EVOLUTION OF RECORDING METHODS: THE AACHEN CATHEDRAL WORLD HERITAGE SITE DOCUMENTATION PROJECT

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ABSTRACT:

Modern terrestrial laser scanners and photogrammetric imaging systems can provide highly accurate and objective as-built records of existing architectural, engineering, and industrial sites. This comprehensive digital recording benefits culturally significant places like heritage buildings, monuments, and other vital structures. The collected data can be instrumental in various ways, including aiding in conservation, management, monitoring and repair efforts and serving as an educational resource for scholars and the general public. These technical capabilities are especially well-suited for architecturally complex, ornate buildings like the Aachen Cathedral UNESCO World Heritage site. This paper describes the recent recording efforts at the Aachen Cathedral and is a comparative study of the previous documentation work done at the Cologne Cathedral.

The 3D documentation of the Aachen Cathedral UNESCO World Heritage Site is an ongoing collaborative project between the Sapienza Università di Roma, Rome, Italy, Robert Gordon University, Aberdeen, Scotland, and in partnership with RWTH Aachen University, and the Dombauhütte Aachen.

1. INTRODUCTION

Ongoing technological advancements have significantly improved the performance and capabilities of remote sensing technologies. These systems make it possible to comprehensively record cultural heritage sites faster, more efficiently, and less costly than in previous years. To gauge the impact of technological evolution in this field, studying and comparing the latest systems and methods at a World Heritage site with previous similar projects is essential. Additionally, looking at past and recent events, important heritage sites and collections must be appropriately and precisely documented.

The Aachen Cathedral and Cologne Cathedral UNESCO World Heritage sites in Germany are excellent comparative documentation case studies. The two structures are the most famous cathedrals in Germany and are excellent examples of Gothic architecture. The Cologne Cathedral represents High Gothic architecture, while the Aachen Cathedral combines Romanesque and Gothic architectural styles. Cologne was documented in 2017 (Pritchard et al., 2017), and Aachen is an ongoing project.

Digitally documenting these sites regularly is necessary to keep pace with the latest technological advancements and ensure we have the most up-to-date and accurate information. Given the rich cultural history of the two cathedrals and their importance as World Heritage sites, studying and comparing the latest digital documentation methods and systems at this location can provide valuable insights into the effectiveness and potential of these technologies in protecting and preserving our cultural heritage for future generations.

Article 29 of the World Heritage Convention requires all UNESCO World Heritage properties to provide regular reports on the condition at their site. These reports are used to assess the sites and, if necessary, to decide on adopting specific measures to resolve recurrent problems. In the Third Cycle of the Periodic Reporting (2018-2024), the Aachen Cathedral described the 3D laser scanning and imaging project, demonstrating the value of 3D documentation as a digital preservation and conservation tool (UNESCO).

2. HISTORY OF THE CATHEDRAL

The UNESCO World Heritage Site of Aachen Cathedral has a long and varied architectural history. Around 1200 years ago, Charlemagne established his court as a Palatine complex at the end of the 8th century (Figure 1). The focus was not on the creation of a settlement but on the construction of impressive stone buildings, which were visible at a distance on a hill in the middle of the valley basin, distinguished from the other houses made of wood and clay in half-timbered construction and thus symbolised the new centre of the empire as well as the exaltation of the kingship. In addition, the complex provided sufficient space for the administration, economy, arts and sciences, thus uniting central functions in one place. Aligned in an exact north-south axis, the secular palace building Aula Regia was in the north, and the original building of Aachen Cathedral, the Palatine Chapel, was in the south. The site consisted of an octagonal central building with a sixteen-cornered

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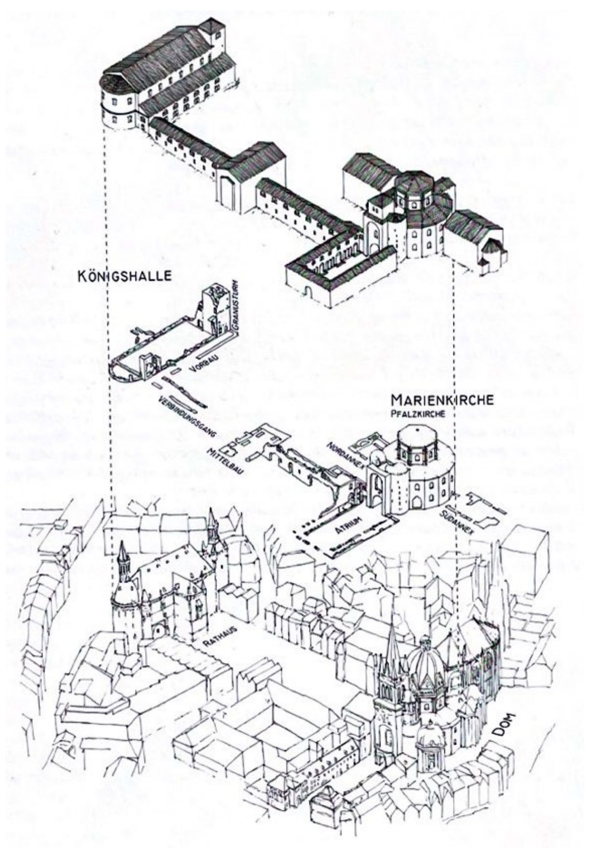

Figure 1. Carolingian ensemble of structures in comparison to the current building ensemble of the Cathedral. Judith Ley / drawing: Frédéric Schnee.

gallery and a west building as an entrance portal dedicated to Mary (Pieper / Schindler 2017, p. 31, 32).

After the death of Charlemagne, Aachen developed into the coronation site of the German kings from the 10th to the 16th century. The building underwent extensive construction and expansion measures, of which only the most important can be mentioned below.

For the time of the Romanesque building epoch, the construction of a cloister, the Quadrum, as well as the emergence of three chapels can be proven in the 11th century, which were rebuilt, expanded or demolished in the following centuries and are therefore preserved today only in a few fragments. (Buchkremer 1955, p. 58).

During the Middle Ages, pilgrimages to Aachen to visit the tomb of Charlemagne and the precious relics increased steadily. Then, since the year 1349, sanctuary journeys have taken place every seven years, during which the four relics - the diapers of Jesus, the loincloth of Jesus, the garment of Mary and the beheading cloth of John the Baptist - are presented to the pilgrims for ten days (Gormans A., Markschies A., 2012).

The large flows of visitors to Aachen Cathedral required a series of expansion measures: First, in 1350, two Gothic chapels were added on top of the Carolingian stair towers of the west building for the storage and instruction of the relics, and in the mid-14th century an ornate and roofed breach was built between the west building and the Octagon (Faymonville, 1916, p. 90). Between 1355 and 1414: The construction of the Gothic Choir Hall. To connect the new building with the octagon, the eastern end of the original Carolingian building was demolished, and the interior was expanded extensively. From now on, the Charlemagne shrine with the bones of Charlemagne and the Mary shrine with the four relics found their place there.

Aachen Cathedral was continuously expanded in the following centuries by chapel extensions. In the southwest, the Matthias Chapel, the oldest chapel extension, was built at the same time as the Gothic Choir Hall. The first floor of this Gothic chapel, preserved to this day, was used from the beginning as a sacristy and the upper floor as an archive. The Anna Chapel was added to the west side of the Matthias Chapel in the middle of the 15th century. Initially, the expansion housed arcades with entrances to the cathedral on the first floor, while the chapel room was on the upper floor. At the end of the 18th century, the first floor was closed, connected to the Matthias Chapel and has since been used as an extension of the sacristy (Maintz, 2007). To the southwest is the extension of the Hungarian Chapel, built in 1357 as a Gothic chapel on a rectangular ground plan with a hipped roof and donated by King Ludwig of Ungan. Due to a lack of maintenance and the city fire of Aachen in 1656, the chapel was so severely damaged that it was replaced by a new Baroque building in 1746. (Siebigs, 2000).

To the northwest of the cathedral, the Gothic Chapel of St. Nicholas and St. Michael was built between 1473 and 1485. It is located on the site of a Romanesque predecessor building, which is still remembered by three Romanesque portals in the current building stock (Konnegen, 2015). The large building, in addition to its liturgical function, with six altars, whose whereabouts are unclear, provided space until the 18th century for the burial places of the clergy of the canonry (Faymonville, 1916, p. 65), whose memorial plaques are still visible there today (Hugot, 1988, p. 48).

The Chapel of Charlemagne and St. Hubert was built in the northeast in 1455. In this place, a vigil was kept by the future kings before their coronation (Hugot, 1988, p. 48). The Gothic building on a heptagonal plan houses the chapel of St. Hubert on the first floor with an entrance to the cathedral, and on the upper floor, there is a chapel dedicated to Charlemagne (Grimme, 2000, p. 105).

The Romanesque cloister northwest of the building ensemble was replaced in the 15th century by a new Gothic building (Faymonville, 1916, p. 58). The square it enclosed, the so-called Quadrum, passed through many functions, from a cemetery to a garden and the school building site to the present-day schoolyard of the cathedral school. The Gothic building had richly decorated vaults, partially replaced by simple vaulted constructions after widespread destruction by the town fire in 1656 (Faymonville, 1916, p. 104). With few exceptions, the surviving Gothic vaults were destroyed during the Second World War (Buchkremer, 1955, p. 57).

During the Baroque era, the cathedral's interior underwent a contemporary revision, emphasising a decoration with the symbolism of the veneration of Charles and pilgrimage. However, today there are no reliable sources about the Baroque decoration in detail (Grimme, 2000, p. 113). The most recognisable

Figure 2. Image of the Catherdral bell tower.

Figure 3. Ceiling of the Palatine Chapel.

constructional measures to date are the new construction of a one-story portal porch in front of the west building of the cathedral in 1788 (Clemen, 1916, p. 107) and the new construction of the Hungarian chapel to the south of it starting in 1756 (Siebigs, 2000).

In the following period, the cathedral was repeatedly the scene of political events. During the Secularisation at the end of the 18th century, the ancient columns of the Octagon were removed by the French and transported to Paris to be later installed in the royal palace (Konnegen, 2016, p. 39). With the Second Peace Treaty of Paris in 1815, the Kingdom of Prussia decided to return the columns to Aachen, but they could not be reinstalled in the Octagon until 1840 (Faymonville, 1916, p. 69).

The Second World War caused extensive damage to Aachen Cathedral, but the building and the surrounding ensemble could withstand the detonations of many bombs. The foundation of a cathedral fire brigade, which extinguished smaller fires from 1941 onwards, deserves special mention (Schein /Wentzler, 2008).

2.1 UNESCO World Heritage

At the second session of the UNESCO World Heritage Committee in July 1978, Aachen Cathedral was listed as one of the first twelve World Heritage Sites and the first German one. The outstanding universal value of the building is achieved by its great historical value as a unifying symbol of Charlemagne's empire and its unique structural characteristics.

The following four criteria were established for inscription as a World Heritage Site: Criterion (i) identifies the Palatine Chapel as an exceptional artistic creation and the first vaulted structure north of the Alps. Criterion (ii) describes the significance of the building as having made it a prototype of religious architecture that has inspired copies and imitations. Criterion (iv) emphasises that the structure is an excellent example of the family of Aulien chapels based on a central plan with tribunes. Criterion (vi) describes the historical importance of the burial place of Charlemagne and the coronation place of German emperors until 1531, as well as the invaluable significance of the cathedral treasure.

On the one hand, the World Heritage Committee concluded the integrity of the building since all the features and structures convey its significance as the Palatine Chapel of Charlemagne is present. On the other, the authenticity of the building is noted since its form and design, material and substance, use and function as a church, and the most important place of pilgrimage north of the Alps have remained unchanged.

2.2 Historic Threats to the Cathedral

During the 1200-year history of Aachen Cathedral, the building has been confronted with various threats. To give an insight into these, three categories of threats will be briefly presented: The threats posed by political developments and disputes, as well as those of a structural-technical nature and those posed by the pilgrims coming to Aachen since the Middle Ages.

The threats of political developments and disputes have already been illustrated using the example of the removal of the ancient columns in the Octagon as part of Secularisation and the later reinstallation by the Kingdom of Prussia and the damage caused by the Second World War. The city of Aachen and Aachen Cathedral has always been at the centre of European disputes since the city and the building have a tremendous symbolic character for European identity and, due to their location in the border region between France, Belgium, the Netherlands and Germany, they were also geographically at the centre.

Challenges of a structural-technical nature have also accompanied the building over the centuries of its history. In this context, the heterogeneity of the various components must be emphasised, which, in addition to stylistic differences, is accompanied by very complex joints and many materials used. The anchor system for the static stabilisation of the Gothic Choir Hall can be cited as an illustrative example. A system of iron rings and cross ties was used to connect it to the stable central structure of the Octagon. However, since a static movement of the Gothic Choir Hall towards the east was discovered at the beginning of the 20th century, the system had to be analysed and strengthened again (Siebigs, 1997). This shows that the extensions of the Aachen Cathedral have been a constant challenge for the building over the centuries up to the present day.

Another source of threat is the impact on the building resulting from the enormous streams of pilgrims who have been coming every seven years since the 14th century to admire the relics and the royal throne. The throne is a vivid example of the fact that visitors actively wear down the architectural-historical substance and that this has a long tradition in Aachen. On the one hand, people have been sitting on the throne for centuries, as apparent

Figure 4. Terrestrial scaning from parapet level.

Figure 5. South view of Cathedral roofs.

traces of wear can be seen on the hand rests, on the seat and on the steps leading up to the throne. On the other hand, the base of the throne shows that it was also used quite actively for a bowing gesture: Between the supports of the base, there are clear signs of wear, which indicate that pilgrims crawled under the throne.

2.3 Contemporary Challenges to the Cathedral

For the long-term protection and conservation of the Aachen Cathedral World Heritage Site, the continuous development of new solutions for known or unknown problems and the regular evaluation of previous measures are necessary. Many of the described historic threads still constitute challenging tasks, some under new or changed auspices and require special attention.

As described above, the heterogeneous structure of the Aachen Cathedral already poses a significant challenge to the maintenance of the building. In the recent past, protecting the building from environmental and increasingly changing climatic conditions has become a very present task. For this purpose, unique materials were developed during construction work on the cathedral to protect the preserved building fabric and supplement it in the long term. As climatic conditions change, these materials must be reviewed and possibly redeveloped. An example of how changing conditions can be seen at the cathedral is the sculptures attached to the exterior of the Gothic Choir Hall. Due to exponentially increasing CO2 emissions over the last centuries, a dark shell formed around the artworks, initially visible in light-coloured limestone, as a result of deposits. This is currently being removed using a specially developed process.

The additional consequences of mass tourism, in addition to the challenges of pilgrimage already described, form an essential task of the present at Aachen Cathedral. On the one hand, action is being taken on a technical level, for example, by installing a CO2 extraction system inside to protect the mosaics from damage. In addition, the humidity inside is constantly regulated by the heating system. On the other hand, action is taken on an organisational level. Guides and accessible areas are designed to protect the structure and equipment to the greatest extent possible.

3. RESEARCH OBJECTIVES

The 3D documentation of the Aachen Cathedral UNESCO World Heritage Site is a collaborative project between the Sapienza Università di Roma, Rome, Italy, Robert Gordon University, Aberdeen, Scotland, in partnership with RWTH Aachen University, and the Dombauhütte Aachen. This ambitious and multi-phase project has two critical objectives, as detailed in the two associated papers.

This first paper presents the methods employed for dimensional recording using various advanced technologies. This includes the development of the most effective approaches, methods, and tools for capturing detailed geometric data of the cathedral. The second paper describes the procedures used to represent and analyse the monument, providing an in-depth understanding of the structural behaviour through the comprehensive documentation of its geometry and constituent materials.

To achieve these goals, the project introduces a digitally integrated methodology that combines Terrestrial Laser Scanning (TLS), Terrestrial Digital Photogrammetry (TDP), and Aerial Digital Photogrammetry (UAVDP) to accelerate data collection, provide comprehensive surface coverage, and simplify texture creation. By mapping deterioration and monitoring the state of conservation of historic structures, the methodology enhances the preservation of cultural heritage sites for future generations.

This project builds upon the pioneering work done in the documentation of other important heritage sites, such as the Baptistery of San Giovanni in Florence (Bianchini et al., 2020), the Athena Project (Bianchini et al., 2019), and the Cologne Cathedral in Germany (Pritchard et al., 2017), the. By examining and comparing these projects, the Aachen Cathedral project offers valuable insights into the evolution of documentation technology, highlighting the importance of continuous technical innovation in cultural heritage preservation.

4. THE DIGITISATION PROJECT

4.1 Integration of Capture Systems

Terrestrial laser scanning (TLS), terrestrial digital photogrammetry (TDP), and Unmanned Aerial Vehicle (UAV) photogrammetry are highly effective technologies for capturing and processing 3D data of objects, surfaces, and landscapes. These tools and methods are well-established in documenting, monitoring and conserving tangible cultural heritage (Remondino, 2012; Fassi, 2013). On their own, both techniques can generate

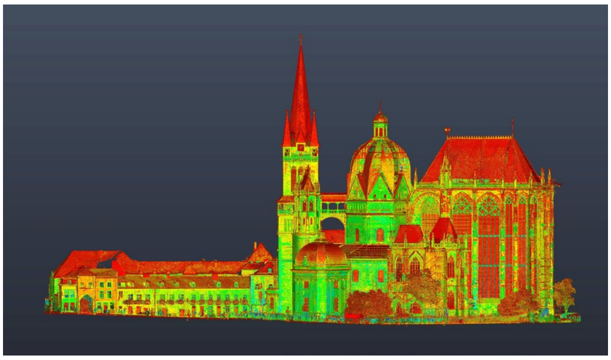

Figure 6. Rendering of point cloud (reflectance) - south

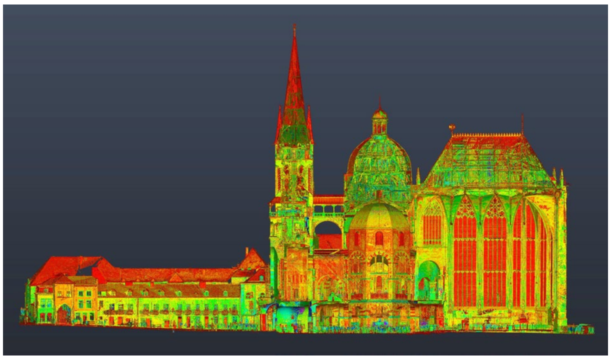

Figure 7. Rendering of point cloud (refectance) - cross section.

exact full-colour 3D models; merging these two methods of data capture makes it possible to create 3D models that are both geometrically precise and visually realistic.

TLS provides fast and accurate point data of an object's surface but with lower image resolution and is restricted to line-of-site capture. However, TDP generates highly detailed and realistically coloured points, although with lower metric accuracy and requires proper lighting.

By integrating laser scanning with terrestrial and drone-based photogrammetry, the weaknesses of each method can be accommodated while benefiting from their combined strengths, resulting in a more comprehensive surface capture and data coverage, improved modelling accuracy, and better-quality texture generation. (Galeazzi, 2017)

According to Rönnholm et al., there are four types of data integration of terrestrial lidar and digital photogrammetry: object-level integration, photogrammetry aided by laser scanning, laser scanning aided by photogrammetry, and tightly integrated laser scanning and optical images. The Aachen project would be considered colourised laser scanning aided by photogrammetry.

These two technologies complement each other well, so they were utilised in the Aachen project. As an analogy, the scan data acts as the dimensional skeleton, and the photogrammetry is the skin.

4.2 Terrestrial Laser Scanning

The benefits of TLS in surveying and measuring architectural structures have been well-established (Costa et al., 2016). Whereas the Cologne project mostly used the Z+F 5010C manufactured by Zoller + Frohlich (Z+F), Germany, the Aachen Cathedral project used two terrestrial laser scanning systems, the Imager 5010X and Imager 5016.

All three types of scanners are phase-based measurement systems that utilise a Class 1 infrared laser, which is invisible and completely safe for both the operator and the public eyes. This safety consideration is particularly relevant for scanning activities at a World Heritage site with heavy tourist activity. The 5010X generates 360-degree point data based on a local coordinate system with intensity values and has an approximate range of 187 meters, while the 5016 has a range of almost double that at 360 meters. The 5010X and 5016 have an acquisition rate of 1.06 million points per second, with a linearity error of less than 1mm within 20m from the surface.

All three scanning systems, the 5010C, 5010x and 5016, have an integrated camera system, the CCD, positioned at the nodal point of the scanning unit. On the 5010C/X, the camera is positioned slightly off-centre, so a slight parallax is noticeable on the first few meters but comparably small. This is not an issue with the 5016. The result is that during the post-processing, the imagery sits precisely onto the point data without parallax, providing an aligned, photorealistic scan dataset. The automated data alignment avoids using a panoramic head or dealing with a camera offset. Upon completing the scanning sequence, the scanners initiate a series of 42 individual images that combine to form an 80-megapixel panoramic image.

The other difference between the 5010C and the 5010X is that the 5010X has on-site registration (tablet), an integrated GNSS, IMU, altimeter and compass. The 5016 is approximately 30% smaller in volume, 30% less in weight, has a parallax-free camera, and 40% faster image acquisition. The 5016 also has considerably less range noise.

During the Cologne project, to illuminate dark spaces and avoid external lighting systems, the 5010C and 5010X used an add-on Z+F SmartLight. This accessory is mounted on the scanner housing, resulting in a little contour shadow. The 5016 has a fully integrated illumination with four LED spotlights around the rotor's camera window. This system is parallax-free without any shadowing in the imagery.

Although the Aachen project utilised digital photogrammetry, adding colour to point cloud data can improve its visualisation and help to identify different features or objects in the registered data. Coloured point cloud data can help in better object recognition and classification, such as different stone colours. Coloured point clouds can also enhance the accuracy of 3D mapping and modelling applications. Adding colour to the point cloud data provides more accurate 3D models and better represents the real-world environment.

4.3 Digital Photogrammetry

Digital photogrammetry has improved significantly over the last decade due to advances in camera systems and processing software (Giuliano et al.). With the advent of high-resolution digital cameras, image quality has improved significantly, providing more accurate and detailed data for photogrammetric processing. Computer processing power has also increased significantly, permitting faster and more complex photogrammetric processing. Photogrammetric software such as

Reality Capture and Agisoft Metashape has become more automated, reducing the need for manual intervention (hole filling) and increasing processing speed. Creating fully textured ‘watertight’ 3D geometry is considerably faster and has a more straightforward workflow.

The Aachen project incorporated two digital cameras for terrestrial photogrammetry, a Nikon Z 7II (47.7 MP) mirrorless, full-frame digital camera with a 24mm prime lens and a Sony Alpha ILCE-A7 II (24.3 MP) full-frame with a 24mm prime lens.

4.4. UAV Photogrammetry

UAV photogrammetry offers numerous benefits for recording heritage buildings, including cost-effectiveness, non-invasiveness, safety, and detailed data analysis, making it an excellent tool for conservation, restoration, and documentation (Lo Brutto, 2012). The UAV can also go beyond the line of sight of the terrestrial laser scanner or the terrestrial photogrammetry. It does not require scaffolding, ladders, or other equipment that could damage the building's structure or delicate surfaces.

Although UAV systems can carry high-resolution cameras, thermal cameras and lidar systems, these tend to be heavy and loud, requiring special permits. The operation of UAVs is subject to the German Aviation Act (Luftverkehrsgesetz) and the German Regulation on the Operation of Unmanned Aircraft Systems (Drohnenverordnung). The regulations also require the registration of all UAVs weighing more than 250 grams. There are similar restrictions in the United Kingdom. Considering these restrictions, the project used a DJI Mini 3 Pro drone weighing 249 grams. The unit has a 1/1.3-inch CMOS camera sensor providing 48 MP imagery and an f/1.7 24 mm lens.

The UAVDP and TDP utilise the same 24mm lens focal length to aid the photogrammetric processing.

5. AACHEN CATHEDRAL DOCUMENTATION

5.1 Project Planning

Given the complex nature of the architecture of the Aachen Cathedral and the need for high-resolution data, the project utilised short-distance scanning, multiple scan setups, and extensive digital imaging. This approach ensured that every detail of the building was accurately captured, from the intricately decorated interior to various roofs and spires on the exterior.

The project planning used existing 2D CAD drawings of the cathedral to determine the positioning of the terrestrial scan stations by drawing 50m diameter circles around the building to establish setup locations, ranges and overlaps. This document was also used to determine the necessary time on site, identify any health and safety issues, and act as a communication tool for the Cathedral management. These drawings were also used to plan the flight paths of the UAV.

Like the Cologne project, the Aachen Cathedral project considered several factors when positioning the terrestrial laser scanners, including capturing the building's overall architectural form and extensive exterior and interior surface area. To achieve optimal scanning results, factors such as ideal laser range, data resolution, data overlap, areas of occlusion, and visual obstruction were carefully considered. The adjacent architectural context, including adjacent buildings, was also included in the project's archival dataset. The project encountered several specific challenges, including the highly decorated and reflective interior, various parapet levels, and the height of the central bell tower, like those encountered during the Cologne Cathedral project's planning stage.

Aachen Cathedral Documentation	
Images	8145
Exterior Scans	128
Interior Scans	162
Cross-over/Threshold Scans	12
Data Bundle Error	0.005m
Overlap Percentage	44%
Strength	0.004m
Cloud-to-cloud	0.005

Figure 8. 3D Rendering of the Palatine Chapel, Aachen Cathedral interior.

It was decided that at the project's outset, the 5016 would handle all interior scanning, and the 5010X would provide all the exterior scanning. The main reason is that although the 5010X has the capability of an external illumination system, the 5016 has four built-in 700-lumen LED spotlights providing the ability to capture imagery without an external light source.

5.2 Data Capture and Registration

After five days of scanning and photography, there were 301 individual TLS scans with the 5010X and 5016 and approximately 8,145 images with the TDP and UAV.

The data was organised per interior, exterior and roof levels for production purposes. Due to the high number of overlapping scans, the registrations were successful. There were also 12 cross-over scans connecting interior and exterior datasets.

The individual interior and exterior scan files were brought into Z+F Laser Control (Sapienza) and Leica Register 360 (RGU). Data from the registered dataset were then exported as individual E57 format files, and like the Cologne Cathedral project, into Autodesk Recap 360 (v. 2023) for further data clean-up. Although there is an optimisation and reduction of the original data when importing into Recap, the ease of real-time navigation for data quality review and client presentation purposes has proven exceptionally beneficial. For further development, RCP files can be quickly brought into other Autodesk applications, such as Autodesk AutoCAD and Revit.

5.3 Visualisation

The acquired TDP and UAV images were organised into interior, exterior and roof-level groups for production. All the raw files were colour balanced and converted to JPEG. The registered E57

Figure 9. Rendering of the 3D model of the Palatine Chapel.

files and images were combined in Agisoft Metashape (Sapienza) and Reality Capture (RGU).

The UAV photogrammetry filled in missing areas due to occlusions or hard-to-reach surfaces that the laser scanners may have missed. Combined with the terrestrial imagery, this coverage method provided a comprehensive dataset of the cathedral's exterior. The UAV was not flown inside the cathedral, and the interior dataset consisted of laser scans and terrestrial imagery.

A DJI RS 3 Pro gimble was used to operate the cameras to remotely speed up the imaging process. The gimble method worked in the Aachen project, and the laser scans provided the meshing data, but the images could only be used for texturing. An additional benefit is that having the system on a high tripod, the camera was above the heads of the occasional tourist. It is important to point out that this data capture method is not recommended for non-laser scanned photogrammetric projects as there is no parallax between the images. Had the photos only been used to build the 3D model, it likely would not have registered correctly.

The Reality Capture software was able to generate an exceptional photorealistic 3D model. Once exported into an application like 3D Studio Max, generating images was slow but straightforward. Future development of this project will include integration into the Unreal Game Engine.

One of the challenges of the 3D photogrammetric approach is that even with decimation, the size of the meshed model can be challenging on average-specified computers. There is also an issue with a strict file structure system, making interoperability an issue. Also, due to the proprietary nature of the temporary files and rigid file structure, exporting to a long-term archive would be problematic.

A point cloud dataset of a historic structure can be used to create accurate measurements and detailed documentation of its condition and brought into many 3D and CAD packages. Point cloud data is valuable for documentation and preservation, while 3D mesh models are more useful for visualisation and presentation. In contrast, the 3D mesh models are cumbersome for CAD purposes but can be used to create photorealistic virtual representations for interpretation purposes.

A secondary benefit of a photogrammetric project is that it requires comprehensive imaging of a heritage site's primary and secondary spaces. If the images are correctly organised, they can provide an additional, valuable building and artefact collection information source. If a cultural heritage property were ever damaged or destroyed, the images would be used for reconstruction efforts. If such an unfortunate situation occurred, no one would likely complain about having too much data.

The acquired data was used to analyse the chapel and is reflected in the subsequent paper: The Vaulting System of the Palatine Chapel: The Aachen Cathedral World Heritage Site Documentation Project.

6. COMPARISON OF PROJECTS

Regarding the evolution of laser scanning recording methods at Aachen and Cologne, there was a slight increase in scanning and imaging speed with the 5016 vs the 5010X. The acquired data from the 5016 seemed to have less noise, but hard to determine as it was mainly used indoors. Outdoors, both systems provided well-balanced colour imagery, but the built-in LED light helped illuminate dark interiors. Still, the real change was the ability to review and register the scans via a wifi-connected tablet.

Ergonomics is often an underappreciated consideration when purchasing a TLS. The design of the 5016 is different from the 5010X and includes two fixed handles and an anchor point, which is highly beneficial when setting up the scanner on uneven surfaces on a heritage structure. These features are essential when lifting, repositioning or securing the scanner. The reduced size and weight of the 5016 vs the 5010X add to the system's versatility.

The most significant change between the Cologne and Aachen project is the integrating of TLS, TDP, and UAV digital photogrammetry. The combined systems will increase the documentation time at a heritage site and possibly require certified UAV staffing. However, the increased recording capabilities and quality of data are significant.

7. CONCLUSION

The Aachen Cathedral documentation project is a collaborative effort between the Sapienza Università di Roma, Rome, Italy, Robert Gordon University, Aberdeen, Scotland, and in partnership with RWTH Aachen University and the Dombauhütte Aachen that aims to comprehensively document the cathedral architecture and constituent materials using advanced technologies. The project offers practical insights into the evolution of documentation technology, highlighting the importance of continuous technical innovation in cultural heritage preservation. It was an opportunity to gauge the development of recording methods from the Cologne project by using a more current laser scanner and integrating digital photogrammetry and UAV technology into the production system.

The project provides a digitally integrated methodology that simplifies texture creation and accelerates data collection by combining terrestrial laser scanning, terrestrial digital photogrammetry, and aerial digital photogrammetry. Despite encountering specific challenges during the project, the team carefully considered multiple factors to achieve optimal scanning results, including the building's overall architectural form, extensive exterior and interior surface area, and adjacent architectural context. Ultimately, the project and documentation methodology enhances the conservation of cultural heritage sites for future generations.

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