparing the hardware for travel, one should ensure there is enough memory available for the size of the files to be scanned, even if using a cloud-based storage system; ensure equipment is in working order and test prior to leaving; ensure units are properly charged and that chargers include adapters and converters appropriate for the outlet and voltage of the destination country; and, finally, ensure the cases housing materials are appropriate and allotted size for the airline or mode of transportation to the location given size and weight limitations. Check the weather for the proposed data of scanning. As the system used for this project was pre-LiDAR, overcast skies and diffused lighting was preferable. With optimal conditions, less disruption between scans can be ensured. If the light sources change during scanning, the scans may read, and thus render, shadows as objects.

When onsite, first note how people naturally move through a space (if appropriate) in order to map out an appropriate path that reflects how a visitor would traverse in reality. Any worn paths should be used in exterior locations and cut corners should be mapped. This process will ensure user experience is considered as oftentimes those viewing a location in VR will take the shortest route instead of the intended urban planning route to move between locations. The scans and movement throughout a location should ensure there is no break in viewing between movement in VR or how the space would be seen in reality. Start with a reference point, such as scanning outside of a space. In this instance, the façade was the reference point and was scanned prior to entering the structure to provide a natural orientation for the user even if the intended subject is primarily the interior of the structure. The reference point is necessary for the dollhouse view to process properly as well as provide an understanding of geographically where the location is within the larger city or location. Once this is established, and natural traversing of the interior is observed, the team should walk through and open any doors and turn any artificial lights on prior to starting the scanning process. More seasoned users of digital twins in virtual space will jump from one scan to another and through this process, one can better ensure continuity of experience and lighting.

Production

Time should be factored in location. For the project here, two hours was originally projected but took four in total. When setting up equipment, begin by setting the center of the aperture to the average height of the intended user. In this instance, the team set the average height of a local Florentine to allow a user to embody the experience. Next, ensure the camera is level. As many historical spaces are not level and are often off-center, resetting the center of the aperture height and re-leveling may be required in each scan. In order to reduce VR (motion) sickness during use, and to ensure the experience is well-crafted, pre-plan scanning locations to create a triangulation and a grid of triangles. When moving in the virtual space forward or laterally, the movements will be smoother. After mapping out a triangulation, ensure that behind and around all objects are included in scans. Given the purpose of this exercise is to afford a high-quality digital twin for historical investigations, being able to see behind artifacts is useful, such as behind the high altarpiece and in the apse. In this case study, seated scans were also taken by adjusting the height of a person sitting in a pew in the church so that the team could return and record a live mass and then embed the recorded file as a hotspot.

During the scanning process, the team should ensure everything is located correctly with the hardware. The software oftentimes may not put up an error when a scan is off slightly from the point the technician is located. As such, adjusting scans in real-time is crucial. Even if a scan may seem close to level, the inconsistency of small variances will be compounded scan after scan and disrupt processing in the cloud. For instance, small variants in the scan were noticeable for the Piazza del Limbo where, after 125 scans, incremental changes in level, height and focus resulted in discontinuity of experience. The only recommended time to break with the regimented pattern outlined above is when there is a change in elevation or a doorway or other funnel spot. In order to more smoothly transition between locations (such as inside and outside of a structure) a scan should be taken before the step, on the threshold, and, finally, the first step inside the structure.

Postproduction

After scanning, postproduction can begin. In this stage, the integration of content should be considered. The inclusion of metadata is crucial the "fly in" homepage should at this point include the sponsoring organization's information, as well as basic information in the dollhouse view. The landing page, so to speak, is the first experience the user will have with the digital twin. In laying out interior, user experience should be the guiding principle to ensuring the least number of clicks is required to gain access to the information and experience desired. Layout view should be blocked out with the space labeled for each area. General information should be included so that on return visits, users will be able to discern where they are headed when jumping from skybox to skybox. The most front-facing method is advisable and intuitive presentation the goal of the process. With the number of interactions with the software required, additional information should only be included in the first scene. The user should be provided with contextual information to understand the purpose of the experience and, if desired, additional content embedded to allow users to "drill down" into specific spot. Embedded content should only link out to other sites, such as the link to the Uffizi with related paintings onsite, when deliberately seeking to gain more information about one specific element as the process will open a new browser and take the user out of the virtual experience. A placeholder, such as a JPEG should be included in hotspots to communicate what the link will do and where users will move to if engaging with it. Linking out in many digital twins is simple, but cumbersome to get back into the experience. Finally, given that the initial scan is where general information tags are located, one should carefully consider the contextual presence for embodiment and ease of use. As the "home" scan is selected randomly, ensure the point of reference is the entrance for a real-world person visiting the location. Everything else will be based on observations of how people move in real-world experience. Entering the experience at the point of entrance is thus natural.

Future Use Case Recommendations

Researchers recommend future use cases take the following into consideration. With regard to hardware, the new LiDAR scanners, such as the Matterport Pro 2, afford greater forgiveness in lighting considerations. Given that LiDAR recognizes solid objects, the light source is disregarded, and weather is no longer a critical factor in scanning. Exteriors can now be mapped out in their entirety, which has only been possible through painstaking returns at the same time of day (usually early morning) repeatedly until all sides of a structure can be mapped. The new exterior-scanning ability is quite useful for the generation of dollhouses. The process now also allows for capturing accurate surface data, which then allows for ease of integration into skyboxes in game engines, such as Unity. Previously, Matterport packages were not useful for 3D modeling of structures, and 3D modelers could take measurements of the structure and build out in software like 3Ds Max, Blender, or Sketchfab more quickly than editing the file provided with the scan. Speaking of software, the existing Matterport software works quite well for use cases like that presented here. The updated VR integration experience pulls an embedded feature that was previously only available in the desktop version. Finally, the guiding principle for future digital twin creation should always be based on user experience best practices that are applied in a real-world setting.

3. Conclusion

The use of digital twin technologies to preserve cultural heritage will accelerate with the use of processes such as those outlined here. The workflow and development pipeline most commonly used today for the creation of such experiences is cumbersome, expensive and time-consuming. The immediacy of 3D artificial intelligence (AI) generative content and the latest generation of photogrammetric scanning already allows non-specialists to create digital twins for historical research. Previously, ultra high-end 3D cameras, such as that used prior to the 2019 fire of Notre Dame in Paris, allowing for the structure to be rebuilt, were not available to the general public; only insurance companies and high-end contractors used such equipment to map workspaces. Now, 3D cameras are much more affordable and one can be trained on how to effectively use them (as outlined above) in a matter of hours. Systems like the Matterport are still almost exclusively used for residential and commercial real estate and insurance to protect workers from fraud. This study, however, demonstrates the viability of using the same technology and processes to create a digital twin to allow for cultural heritage preservation. Given the ease of use and commercial availability of such systems, international standards for methodological reproducibility may now be considered. The current limitations of the anchor points and three degrees of freedom (3DoF) will be overcome and true six degrees of freedom (6DoF) made possible through 3D AI generative content. The value for museums and cultural heritage institutions cannot be overstated with the potential for future use and adoption for the quick and affordable creation of digital twins to preserve irreplaceable historical sites and objects. Finally, future research on the creation of digital twins and cultural heritage preservation should include the creation and distribution of training materials for use onsite and studying the long-term preservation and storage of digital twins in order to ensure that they remain accessible and usable for future generations.

Acknowledgements

The researchers would especially like to thank the archdiocese of Florence and P. Daniel Mauricio Filho, L.C. of the Parrocchia Santi Apostoli e Biagio for permission to create a digital twin of the church for research and educational purposes. The College of Arts and Humanities and Mane Media Productions at Lindenwood University, Saint Charles, MO likewise provided the equipment and software for scanning, which made the digital twin possible.

Authors Contributions

The author confirms contribution to the paper as follows: study conception and design: Hutson, J.; analysis and interpretation of results: Hutson, J, Weber, J., Russo, A.; draft manuscript preparation: Hutson, J.

Availability of Supporting Data

Data available upon request.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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