Safeguarding Banteay Chhmar through Digital Twins: Integrated Approaches for Research, Management, and Conservation

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Abstract

This study presents the first phase of a digital twin initiative for the Banteay Chhmar archaeological complex, a large-scale and largely unrestored Khmer heritage site in northwestern Cambodia. In preparation for potential World Heritage nomination and ongoing conservation planning, the digital twin aims to integrate precise 3D documentation, monitoring capabilities, and public dissemination. Field surveys conducted in March 2025 employed a hybrid approach combining fixed terrestrial laser scanning, mobile SLAM LiDAR, and UAV-based photogrammetry. Each method was optimized according to site-specific requirements for accuracy, efficiency, and accessibility. The collected data were processed into high-resolution geometric models suitable for a range of applications, including structural behavior monitoring, restoration planning, academic analysis, and educational outreach.
To ensure broad usability, the datasets are being published on the web-based 3D Digital Database (3DDB), which supports international standards such as 3D Tiles and COPC. The platform allows for accurate geospatial positioning and interactive visualization through web browsers and external tools. This paper discusses the documentation strategy, workflow, and technical challenges, while also considering the potential of the digital twin to support multi-stakeholder collaboration in heritage preservation. The results demonstrate a scalable, interoperable model for digitally managing complex archaeological landscapes.

1. Introduction

Banteay Chhmar is a provincial city ruin of the ancient Khmer Empire, constructed in the late 12th century and located in northwestern Cambodia. Even today, it remains distant from major cities and the Angkor archaeological complex near Siem Reap, which is a major tourist destination. As a result, it has largely been excluded from site development and tourism projects. Consequently, the site’s monumental structures—primarily composed of sandstone—remain mostly in a collapsed and untouched state. Academic research on the ruins began in the early 20th century, and while substantial studies have been conducted across various disciplines, the site still holds significant potential for further scholarly investigation. Building upon previous research achievements, continued academic exploration of the Banteay Chhmar complex is strongly anticipated.

In recent years, the Cambodian government has been actively promoting research and the establishment of a conservation and management framework at the site in preparation for a nomination to the UNESCO World Heritage List. Our research team has been collaborating in this effort through archaeological investigations and the digital documentation activities presented in this paper. For the World Heritage nomination, it is essential to demonstrate the Outstanding Universal Value of the site by clarifying its distinctive characteristics in comparison to the Angkor complex, and to establish effective methods and systems for its preservation and management. As part of this initiative, we are attempting to construct a digital twin of the site to support these objectives.

It is widely recognized that digital twins—virtual representations that synchronize with physical objects and environments to enable real-time sharing, monitoring, and analysis through online platforms—are increasingly being explored for the documentation, preservation, and utilization of cultural heritage. In the case of Banteay Chhmar, where many structures are at high risk of collapse and where establishing a comprehensive system for physical management and monitoring is challenging, digital twins are expected to offer significant value. Moreover, in contexts such as World Heritage nominations, where a wide range of stakeholders—including researchers from various fields and governmental officials responsible for heritage management—are involved, the digital twin serves as a useful platform for sharing accumulated research, current conditions of the heritage, and alternative intervention options for conservation and site development planning. Additionally, for general visitors, the digital twin provides a foundation for linking diverse content with immersive experiences of the complex spatial structure of the site, supporting both on-site and remote learning.

Efforts to document the geometry of large-scale cultural heritage sites, such as the Banteay Chhmar complex, have been undertaken at numerous archaeological sites worldwide. Among these, the most comparable case is the digital documentation project of the Bayon Temple, located within the Angkor complex (Ikeuchi et al., 2005). This three-dimensional archiving project, conducted by the Ikeuchi Laboratory at the University of Tokyo in collaboration with the Japanese Government Team for Safeguarding Angkor, primarily employed multiple types of fixed terrestrial laser scanners as the main survey tools. In addition, various methods and sensors were developed to efficiently capture data in narrow and complex spaces (Matsui et al., 2005), and to overcome the limitations of fixed scanners in measuring the upper portions and surfaces of the temple structures (Banno et al., 2005; 2007).

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As a result, a near-comprehensive digital record of the interior and exterior geometry of this intricate monument was achieved. Approximately two decades have passed since the Bayon Temple documentation project, during which time 3D shape data has come to be utilized to meet a broad range of societal needs. Concurrently, significant advancements have been made in surveying technologies and methodologies, resulting in increased speed and efficiency. Furthermore, technologies and interfaces that allow for the seamless online sharing and manipulation of large-scale geometric data are increasingly being developed. In this project, we aim to examine and refine survey methods, data processing workflows, and dissemination approaches using current measurement devices, software tools, and web-based platforms. These efforts are focused on optimizing the accuracy and functionality of the 3D models to meet the specific needs of site management, conservation, and restoration at the Banteay Chhmar complex.

As a first step toward constructing a digital twin of the site, our team conducted a 3D geometric documentation of part of the Banteay Chhmar complex in March 2025. By employing multiple surveying methods, we evaluated the efficiency and accuracy of each technique when applied to large-scale and complex heritage structures. Recognizing that accuracy and efficiency often present a trade-off, we examined which approaches were best suited to various practical needs. Subsequent data analysis and integration have been carried out using several software platforms. In parallel, we began testing the publication and sharing of this data through a web-based platform, assessing current limitations related to data visualization, file size capacity, and operational performance. Looking ahead, we plan to develop and implement additional tools required to support diverse applications of the platform. This paper introduces the background of the targeted heritage complex, identifies the anticipated roles of the digital twin, evaluates the optimal measurement strategies based on the balance of efficiency and accuracy for various purposes, presents the current web platform used for data sharing, and discusses challenges that must be addressed to meet the range of emerging needs.

2. Overview of the Banteay Chhmar Complex

During the reign of Jayavarman VII in the late 12th century, the Angkor dynasty completed the construction of numerous large-scale temples, including those within the Angkor archaeological complex, which served as the royal capital. This period marked a significant political and religious transformation, as the kingdom shifted from a centralized Hindu theocratic state to one centered on Buddhism. This transition was accompanied by a broad religious policy aimed at spiritually unifying the populace under the new regime. In parallel, the royal roads—major transportation arteries connecting key provincial cities—were restored and expanded. These vast public works projects were intended to reunify and revitalize a territory that had been weakened during the preceding era.

The Banteay Chhmar complex is believed to have had a close relationship with Angkor Thom, the royal capital during the same period (Sharrock, 2015). It represents a critical archaeological trace for examining the reign of Jayavarman VII (r. 1181–1218?), who played a central role in the revival of the Khmer Empire following a period of warfare and decline. The site also served as a strategic provincial center in the empire's foreign relations, particularly with neighboring polities such as Champa and Siam. Furthermore, based on the enshrinement of multiple images of the Medicine Buddha (Bhaisajyaguru) in the central and satellite temples, it is believed to have functioned as a medical hub. These features underscore its significance as a key regional outpost of the Angkorian state, and further exploration of these characteristics is highly anticipated.

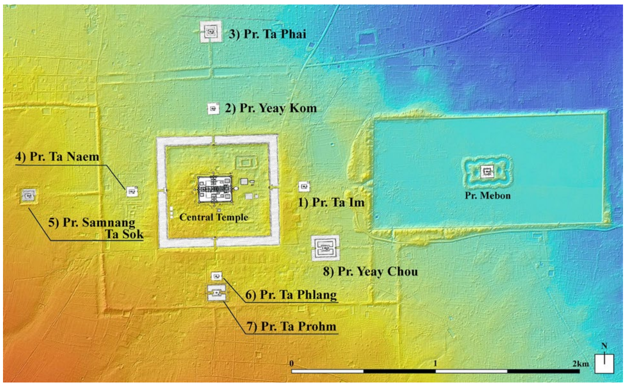

Figure 1. Layout of major structures within the Banteay Chhmar archaeological complex (background topographic map generated from CALI 2015)

The central temple complex is enclosed by a large moat measuring 2.2 km east–west and 1.7 km north–south. It is notable for its distinctive architectural layout, which includes an extensive arrangement of towers adorned with enigmatic face sculptures and elaborate bas-reliefs. The temple's architectural and sculptural elements, including the numerous face towers, rival those of the principal temples of the Angkor complex. Particularly remarkable are the continuous bas-reliefs carved along the galleries, which reach approximately 3 meters in height and span over 700 meters in length. These reliefs are thought to depict historical events from the time and are considered one of the most significant archaeological sources for understanding Khmer history.

Surrounding the large central temple are eight smaller satellite temples, and in front of the temple lies a massive baray (reservoir), within which a small central island temple is situated—together forming the urban core of the site (Figure 1). These associated temples are arranged in a geometric layout, demonstrating a distinctive characteristic of planned urbanism under the Angkorian dynasty. Some scholars have also suggested that the spatial configuration of the entire city may represent a mandala-like cosmological model.

Research on the Banteay Chhmar complex began in the early 20th century and has accumulated across several disciplines. Art historical studies have focused on the temple's wall carvings (Parmentier, 1910; Cœdès, 1932; Boisselier, 1965; Groslier, 1973; Roveda, 2007), while historical research based on epigraphic analysis has provided insights into the site's past (Cœdès, 1929; Jacques, 1968, 2007; Maxwell, 2009). Architectural studies have examined building typologies and proposed reconstructions (Cunin, 2005; Im, 2014). More recently, surveys have documented the spatial distribution of structures both within and beyond the central complex (Bruguier et al., 2015). In 2015, a large-scale airborne LiDAR survey was conducted, covering not only the temple complex but also its surrounding landscape. This enabled significant progress in archaeological and geographical studies related to the site's hydraulic infrastructure, using highly detailed topographic data (Evans and Sanday, 2011; Evans, 2016; Im, 2019). In addition to the geometric documentation for the construction of a digital twin, our team also initiated an

archaeological excavation in 2025 at one of the satellite temples.
The Banteay Chhmar complex was abandoned for several centuries and suffered severe deterioration due to the encroachment of dense forest vegetation. It was only about two decades ago that initial conservation efforts were undertaken by international organizations (Killmer, 2015). Over the past ten years, restoration work has been carried out by Cambodian institutions, including the reconstruction of sections of the temple precinct, such as some of the sanctuaries, galleries, and the causeway depicting mythological scenes spanning the surrounding moat. Notably, the continuous bas-reliefs preserved in relatively good condition along the gallery walls have been successfully restored, representing a significant achievement in terms of historical and artistic value. However, considering the vast extent of the site, the areas that have undergone conservation remain very limited. Many of the stone structures have collapsed, and the temple grounds are layered with fallen sandstone blocks. In some areas, there is a growing risk of further damage due to tree falls and erosion. In response, Cambodian governmental agencies are currently working to develop risk assessment maps for the site.

3. Purposes and Tools Envisioned for the Digital Twin of Banteay Chhmar

This archaeological complex is characterized by its large scale, structural complexity, and severe deterioration, resulting in a high demand for stabilization and restoration interventions. Accordingly, the digital twin is expected to serve a wide range of functions. These are categorized into five primary application areas, each requiring specific types and levels of geometric models, associated content, and interaction functionalities, as summarized below.

3.1 Preservation and Monitoring

For purposes of preservation and structural monitoring, high-precision geometric documentation is required, particularly for portions of the site identified as structurally vulnerable. In order to detect deformation or movement over time, the 3D data must enable comparisons of distances and angles between fixed reference points when necessary. Ideally, supplementary 3D surveys should also allow for the visualization of surface-level structural changes. To extract and evaluate such differences accurately, it is essential to establish and maintain a set of absolute reference points as part of the documentation framework.

3.2 Structural Reinforcement, Restoration, and Reconstruction

In cases of structural reinforcement—such as the addition of external supports without direct intervention into the existing structures—or during repair and reconstruction efforts involving the relocation of collapsed or remaining stones, the digital twin serves as a valuable tool for planning on-site procedures and evaluating their effects. This is especially critical at Banteay Chhmar, where the risk of further collapse is high and physical workspace is limited. Sharing simulations among multiple stakeholders prior to any physical intervention is thus a vital process.

Such simulations require interactive manipulation within the existing 3D model, including the addition and repositioning of elements such as support structures or individual stones. In complex projects like reconstructions involving multiple disassemblies and repositionings, it is essential to record geometric data at each stage and visualize it chronologically for verification and review. Moreover, if the digital twin allows for the virtual movement and reassembly of stones—enabling these reconstructions to be visualized either on-site or remotely—it may also prompt reconsideration of the necessity and effectiveness of physical reconstruction itself.

In practice, many restoration projects at sites like this involve the use of numerous new stones, and for safety reasons, reconstructions are often not returned to their original state. As a result, a considerable number of original components are left unused and eventually become untraceable. To prevent such loss of historical value, digital reconstructions within the digital twin framework offer an effective alternative. Additionally, the digital twin serves as an important medium for recording and archiving the restoration process, allowing details such as the repair of components and documentation of new and reused materials to be comprehensively linked to the 3D model.

3.3 Management as a Cultural Heritage Site

The management of cultural heritage sites encompasses a broad range of activities, and the digital twin can support many of them, particularly in terms of physical monitoring. For example, it can be used to track the condition of the numerous trees growing within the complex, as well as to monitor the deterioration of wooden walkways that serve as the main paths for visitors. In terms of visitor management, the digital twin could also be employed to analyze movement patterns beyond designated walkways, document and assess hazardous areas for visitors independently from the structural conditions, and

Application	Associated Content	Required Tools
[a] Preservation and Monitoring		
Deformation Monitoring	List of monitored target points Partial 3D documentation from multiple time periods	➢ Low-resolution global 3D documentation ➢ Detailed local geometric recording ➢ Measurement of distances and angles between two or more points ➢ Geometric difference analysis between 3D datasets
Structural risk map	Photographs and descriptive records of hazardous areas (condition and risk level)	➢ Detailed local geometric recording
[b] Repair and Reconstruction		
Design and evaluation of temporary support structures for structural reinforcement	Attribute data of simulated objects (e.g., material, dimensions)	➢ Insertion of objects into the digital model
Management of components and virtual pre-assembly for reconstruction planning and execution	Attribute data of simulated objects (e.g., materials, dimensions)	➢ Insertion of objects into the model ➢ Segmentation and repositioning of individual stone blocks within the model ➢ Chronological display of model states across different project phases
Documentation of restoration work	3D geometric documentation before and after restoration Documentation of restored components Records of newly added materials Visual records including restoration plans and site photos	➢ Linking of information to specific locations and components within the model
[c] Site Management		
Management of elevated wooden walkways	Layout plans and installation/maintenance records	➢ Linking information to specific points within the model
Management of vegetation and individual trees	List of trees with associated images, health assessments, and pruning history	
[d] Academic Research		
Sharing of previous research findings	Archival photographs, architectural drawings, inscriptions, sculptural motifs, excavated artifacts, relocated statues, pigment traces, and past excavation records	➢ Linking information to specific points or surfaces within the model ➢ User-generated updates and annotations by authorized contributors
[e] Education and Tourism		
Provision of scholarly information	Segmented content from books and academic papers relevant to specific locations	➢ Linking information to specific points or surfaces within the model
Supplementary information from related sites	Photographs and descriptive data from related heritage sites	➢ Linking information to specific points or surfaces within the model
Presentation of reconstruction visuals	Reconstructed 3D models	➢ Visualization of reconstructed plans ➢ 3D models through AR and VR

Table 1. Intended Applications, Associated Content, and Required Tools for the Digital Twin of the Banteay Chhmar Complex

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monitor surface runoff and water pooling during rainfall. These applications would contribute to both safety management and environmental monitoring of the site.

3.4 Academic Research

For academic research, the digital twin offers the potential to spatially integrate and visualize the wide range of scholarly findings previously obtained within the Banteay Chhmar complex. It allows the linking of various academic resources—such as historical photographs, interpretations of bas-reliefs, and the content of inscriptions—to specific architectural features within the 3D model. This, in turn, may provide valuable insight into the spatial rituals and functions of the temple precinct. Since such academic interpretations are subject to continual refinement, it is desirable to develop a system that allows authorized contributors to update the information dynamically.
Furthermore, artifacts and sculptures that have been relocated to museums or storage facilities can be virtually reintegrated into their original discovery locations within the model. This function offers promising applications not only for academic study but also across museums, heritage sites, and digital visitor platforms.

While visual realism is not necessarily a priority in applications focused on preservation or management—where the emphasis is placed on geometric accuracy—for research and for the educational and tourism functions described in the following section, visual clarity and spatial readability become much more critical. Therefore, in these contexts, the use of mesh data, which offers higher visual fidelity and better usability in online environments than raw point cloud data, is considered more appropriate.

3.5 Education and Tourism

The diverse information integrated and visualized within the digital twin has the potential to respond interactively to the varied interests of visitors, thereby offering significant educational value. However, merely presenting scattered pieces of information may not be sufficient to sustain user engagement or facilitate deep understanding. It is therefore desirable to design narrative-based experiences that guide users along defined routes, providing structured content aligned with those pathways. Incorporating gamification elements—such as quizzes or exploratory challenges—can further enhance user engagement and learning.

Additionally, features that allow users to view reconstructed 3D models alongside the current condition models would be highly beneficial. On-site, these comparative visualizations could be enhanced through the use of Augmented Reality (AR) or Virtual Reality (VR), offering immersive experiences that bridge the past and present of the site.

By integrating diverse types of information within a single digital twin, it becomes possible to perceive these datasets in a cross-referential manner, potentially leading to new insights and discoveries. While the approach of linking various types of information to a 3D model shares commonalities with Heritage Building Information Modeling (HBIM), the digital twin framework further accommodates a wider range of needs by enabling simulations in virtual space and by supporting the simultaneous visualization of current conditions and reconstructed models.

Table 1 summarizes the functional needs addressed by the digital twin, the types of content handled, and the tools required on the platform. As outlined above, the digital twin must support multiple applications, but the core tools include: measurement capabilities within the model, insertion and manipulation of objects, linkage of content to specific locations, and visualization of both current and reconstructed models—either through superimposed displays (e.g., AR) or side-by-side comparisons.

In terms of the geometric accuracy required for the 3D model, high precision is essential for monitoring structural behavior and for supporting restoration work. For other purposes, however, usability and visual fidelity often take precedence over strict accuracy. In such cases, mesh-based models may be more suitable, even if they sacrifice some geometric precision. Ideally, the platform should allow users to selectively view multiple base models depending on their purpose.

4. Three-Dimensional Documentation Technologies Applied to Large-Scale Archaeological Sites

4.1 Target Areas for 3D Documentation

The digital twin planned in this project is based on digital geometric records of various locations within the Banteay Chhmar complex. The most extensive dataset currently available is derived from an airborne laser scanning survey conducted in 2015, which produced topographic data covering an area of approximately 225 km², including the surrounding region of the archaeological site. This dataset serves as a foundational layer for the digital twin and is highly valuable for analyzing the ancient city’s infrastructure, residential areas, and agricultural zones that supported urban life. It also provides a critical resource for future site management, conservation planning, and regional tourism development strategies.

Building upon this base data, new high-resolution 3D documentation has been planned for key architectural components of the site to support the direct management of the Banteay Chhmar complex. This includes the central temple complex (approximately 70,000 m²), eight satellite temples (with the four inner temples each covering around 10,000 m² and the four outer temples each around 30,000 m²), and the Mebon temple located at the center of the baray reservoir (approximately 2,500 m²). These surveys aim to generate detailed geometric models capable of capturing stone-level information.

For these documentation efforts, in addition to the use of conventional fixed terrestrial laser scanners, which have been widely applied in previous heritage recording projects, more efficient methods were introduced. These included mobile laser scanning using SLAM LiDAR systems, as well as photogrammetry. Surveying methods were selected based on the specific functional requirements of different areas within the digital twin framework. The first full-scale field campaign was carried out over a period of approximately two weeks in March 2025, during which the central temple’s main zone and two satellite temples were successfully recorded.

4.2 3D Documentation Using Fixed Terrestrial Laser Scanners

Fixed terrestrial laser scanners offer high resolution and accuracy; however, they are limited by longer scan durations—

ranging from several to over ten minutes per scan depending on the resolution—and by restricted scanning range. As such, their application in this project was focused on areas where high-precision geometric data are essential, such as for monitoring structural behavior or simulating reinforcement and restoration scenarios.

In this campaign, a FARO Focus S150 scanner was employed. This device offers a maximum range of 150 meters and enables full 360° horizontal and 300° vertical coverage. The sensor’s angular resolution is 0.009° in both horizontal and vertical directions, and the measurement range accuracy is ±1 mm, allowing for high-resolution and high-accuracy surface geometry acquisition of built structures. Over the course of three days, a total of 100 scan positions were completed, covering the central zone of the main temple (Figure 2). Figure 3 presents an overview of the scanned area. The total number of points captured in the model is approximately 264.32 million, and the resulting mesh contains approximately 484.56 million polygonal triangle patches.

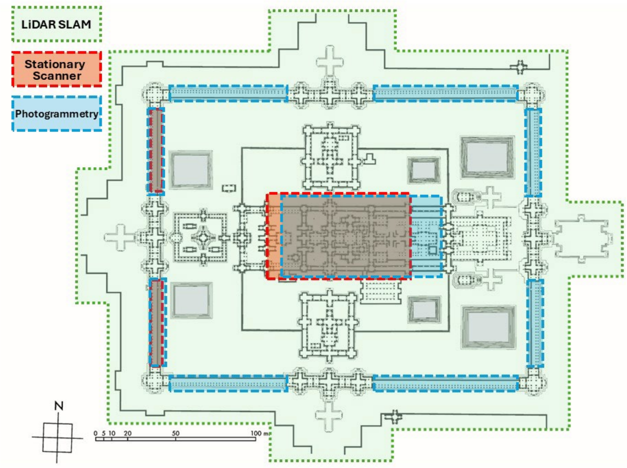

Figure 2. Coverage areas of the three types of 3D documentation methods at the central temple of Banteay Chhmar

Figure 3. Point cloud data of the central temple acquired using fixed terrestrial laser scanners

In the gallery of the central temple, additional high-density point cloud data acquisition was conducted, focusing on the intricately carved bas-reliefs. The surveyed area covers approximately 100 meters in horizontal length and about 3 meters in height along the western face of the gallery. By increasing the density of scan positions, it was possible to generate a model with sub-millimeter resolution, achieving a minimum vertex spacing of 1 mm for capturing fine surface details (Figure 4).

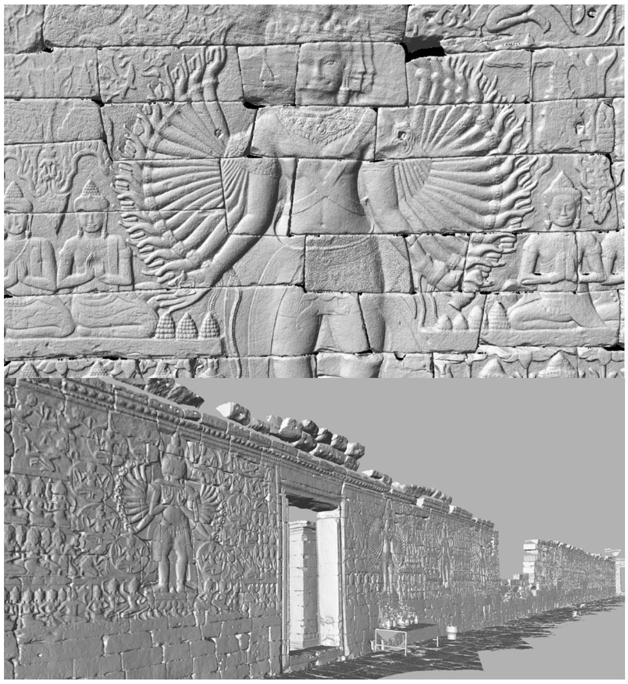

Figure 4. High-resolution recording of a bas-relief depicting a part of Bodhisattva Avalokiteshvara on the west gallery of Banteay Chhmar

A similar high-resolution survey was conducted at the central sanctuary of Pr. Ta Phai, one of the satellite temples. Over a period of approximately three hours, scans were taken from 20 positions (Figure 5). The upper structure of this monument is in a highly unstable condition, with an urgent need for deformation monitoring and the installation of temporary structural supports. The sanctuary is located atop an elevated mound, making it difficult to secure scanning positions that cover the entire structure. As a result, some areas remain unrecorded. Nevertheless, the survey achieved a distance measurement accuracy of less than 1 mm, providing sufficiently precise data for monitoring structural changes.

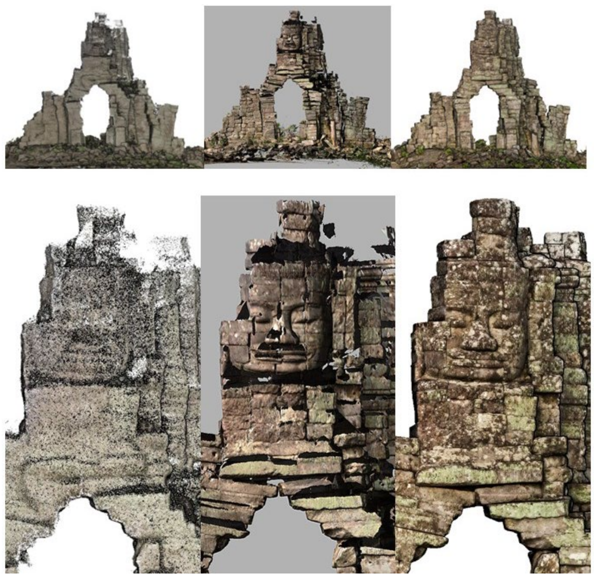

Figure 5. Comparison of visualization outputs from three different surveying methods, Prasat Ta Phai – East Elevation
Left: Captured using mobile SLAM LiDAR
Center: Captured using fixed terrestrial laserscanner
Right: Capture using photogrammetry

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4.3 3D Documentation Using Mobile Laser Scanners (LiDAR SLAM)

For SLAM-based LiDAR scanning, two GS-1 SLAM LiDAR units manufactured by GreenValley International were used. GNSS data were recorded in absolute coordinates using real-time kinematic (RTK) positioning via the GreenValley LiBase station, which was installed at a known control point within the archaeological complex. The GS-1 scanners have a maximum measurement range of 120 meters and offer full 360° coverage. With a measurement accuracy of ±3 cm and a scan rate of 320,000 points per second, each unit is capable of continuous scanning for up to 15 minutes.

Over the course of six days, 52 scans were conducted using the two units, resulting in full coverage of the central zone of the main temple (approximately 70,000 m²) (Figure 2). In addition, complete scans of two satellite temples—Pr. Ta Naem and Pr. Ta Phai—were carried out with four scan passes each, totaling approximately 60 minutes per site (Figure 6).

Figure 6. SLAM LiDAR survey data of Pr. Ta Naem (after removal of noise elements such as trees)

Although the accuracy of SLAM LiDAR is lower than that of fixed terrestrial laser scanners, it enables much faster and broader area coverage. Due to this characteristic, SLAM LiDAR plays a valuable role in the development of the digital twin for the Banteay Chhmar complex, particularly in supporting a wide range of cultural heritage management tasks. It also complements fixed scanner data by providing continuous spatial context, making it especially useful for visualizing the entirety of individual structures.

4.4 3D Documentation Using Photogrammetry

Photogrammetric data acquisition was conducted using handheld photography, an extended monopod (7.5 meters in length), and an unmanned aerial vehicle (UAV). The equipment used included a handheld camera (SONY A7 III with EF 20mm F1.8 lens) and a UAV (DJI Matrice 4E). For georeferenced imaging, the UAV was equipped with the DJI-RTK system—a GNSS-based real-time kinematic positioning module—which enabled precise flight path planning, automated image capture, and accurate coordinate logging.

At the central temple, a total of 9,814 photographs were taken over approximately ten days, covering the main zone of the monument (Figure 2). Approximately 90% of the images were aerial photographs captured by drone, while the remaining 10% were ground-based images taken with the handheld camera (Figure 7). For interior spaces and narrow or complex areas of the structure, handheld or monopod-mounted photography was employed.

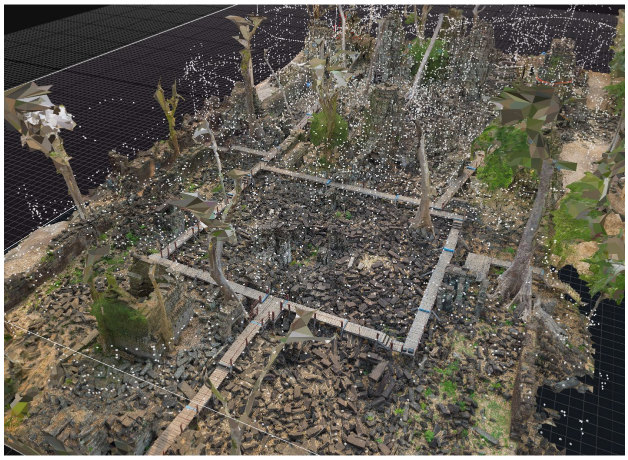

Figure 7. 3D model of the central zone of Banteay Chhmar's main temple generated by photogrammetry, including camera position information

Although the drone supports automated flight and capture, the presence of dense tree canopies in the survey area posed visual obstructions that could not be reliably detected by the onboard sensors. Therefore, all UAV operations were conducted manually. To account for solar illumination conditions, photography was restricted to specific time windows, resulting in a longer overall survey period.

For photogrammetric processing, both *Reality Capture* and *Metashape* were used. However, given the large number of images, *Reality Capture* was ultimately chosen for all processing due to its superior computational efficiency. In some cases, automatic 3D reconstruction produced inaccurate camera positions, which required manual correction. These issues often arose from inconsistencies in shadow direction caused by variations in sunlight conditions across image sets.

In addition to the central zone of the main temple, a separate image set was acquired for the bas-reliefs in the surrounding gallery, totaling 1,078 photographs. For the satellite temples Pr. Ta Naem and Pr. Ta Phai, image acquisition focused on the main structural components at the center of each complex. At Pr. Ta Naem, 2,794 images were captured over two days, while 2,146 images were collected in a single day at Pr. Ta Phai. For both sites, 60–70% of the images were aerial photographs captured by drone, with the remaining 30–40% taken using handheld cameras.

For each photogrammetric target area, GNSS-based RTK was employed in conjunction with UAV operations to record accurate camera positions. As a result, the 3D models generated through photogrammetry were georeferenced within a global coordinate system. However, it was observed that the photogrammetric models were slightly larger in scale compared to those created using fixed or mobile laser scanning. While the relative geometry within the photogrammetric models was consistent and accurate, scale discrepancies could be adjusted by referencing multiple known control points within the model. Nevertheless, these findings suggest that relying solely on RTK data for automatic scaling may introduce scale errors, which should be taken into account.

In terms of workflow and operational efficiency, photogrammetry occupies a middle ground between fixed and mobile laser scanning. A major advantage, however, lies in its ability to comprehensively capture upper surfaces and elevated areas of structures through UAV-based imaging. Additionally, due to the high level of visual realism it offers, photogrammetric modeling proves especially effective in meeting educational and tourism-related demands within the digital twin framework.

5. Web-Based Platforms for Publishing Large-Scale 3D Models

5.1 Developers and Users of the Digital Twin Platform

The integrated large-scale models generated from the collected survey data are intended to be published on an internet-based platform accessible to a wide range of users, including researchers, site managers, and tourists. For this purpose, we plan to utilize the 3D Digital Database (3DDB) platform, which is developed and continuously updated by the National Institute of Advanced Industrial Science and Technology (AIST). This platform is jointly operated by AIST and the Nara National Research Institute for Cultural Properties, and enables the combined visualization of digital 3D models of cultural heritage along with geospatial information. Although initially focused on heritage sites in Japan, the platform is now expanding to include and disseminate cultural heritage data from across the world (Nakamura, 2023).

5.2 Technical Features of 3DDB

The 3D Digital Database (3DDB) enables the storage, analysis, and public dissemination of a wide range of 3D datasets—including those acquired via LiDAR and photogrammetry—together with absolute geospatial coordinates. It adopts the Earth-Centered, Earth-Fixed (ECEF) coordinate system, and all 3D datasets are stored along with a 4×4 transformation matrix that converts their original local coordinate systems into ECEF.
For visualization, the platform employs *Cesium*, an open-source geospatial engine widely regarded as the de facto standard in this field. This allows users to access, search, and view data directly through a standard web browser, without requiring any proprietary software or paid applications. Moreover, Cesium allows users to set custom basemaps such as satellite imagery, aerial photographs, or 3D terrain data as backgrounds. This functionality enables intuitive visualization of the site's geographical context and present-day environmental conditions.

5.3 Supported Data Types, File Sizes, and Upload Procedures on 3DDB

While the general public can only access open datasets registered by AIST or the Nara National Research Institute for Cultural Properties (Nabunken), users affiliated with these institutions may register their own 3D datasets for collaborative analysis or academic publication purposes. Currently, the platform supports three primary input formats: LAS and LAZ (point clouds), OBJ (meshes), and FBX (CAD-based models). Additional formats are planned to be supported in the future in response to user demand. To ensure smooth downloading and system performance for general users, the current upload size limit for LAS files is set to 10 GB. Once uploaded and properly licensed through agreement among stakeholders, the data may be made publicly available as open data.

In the case of small- to medium-scale structures such as Pr. Ta Naem and Pr. Ta Phai, the point cloud size can be reduced appropriately during preprocessing to meet this 10 GB limit. However, for the central temple of Banteay Chhmar—due to its relatively large scale and high-density data—uploading the entire dataset as a single file is not feasible. Excessive downsampling of the point cloud would compromise the fidelity of the recorded details. Therefore, a segmentation strategy is necessary, in which the model is divided into manageable units (e.g., inner sanctuary, outer enclosure walls, individual road segments, gate structures) for separate upload and visualization.

5.4 Functional Features and Tools of 3DDB

In recent years, LiDAR systems integrated with GNSS have become widely available commercially, and data acquired using such devices are typically georeferenced with absolute positional coordinates. When uploaded to 3DDB with the appropriate EPSG code, these datasets are automatically displayed in their correct geographic location.

By contrast, data acquired indoors or outdoors without GNSS support typically only include local coordinate systems, and photogrammetric datasets may also lack scale information. For such cases, 3DDB provides an interface for manual geolocation, allowing users to position the data accurately by referencing base layers such as satellite imagery and terrain models. Additionally, in Japan, several prefectures—including Shizuoka, Tokyo, Nagasaki, and Hyogo—have released full-coverage point cloud datasets as open data via the G-Spatial Information Center. In such areas, users can perform automatic alignment of 3D data captured with consumer devices such as smartphones, by referencing these open-access point clouds.

For the Banteay Chhmar dataset, the point cloud files generated during the LiFuser integration process retained embedded GNSS metadata within the LAS file format. As a result, during upload, 3DDB automatically read the coordinate information, and by assigning the appropriate EPSG code, the model was positioned accurately on the globe without the need for manual adjustments (Figures 8and 9).

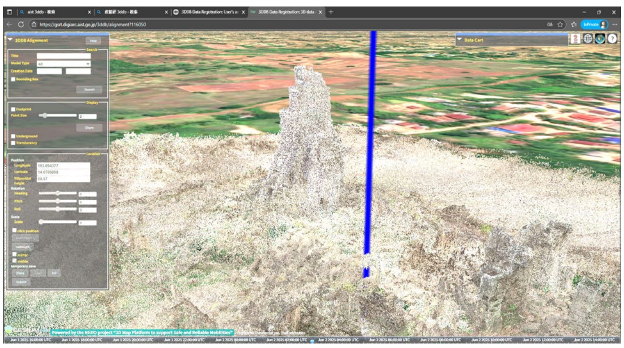

Figure 8. Pr. Ta Naem displayed in the 3DDB Viewer (TDV) running in a web browser

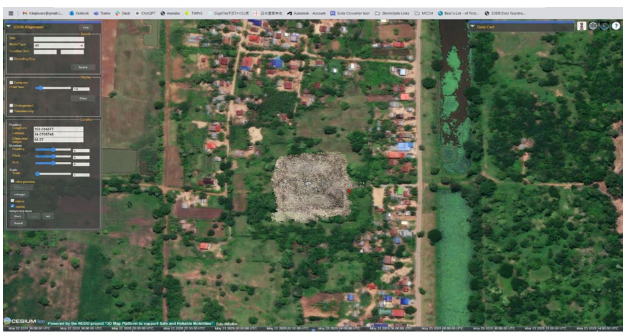

Figure 9. A wider view of the same area as Figure 8, displayed with satellite imagery as the background

5.5 Planned Interface and Functionality Enhancements

As noted earlier, the main interface for 3DDB operates within a standard web browser (https://gsrt.digiarc.aist.go.jp/3ddb_demo/tdv/index.html), but data delivery is conducted using international standard formats such as 3D Tiles and COPC. This enables access to the data through various external platforms beyond web browsers. For example, ongoing development efforts are facilitating integration with GIS software such as QGIS and ArcGIS, point cloud visualization tools such as Potree, and game engines like Unity via dedicated plugins (https://www.digiarc.aist.go.jp/team/gsvrt/information/tdv-client4unity-plugin/).

As of June 2025, users can download registered datasets only in their original formats and coordinate systems. However, the development of new features for point cloud data—including format conversion, coordinate transformation, and custom area extraction—is underway, with public release expected within the fiscal year. Additional functionality currently under development includes automated feature extraction using AI from large-scale point clouds, as well as manual boundary tracing tools to generate vector data from user-defined regions.

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