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Evaluating Rapid Data Acquisition Methods for Structural Analysis of a Church at Risk from Climate Change Induced Subsidence

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Abstract

The cost and time required for adequate data capture for structural analysis can be prohibitive and yet the advent of climate change induced impacts suggest demand will increase. Subsidence cases in the UK are rising, with climate change increasing risks, particularly in areas with shrinkable ground such as London clay. Heritage sites are especially vulnerable, and a lack of precedent for their three-dimensional digital structural analysis slows the development of conservation measures. This project focuses on a red brick Gothic Revival church; St John the Evangelist, in Upper Norwood, London, a Grade II* Listed building on London clay, which is currently facing subsidence due to soil expansion and shrinkage. This project aims to test the readiness of rapid data acquisition techniques in support of structural analysis. Using 3d data derived from both static and kinematic terrestrial laser scanning as well as aerial photogrammetry, a physical-based model will be developed in collaboration with LUSAS which kindly supported this project allowing the use of their in-house software. The adequacy of the data capture methods will be compared in order to support analysis of the causes and extent of structural movement. The aim is to develop this as a pilot project to aid stakeholders in creating adaptation plans for future conservation in response to climate change. The project aims to promote using rapid mapping tools that could become more readily available through research infrastructure hubs.

1. Introduction

1.1 Context

In England, 78% of churches are listed buildings, yet their preservation faces significant challenges due to limited funding and the lack of comparable data. The Churches Action Trust state: "The future of our churches, chapels and meeting houses is the single biggest challenge facing the heritage of the United Kingdom. It is also a challenge that goes to the heart of questions about the future of our communities, above all those that are more isolated and vulnerable. Our churches include nearly half our most important historic buildings, listed Grade I or equivalent. Despite their profound significance, our churches face a very uncertain future. Churches and chapels are closing or being mothballed and the debate about their future is inadequate. In Wales, about a quarter of historic churches have closed in the last ten years, and many more are now in danger. In Scotland, the Church of Scotland is actively planning the closure of as many as 40% of its churches, while in England there are now over 950 cathedrals, churches, chapels and meeting houses on Historic England's 2024 Heritage at Risk Register" (National Churches Trust, 2024).

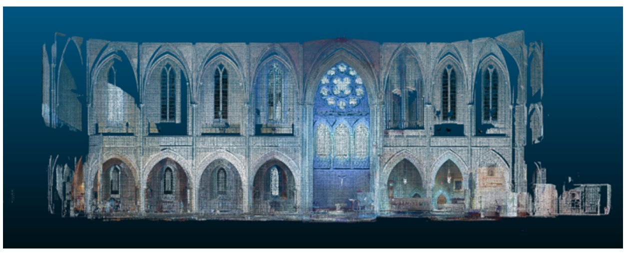

Figure 1. St John the Evangelist, Norwood Long section (N) from FARO TLS

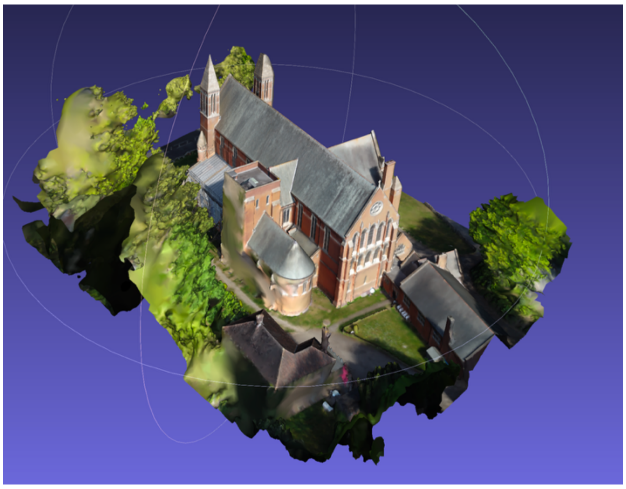

Figure 2. St John the Evangelist, Norwood Aerial mesh from drone photogrammetry

Religious buildings generally are manifestly the most complex and ambitious historic buildings (requiring significant resources for their maintenance, yet with declining attendance they are a critical challenge for straightened budgets to support. Typically designed to dominate the skyline and attract attention from afar, they frequently represent structural feats of ingenuity in their development. Masonry arches, domes, spires, towers and steeples form the notable historic profile of almost every city skyline and village cluster. These familiar historic profiles have been re-iterated over time. Such inaccessible and treasured elements require significant resources to monitor and maintain. In addition, to compound these issues, in the context of climate change, the issue of rapid changes in patterns of groundwater levels is causing subsidence to be a repeated problem.

The digital documentation of cultural heritage sites has become an increasingly valuable tool for conservation appraisal, structural analysis, and public engagement. However, documenting active religious buildings—referred to as "living heritage" sites—presents unique challenges due to their continuous public use, complex geometries, and the presence of fixed furnishings or visual obstructions. This paper focuses on St. John the Evangelist Church in London, a Grade II listed building that remains in regular use for religious and community functions and has suffered both bombing in World War II and significant subsidence in more recent years.

The aim of this study is to develop and demonstrate a practical methodology for its digital documentation and preliminary structural assessment that could be adopted by other similarly challenged religious buildings impacted by subsidence in the UK. The RIEGL scanner used here is being acquired as part of a suite of facilities under Cardiff University's PERFFORM award under the UKRI funded RICHeS (Research Infrastructure for Cultural Heritage) initiative. These items together with a range of laboratory based analytical tools will be made available for both academic and stakeholder deployment to address the challenges of monitoring and assessing environmental, structural and conservation related concerns for built heritage generally. To this end this project, funded by an EPSRC Impact Acceleration Account, is developing a prototypical case study.

Figure 3. St John the Evangelist, Norwood RIEGL VZ600i in use

By integrating data from multiple sources—including terrestrial laser scanning (RIEGL VZ-600i), interior scans (Leica BLK), drone-based photogrammetry, and traditional photographic techniques—the paper evaluates the comparative strengths and limitations of each method. In doing so, it explores how these tools can effectively capture geometry and pragmatically assist in identifying structural issues. The findings contribute to the wider discourse on digital heritage practices and the role of 3D technologies in preserving and interpreting active historic sites.

The RIEGL VZ-600i, a state-of-the-art terrestrial laser scanner designed for rapid and high-precision data acquisition. Capable of capturing up to 2.2 million points per second with a range of up to 1000 meters, it is well-suited for both large-scale and detailed architectural documentation (RIEGL USA, 2025a). In tandem a FARO Focus 3D scanner (FARO Technologies, 2010) and a handheld LEICA BLK2go (Leica Geosystems, 2019) were also used to gather terrestrial data. Due to the considerable height of the church building, a photogrammetric model was simultaneously used to achieve a complete model, using a modest DJI Mavik mini 3 drone (DJI, 2022) to complete the envelope of 3d data. In addition to these advanced methods, classical survey techniques were also applied by photographing visible cracks and surface damage. A reference object, such as a coin, was placed next to the cracks to estimate their size and monitor changes over time. Although less comprehensive than laser scanning, this approach remains valuable for basic structural assessment, particularly in areas with limited access or where equipment use is constrained.

Figure 4. St John the Evangelist, Norwood Vertical crack in the south wall indicating possible settlement

In this case, the church represents a complex historic structure where certain areas are relatively accessible and architecturally defined, while others are densely occupied or obstructed by layers of physical alterations and ongoing human activity. Although the building is not continuously in use like an active marketplace, the presence of high vaults, intricate detailing, and limited physical access posed significant challenges for standard laser scanning. As a result, a combination of targeted methods was required to effectively capture both the structural geometry and surface conditions.

In the field of structural engineering, the use of 3D scanning technologies has increasingly become a comprehensive and reliable tool (Waqar et al., 2023). As the demand for accurate and non-invasive assessment of historic and sensitive buildings grows, these technologies play a crucial role in generating analytical models that reflect the true geometry and current condition of structures(Puerto et al., 2024). Traditionally, structural analysis relied on simplified drawings and limited geometric assumptions; however, the availability of precise scan data now enables the development of finite element models (FEM) based on actual measurements. This approach significantly improves the accuracy of vulnerability assessments and dynamic behaviour simulations, while also providing a foundation for diachronic analysis, seismic scenario modelling, and data-informed decision-making (Ursini et al., 2022). As such, 3D scanning has evolved beyond mere geometric documentation to serve as a bridge between digital surveying, technical analysis, and structural conservation planning (Al-Bayari and Shatnawi, 2022)The integration of advanced 3D scanning technologies with classical survey methods—such as manual measurements and photographic documentation—offers a more comprehensive approach to capturing both geometric accuracy and contextual detail (M. Eissa et al., 2023). Here, the limitations and potentials of this integration have been explored through a series of efforts carried out at the church.

1.2 Case study

St John the Evangelist, a Grade II Listed building (c. 1887) in Upper Norwood, London, built between 1878 and 1887 designed by the noted English architect John Loughborough Pearson (1817–97) (Quiney and Paul Mellon Centre for Studies in British 1979). It replaced a prefabricated church and was established to be the centre of a “new district” of 600 acres (Ashby, 2016).

Pearson was a celebrated ecclesiastical architect and restorer who most notably designed Truro Cathedral and “practically rebuilt” the front of Westminster Abbey (Louth, 2022). The church is facing severe structural damage from drought-induced subsidence, a problem potentially worsened by climate change. With limited funding and expert access, further adaptation measures are challenging. St. John the Evangelist is part of the "Heritage at Risk" programme managed by Historic England. The routine structural adaptation of existing buildings in response to or anticipation of climate change is still in early stages and the lack of precedent in local case studies often complicates decision-making in conservation planning.

St John the Evangelist is a prominent example of late 19th-century English Gothic Revival architecture. With its cruciform layout, vaulted brick ceilings, and thick load-bearing masonry walls, the church is described as typical of Pearson in who built no less than 14 churches during a nine-year period whilst Truro Cathedral was being erected (Quiney, 1979). Originally intended to feature a 208-foot tower (which remained incomplete), the building’s design reflects ambitious verticality, while the use of Bath stone and solid brick provides substantial mass and stability (National Churches Trust, 2025). However, over time, the church has faced structural challenges, including subsidence and cracking along the building and the southern aisle, necessitating detailed condition assessments and repair strategies (Church of England, 2023).

These factors made it an ideal candidate for multi-method documentation, combining terrestrial laser scanning, drone imaging, and traditional photographic techniques to capture its condition and geometry for both conservation and structural analysis purposes. A multi-disciplinary team from Cardiff university consisting of Structural Engineers, Material Scientists, Architectural Conservation together with an industrial partner, RIEGL drew together to generate survey material over a two-day period in spring 2025.

1.3 Challenges

Surveying the Grade II listed St. John the Evangelist in London posed a series of logistical, spatial, and methodological challenges typical of documenting a living heritage site in active use. Ideally, to achieve full geometric capture, the church would have been temporarily vacated, cleared of all furniture, audio equipment, decorative elements, and foot traffic. The visual complexity of the church’s vaulted ceilings, gothic arches, and layered structural elements presented further challenges in terms of occlusions and variable lighting conditions. The limited natural light within the sanctuary and aisle spaces necessitated adjustments in scan exposure and data filtering during post-processing.

Figure 5. Furniture and fixed elements that limited full scan visibility and access

The dynamic interaction between the historic structure and its contemporary daily use introduces localised stress patterns in materials and connections—such as floor wear, moisture ingress, or shifting cracks—that are not easily detected through single-instance scanning yet are vital for long-term structural evaluation. These gradual changes require longitudinal observation and cannot be fully captured by static point cloud models alone. The constraints of working within a historic, actively used urban site—not governed as a closed heritage monument but as a functioning religious space—limited the possibility of extended access or invasive data capture. Nevertheless, by combining multiple low-impact technologies and minimizing intervention, a comprehensive and respectful record of both the structure and its condition was achieved, serving as a foundation for future conservation and structural analysis.

2. Summary

2.1 Objectives, relevance, solution, evaluation

Objective 1 Assess conditions. A site survey using terrestrial laser scanning, photogrammetry, and photographic documentation is planned (Task 1).

Objective 2 Understand the physical problem. A physically-based numerical model of St John will be generated

Objective 3 Advise adaptation. The project findings will inform an efficient adaptation plan (Task 3), refined with case study insights

This project seeks to address these issues by developing an Adaptation Plan for the important case study of St. John the Evangelist. The data capture process aims to test rapid yet sufficiently accurate methods of both kinematic and static acquisition from three terrestrial laser scanners. In addition, A drone will be used to capture external images in order to enhance the unreachable surfaces for the spire and roof externally. Due to the site's active religious use and architectural complexity, a combination of terrestrial laser scanning (RIEGL VZ-600i and FARO), drone-based photogrammetry, and complementary methods including Leica BLK and 360° video capture were employed. The resulting point clouds were processed using RiScan Pro (RIEGL USA, 2025b), CloudCompare (CloudCompare Development Team, 2025), and Autodesk tools—ReCap, Revit, and AutoCAD (Autodesk, 2025)—to produce accurate 3D models and architectural plans.

These outputs enabled the mapping of observed structural cracks and provided a geometric foundation for further analysis. The study highlights the practical challenges of surveying an actively used site and demonstrates how multi-sensor data integration can overcome occlusions, limited access, and variable lighting. The resulting digital record supports conservation planning, structural diagnostics, and future integration into HBIM systems. A detailed site survey in parallel will investigate subsidence factors, informing the creation of a Finite Element Method (FEM) model. Reference to global approaches to climate change adaptation will provide valuable perspective: this knowledge will form the basis of a robust plan to protect heritage structures from growing threats of climate change.

3. Workflow

3.1 Data acquisition - 3d

3d data were collected in parallel using a RIEGL VZ-600i for the whole project, this included a total of 153 scans including a high resolution scan from the gallery at the west end, a further 15 scans were made using a FARO X1303D for an overall interior and to provide detail of the interior ancillary spaces, a Leica BLK2go and a DJI Mavik Mini 3 drone for aerial photogrammetry of occluded roof slopes.

3.2 Data acquisition – historic

There are several indications in the history of the building that highlight structural vulnerabilities. Primarily the fact that the building was not continuous, secondly that it was bombed in the second world war and thirdly that it has been moving in response to subsidence in the 21st century. The Choir and aisles and part of the nave were built between 1881 and 1882 whereas the Lady chapel, base of the tower, north transept, western bays of the nave were not built until 1886-7. The upper part of the tower and the spire as proposed, were never built (Quiney, 1979).

Figure 6. Photomontage of war damage in church

A framed photo-montage in the entrance to the church illustrates the extent of aerial bomb damage in 1944. The church was repaired and restored between 1946 and 1951 unlike the more catastrophically damaged St John the Evangelist in Red Lion Square (1878) also designed by Pearson, which was demolished following severe bombardment in 1941 (Ashby, 2016).

Figure 7. Visible repairs

Evidence of this rebuilding in visible in the contrasting brick repairs in vaults. In 2016, further damage was incurred where large cracks emerged between the main body of the church and the South aisle. These were underpinned in 2017 with work funded by the Heritage Lottery Fund and timber propping remains externally (National Churches Trust, 2025). In addition, a set of nine signed architect's original drawings of the church dated 1878 are on display in the vestry area. A history of the church written in 1937 (Bateman, 1937) and another available online through the church's website provide further accounts of iterative change (Ashby, 2016).

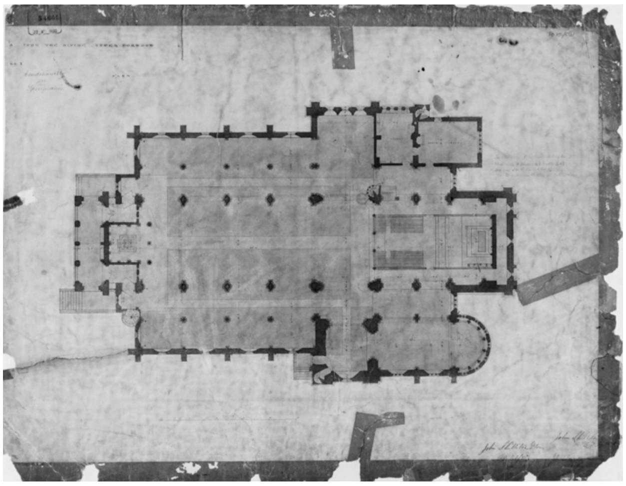

Figure 8. St John the Evangelist, Norwood, Architect's signed plan 1878 (onsite)

Quiney observes that the church is exceptionally wide – he observes that "the nave bays are twice as long, and wide as they are high up to the springing of the vaulting arches -a much lower proportion than the Golden Section" (Quiney, 1979). It is possible that this disproportionate breadth may also provide a vulnerability in terms of subsidence – indeed the undulations in the pavement are clearly visible. The provision of access to measurable 3d modelling particularly in grayscale and depth map renditions of the detailed scan data make this immediately obvious and also provide an opportunity for monitoring change over time.

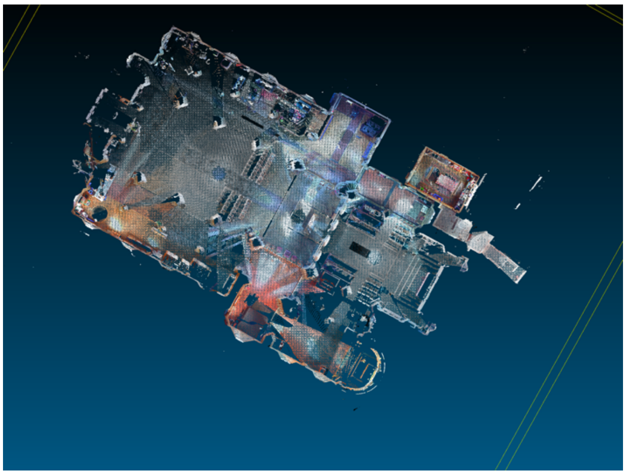

Figure 9. St John the Evangelist, Norwood cutaway through RIEGL pointcloud to show undulating floor

3.3 Post-processing: Registration

The entire RIEGL laser scanning dataset was processed and registered in RiScan Pro (RIEGL USA, 2025b). One-touch Wizard reports and manual alignment procedures were used to assess scan quality and achieve geospatial coherence. A Master Scan Alignment (MSA) Report was generated to document the registration accuracy and matching transformations. Processed datasets were filtered to remove outliers and overlapping noise using RiScan Pro’s built-in cleaning tools (RIEGL USA, 2025b). Final scans were exported in OSTN15 coordinate system to ensure compatibility with local heritage GIS platforms. These were exported as a single point cloud at 0.0005 m resolution as an E57: the FARO data with FARO Scene (FARO Technologies, 2025), again exported as an E57; the Leica BLK2go with Cyclone REGISTER 360 (Leica Geosystems, 2025), also exported to E57; and the drone images with Agisoft Metashape (Agisoft LLC, 2025), which were also used to generate a simple mesh for communication purposes in advance of a workshop.

3.4 Data Exports and Integration

The processed scans were exported in multiple formats for broad accessibility and cross-platform use:

- **KMZ** files for Google Earth visualization showing individual scan setup positions.
- **RiPANO** package for offline interactive viewing of the Riegl package without specialized software (RIEGL USA, 2020).
- **E57 exports** of RIEGL, FARO and Leica BLK scans organized by full resolution, octree compression, and “Infill” subsets.
- **Filtered point clouds**, removing background elements such as fixed furniture, musical equipment, and non-architectural features.

Having been generated in Agisoft Metashape, a pointcloud from the drone was also exported as an E57 and registered against terrestrial RIEGL data using RiScan’s external reference point tools (RIEGL USA, 2025b).

At first the Leica and drone pointclouds were aligned using Cloud Compare, however the detail was insufficient on either to reveal structural misalignments. The drone imagery was therefore re-processed at a higher density before being exported to E57 for incorporation with the RIEGL pointcloud using Cloudcompare (CloudCompare Development Team, 2025). Both the drone generated cloud and that from the TLS were closely segmented to remove extraneous points before aligning.

In order to provide accessible means to engage with the relatively large model a free access software, RiPANO was provided which allowed the RIEGL pointcloud combined to be accessed at a range of levels of detail. 0.050, 0.020 m, 0.010 m, 0.005 m (RIEGL USA, 2020). This software allowed for end users to cut sections generate views, orthogonal elevations and plans, however, owing to the limitations of the terrestrial laser scanner’s view, it was necessary to add roof surface data, specifically of the critically affected Southern aisle.

3.5 Model Preparation and Base Plan Generation

The generation of a working plan became a prerequisite for further structural analysis. The E57 data from the FARO X1303D, Photogrammetric model from the drone imagery, and RIEGL terrestrial laser scans (Figure 10) were first combined to produce an integrated point cloud for optimal results (Figure 11).

Figure 10. Point cloud data captured using the RIEGL VZ-600i terrestrial laser scanner, providing high-resolution structural details

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Figure 11: Combined and integrated .e57 point cloud generated from RIEGL, LEICA BLK, FARO Scene and drone datasets, forming the basis for unified modelling

This consolidated dataset was generated in CloudCompare, where non-architectural elements—such as surrounding vegetation and peripheral site features—were removed (CloudCompare Development Team, 2025). This filtering process allowed the church structure to be isolated, enabling more focused and efficient modelling efforts. Also in RiPANO some orthogonal elevations were swiftly generated (RIEGL USA, 2020) (Figure 13). These can be compared with the original design drawings showing the incomplete proposed tower (Figure 12).

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Figure 12. St John the Evangelist, Norwood, Architect’s signed South Elevation (Featuring unbuilt complete tower) 1878 (onsite)

Figure 13: South elevation of St. John the Evangelist generated from point cloud data in RiPANO (RIEGL USA, 2020)

The cleaned dataset was then exported and opened in ReCap, where it was converted into a format suitable for Revit integration (Autodesk, 2025). Once imported into Revit, the model was saved in .rvt format and used as a foundation for analytical tasks (Figure 14).

Figure 14: 3D model of St. John the Evangelist created in Revit

Horizontal section cuts were generated at 0.0 m, 0.5 m, and 1.0 m above ground level, each with a slice thickness of 20 cm, to reduce visual noise introduced by furniture and equipment (**Error! Reference source not found.**20). These section views facilitated the creation of accurate plan drawings in AutoCAD, which were then optimized to produce a refined architectural plan (Figure 21) This plan served as a spatial reference for mapping the crack locations.

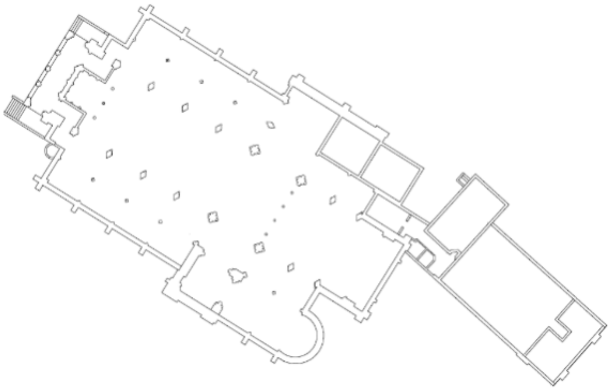

Figure 15: Optimised 2d plan of St. John the Evangelist generated in AutoCAD from cleaned section data (Autodesk, 2025)

documented by the structural engineering team. As part of the assessment process, each crack was visually identified, photographed, and digitally measured to support diagnostic analysis. The combined use of RiPANO’s point cloud viewer (RIEGL USA, 2020) and AutoCAD (Autodesk, 2025) allowed for spatial correlation between real-world damage and the 3D model, enabling targeted interpretation of structural behaviour and deterioration patterns. (Figures 16-17)

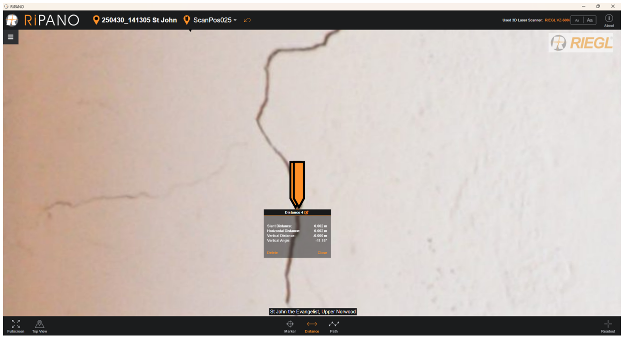

Figure 16: Corresponding crack visualised and georeferenced in RiPANO, enabling spatial linking between 3D point cloud data and site damage records (RIEGL USA, 2020)

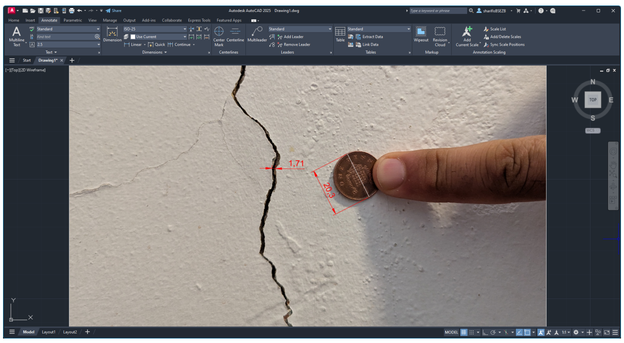

Figure 17: Crack width measurement performed in AutoCAD using scaled reference from a UK 1p coin (Autodesk, 2025)

4. Findings

4.1 Data acquisition – process concerns

One aim of this project and that of PERFFORM is to enhance the ability for under resourced communities to access high quality 3d data of built heritage for analysis. To this end the transparency, speed and ease of use were important as was of course the costs incurred. There is an inherent aim to ensure some pragmatism and efficiency in the LOD required. To this end the relative low-cost (sub £400) drone demonstrating the ability to generate a scaled 3d model within 1 hour of processing and 20 minutes of flight is impressive. In terms of considering apparent ease of use, the Leica BLK2go provided a swift solution, easily explained for data acquisition by a newly initiated researcher. However, the download and registration on site using Cyclone, was slow and the resultant pointcloud relatively lacking in detail in comparison with the other methods (Leica Geosystems, 2025).

The 12-year-old FARO focus X1303D (FARO Technologies, 2010) proved simple to handle, the size and weight allowing a single operator to manoeuvre it. This made it the preferred option for simultaneous scanning of smaller ancillary spaces. However, its relatively slow speed (11 minutes per scan), made it challenging to supervise as members of the community traversed the space during the day. Nevertheless the speed of registration and manipulation of the data in FARO Scene (FARO Technologies, 2025) was relatively seamless although this had to be done using a fixed licence.

The RIEGL TLS (RIEGL USA, 2025a) is significantly newer and more expensive than either of the other devices. Its image capture is at a significantly higher resolution. It is larger and heavier but also significantly quicker than the FARO X1303D, taking around 1.5 minutes per scan (15 minutes for a detailed scan). Although not used on this occasion, a mobile tripod on wheels and a kinematic option will serve to bridge the gap between the capacities of the fixed TLS and the SLAM based BLK. Inevitably, the data acquired was of a significant magnitude (just under 1TB). Despite our capacity as a university, we were forced to resort to posting hard drives in order to share the scan data download speeds made reliance on online sharing platforms untenable.

5. Discussion and further work

The integration of multiple 3D data acquisition methods allowed for comprehensive spatial documentation of St. John the Evangelist despite the constraints of working within an active religious space. While the enhanced LOD and speed of laser scanning with the RIEGL (RIEGL USA, 2025a) provided high-resolution geometry, complementary methods such as the lighter, smaller FARO X1303D (FARO Technologies, 2010), photogrammetry from drone imagery and SLAM acquisition with the Leica BLK2go (Leica Geosystems, 2019) filled coverage gaps and facilitated interior modelling.

Given the building’s continuous public function (as is typical for churches), including regular religious services and community gatherings, uninterrupted access for extended periods was not feasible. Instead, scanning was performed in carefully timed phases over two days, with a range of tools. However, the project faced limitations, including occluded areas, variable lighting, and short scanning timeframes. Future studies will explore the development of accessible means to accelerate longitudinal monitoring, integration with HBIM platforms, and automated crack tracking using machine vision.

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RICHeS RESEARCH INFRASTRUCTURE FOR CONSERVATION AND HERITAGE SCIENCE

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