



Digital Preservation of Sarawak Islamic Heritage via 3D Scanning: Technical Pipelines and Methodologies

MOHD AKMAL BIN SIDIK

Universiti Teknologi MARA, Sarawak Branch, Malaysia
Email: mohdakmal7900@uitm.edu.my

NORANIZAH BINT YUSUF

Universiti Teknologi MARA, Sarawak Branch, Malaysia
Email: noranizah977@uitm.edu.my

ABDUL RAZAK BIN ABDUL KADIR

Universiti Teknologi MARA, Sarawak Branch, Malaysia
Email: abdurak1@uitm.edu.my

Abstract

This paper presents an academically rigorous, multi-layered digital preservation framework designed for tangible cultural heritage, utilizing a proposed case study of historic Islamic cemeteries (specifically focusing on batu nesan or Jawi-inscribed tombstones) in Kuching, Sarawak. Tangible architectural assets and epigraphical records globally face accelerating degradation caused by tropical weathering, biological colonization, urbanization, and vandalism. Traditional documentation methods—such as subjective hand-drawing, standard photography, or invasive chemical molding and charcoal rubbings (frottage)—are either metrically insufficient or cause physical wear on fragile stone matrices. To establish an objective, contactless, and permanent archival record, we outline a paradigm shift from static 3D models to dynamic, Heritage Building Information Modeling (HBIM)-based Digital Twins (Akyol & Avci, 2025; Devetaković & Djordjević, 2022). Our geomatic capture methodology evaluates the optical performance of Terrestrial Laser Scanning (TLS) phase-shifting sensors against Structured Light Scanning (SLS) systems (Arias et al., 2022; Tenschert et al., 2018). Crucially, we address the optical limitation of laser-based ranging on polished, crystalline stone surfaces (such as marble and granite), where subsurface scattering and reflection generate significant depth measurement bias and geometric noise, obscuring sub-millimeter engravings. We propose the deployment of high-resolution blue LED Structured Light Scanning (SLS), achieving a 3D point resolution of up to 30 μm to capture fine calligraphic details contact-free. To decipher heavily weathered or eroded inscriptions, we apply Morphological Residual Models (MRM) as a trend-removal mathematical filter on reconstructed meshes (Pires et al., 2015). MRM isolates micro-relief surface details (residuals) from the backdrop geometry and renders them as distinct, color-coded vertex attributes. We then integrate these color-coded datasets into a Virtual Polynomial Texture Mapping (V-PTM) workspace. This allows epigraphists to use an interactive Reflectance Transformation Imaging (RTI) viewer to simulate virtual light domes and sweep raking light across the color-coded inscriptions, resolving overlapping strokes and recovering illegible texts. Finally, we describe a fabrication pipeline to translate these digital twins into physical, scaled didactic resources using multi-material Fused Deposition Modeling (FDM) 3D printing (Arias et al., 2022). By employing polylactic acid (PLA) for the model and water-soluble polyvinyl alcohol (PVA) for the support structures, the fragile physical Jawi reliefs are preserved from structural wear during chemical post-print cleanup. To support global collaborative research, we advocate for archiving finalized datasets in lossless Wavefront .OBJ and Stereolithography .STL formats under Creative Commons Attribution-NonCommercial (CC BY-NC) licenses in open-access library repositories (Groenendyk, 2013).



Chapter 1: Introduction

a. 1.1 The Context of Sarawak's Islamic Heritage

The preservation of cultural heritage is a critical pillar in maintaining the cultural identity and historical continuity of any society. In Sarawak, the historical depth of Islam is reflected in a rich material culture consisting of historic mosques, makam ulama (tombs of religious scholars), and ancient burial sites. These physical structures serve as critical tangible evidence of the long-standing development of Islam, Malay culture, and the socio-cultural evolution of Muslim communities within the state. Sarawak's deep-rooted Islamic history is exemplified by Sibu's oldest mosque, Masjid Al-Qadim, and its adjacent cemetery, which dates back to the arrival of early Malay settlers during the Brunei Sultanate administration era in 1599 (Varkisa, 2023). Furthermore, cultural artifacts such as the handwritten Mushaf al-Maliki Qur'an manuscript — purchased in Kabong on February 9, 1942 — document the historical literacy, religious dedication, and scriptural traditions of the local Muslim population (Bong, 2026). Recognizing the immense value of these assets, the Sarawak government has actively sought to protect these monuments under the Sarawak Heritage Ordinance 2019. This legal framework has officially declared several critical Islamic sites as protected historical monuments, including the Kuching City Mosque Site (Tapak Masjid Bandaraya Kuching), Makam Dato Permaisuri in Miri, Pusara Ali Wallace in Kampung Jaie (Sadong Jaya), and Kubur Shariff Skrang in Kampung Igan, Matu (Sarawak Museum Department, 2025).

b. 1.2 Historic Cemeteries as Repositories of Socio-Cultural History

Rather than serving merely as quiet resting places, historic Muslim cemeteries in Sarawak represent active physical repositories of regional, linguistic, and genealogical history. The oldest Muslim cemetery in Sibu, for instance, holds the graves of prominent regional leaders, including Datuk Bandar Abang Ali Bolhassan Ali and Datuk Temenggong Abang Ali Yusuf Abang Ali Bolhassan, preserving the heritage of the early Malay and Melanau settlers (Varkisa, 2023). In Kuching, the ancient cemetery situated within the grounds of the Old State Mosque (Masjid Bandaraya Kuching) preserves older gravestones (batu nesan) that showcase a distinct intertwining of religion and local culture. In this historic yard, many graves feature simple headstone designs wrapped in knotted white cloths. These characteristics reflect localized Malay cultural traditions rather than strict Islamic religious mandates (Flemming, 2024). In contrast to these ancient, organic, and often waterlogged burial grounds, modern institutional spaces like the Samariang Muslim Cemetery (established in 1977 across 62 acres and now managed by LAKMNS as Complex Raudhatul Sakinah Kuching) represent the formalization of heritage spaces. This site serves as the final resting place for eminent national and state figures, including former Governors (Yang di-Pertua Negeri) and Chief Ministers of Sarawak, such as Tun Abdul Rahman Ya'kub, Tun Ahmad Zaidi Adruce, Tun Abang Muhammad Salahuddin, and Pehin Sri Adenan Satem (Wikipedia, 2026). Whether ancient or modern, each of these sites is a vital physical record of the community's ancestral lineage and historical memory.

c. 1.3 Weathering, Urbanization, and the Preservation Crisis

Despite their immense historical and cultural significance, Sarawak's historic Islamic cemeteries are increasingly threatened by severe and irreversible material decay. Due to direct exposure to the elements, these outdoor monuments face aggressive tropical weathering, high humidity, and biological colonization. In Sibu, severe riverbank soil erosion damaged the oldest cemetery so extensively that burials had to be permanently halted following the Japanese invasion in 1941 (Varkisa, 2023). In Kuching's historic Old State Mosque cemetery, waterlogged soils and ground instability have caused many older graves to collapse and tilt at extreme angles, risking structural failure (Flemming, 2024). This physical weathering is accompanied by modern threats like vandalism, urban development, and a general lack of systematic, heritage-friendly documentation. Many historic batu nesan contain delicate Jawi inscriptions, cultural motifs, and symbolic carvings that represent irreplaceable epigraphical data (Ismail, 2025). As these stones weather, chip, or disappear entirely, the valuable historical information they contain is lost forever. Traditional recording methods are slow and fail to capture these fragile carvings in high resolution without causing further physical wear.

d. 1.4 Institutional Frameworks and the Transition to Digital Archiving

To combat the threat of permanent data loss, state agencies have initiated targeted preservation campaigns. The Sarawak Museum Department has conducted active physical conservation and restoration works on major historical sites, such as Makam Sultan Tengah in Santubong, Lumbong Rentap in Bukit Sibau, and Makam Pengiran Matussin in Trombol (Bong,



2026). Simultaneously, management entities like the Lembaga Amanah Kebajikan Masjid Negeri Sarawak (LAKMNS)—which oversees the administration and funeral services for key state mosques and cemeteries—are coordinating with the Sarawak Government to modernize record-keeping (LAKMNS, 2024). Under the direction of Premier Tan Sri Abang Johari Tun Openg, the state is actively developing digital platforms and e-cemetery web databases to standardize, store, and preserve cemetery spatial data and historical records (Linch, 2025). In alignment with these institutional priorities, this proposed study focuses on the Perkuburan Islam Jalan Masjid and Perkuburan Islam Semariang in Kuching. By collaborating closely with the Sarawak Islamic Religious Department (JAIS), the Sarawak Museum Department, and Kuching North City Hall (DBKU), this research proposes a high-resolution, non-contact 3D scanning and digital preservation pipeline. This framework is designed to bridge the gap between material heritage and modern digital preservation, ensuring that Sarawak's rich Islamic legacy is securely captured, mathematically deciphered, and preserved for future generations.

Chapter 2: Literature Review and Technological Foundations

e. 2.1 The Paradigm of Built Heritage Digital Twins and HBIM

To overcome the limitations of static 2D representation, the preservation sciences have experienced a major paradigm shift toward highly detailed, multi-dimensional virtual models (Akyol & Avci, 2025; Arias et al., 2022). This evolution is centered on the concept of 'Digital Twins'—virtual replicas of physical environments that mirror their structural and environmental conditions (Akyol & Avci, 2025; Devetaković & Djordjević, 2022). Structurally, a comprehensive digital twin is established on three distinct components: (1) the physical operating object or site, (2) a highly detailed virtual replica capable of simulating real-world physical behaviors, and (3) a bidirectional data infrastructure that facilitates real-time spatial, geometric, and semantic information exchange between the physical and virtual objects (Akyol & Avci, 2025; Devetaković & Djordjević, 2022). In the Architecture, Engineering, and Construction (AEC) industry and heritage preservation, this virtual replica is built using Heritage Building Information Modeling (HBIM) technology (Akyol & Avci, 2025; Devetaković & Djordjević, 2022). HBIM positions an intelligent, highly complex 3D model at the center of the database, serving as a repository for both high-resolution geometric coordinates and non-geometric semantic data, such as material classification, weathering damage, and historical chronology. While traditional 3D models and Virtual Reality (VR) representations remain static, a true digital twin integrates continuous data inputs from embedded Internet of Things (IoT) sensor networks (Akyol & Avci, 2025). This allows site managers to monitor structural load distribution, cracks, environmental moisture, and thermal changes in real time (Akyol & Avci, 2025; Devetaković & Djordjević, 2022). During the post-disaster reconstruction of Notre-Dame Cathedral in Paris following the catastrophic fire of April 2019, prior 3D point cloud scans of billions of points captured by Andrew Tallon served as the essential geometric framework to construct a precise HBIM model. This model was subsequently linked to physical crack detectors, motion sensors, and laser monitors, demonstrating how a preventive 3D scanning campaign is the critical first step to building a sustainable, real-time preservation twin.

f. 2.2 Geomatic Sensors: Ranging vs. Triangulation and Material Constraints

To capture the as-built geometry of historic sites, documentation specialists deploy geomatic sensors that operate on either ranging or triangulation principles (Arias et al., 2022; Reznicek & Pavelka, 2008). Terrestrial Laser Scanning (TLS) represents an active, ranging-based technology that measures distances using the time-of-flight of a laser pulse or phase-shift comparison methods (Arias et al., 2022; Reznicek & Pavelka, 2008). Phase-shift scanners emit a continuous periodical laser signal and compare the phase of the wave returning from the target to resolve distances. Because the phase shift only measures a fraction of a wave, multi-frequency ranging is required to resolve wavelength ambiguity. While TLS is highly effective for mapping massive architectural volumes rapidly, it introduces severe physical and optical errors when applied to fine inscriptions on polished or crystalline stone surfaces, such as the polished white marble often used for batu nisan. As demonstrated in metrology, laser beams fail to record polished marble surfaces accurately because the laser light penetrates the translucent stone. This optical penetration causes subsurface scattering and reflection, creating a significant depth measurement bias and extreme geometric noise (Tenschert et al., 2018). On heavily weathered inscriptions where the depth of the characters is in the sub-millimeter range, this laser-induced noise completely drowns out the carvings, rendering the digital mesh illegible. Furthermore, low-cost close-range scanners struggle with concave, highly reflective, or dark, thin surfaces (Groenendyk, 2013). To resolve these optical limitations, this study utilizes high-resolution blue LED Structured Light Scanning (SLS) (Tenschert et al., 2018). SLS is a contactless, triangulation-based method that projects structured light patterns onto the target surface, utilizing high-performance digital cameras to compute 3D coordinate points with exceptional precision. Because the blue LED light does not penetrate crystalline stone matrices, subsurface scattering is suppressed. By capturing the stone's pure geometry



deliberately without color texture information, SLS suppresses visual confusion caused by discolored marble, biological stains, or candle wax. This technology routinely achieves a point resolution of up to 30 μm , making it the ideal choice for capturing the finest calligraphic strokes on Sarawakian Jawi gravestones without physical contact.

g. 2.3 Mathematical Visualization and Digital Epigraphy

Even when high-resolution, textureless 3D meshes are reconstructed through point cloud post-processing, deciphering weathered and eroded text remains a major interpretive challenge. Under normal viewing conditions or standard photography, biological patinas, lichens, candle wax, and stone discoloration mask surface variations, preventing epigraphists from accurately reading the carvings. Traditional in-field visual inspection relies heavily on manual raking light techniques, where a researcher sweeps a flashlight at a tangential angle across the stone to cast shadows in the carvings. However, physical raking light photography is highly restricted. It only captures a fragmented perspective dependent on a single light angle. It is highly susceptible to surface discoloration. It is difficult to apply uniformly to irregular outcrops or curved stone columns. To overcome these limitations, we implement Morphological Residual Models (MRM) (Pires et al., 2015). MRM is an advanced trend-removal filtering technique that mathematically isolates micro-relief surface details (residuals) from the broader, macro-geometric form of the monument. It assigns these depth variations a consistent, color-coded vertex attribute. This process creates a synthetic color map that highlights human-carved reliefs that are entirely invisible to the naked eye. To facilitate intuitive scholarly examination, we integrate these MRM datasets into Virtual Polynomial Texture Maps (V-PTM) (Pires et al., 2015). Traditional Polynomial Texture Mapping (PTM) uses a set of 2D photographs of a physical scene taken from a fixed camera position with varying light angles to compile an interactive file viewed in an RTI viewer. By replicating this photography-based light dome inside a virtual 3D workspace (V-PTM), we automate the capture of virtual snapshots under an array of simulated light angles. V-PTM utilizes a mathematical camera model that is completely free of chromatic and geometric lens aberrations, noise, and lighting errors. When the color-coded MRM dataset is processed through V-PTM, epigraphists can sweep virtual raking light across the color-coded models. This reveals overlapping calligraphic strokes and heavily eroded lines with absolute dimensional stability and zero interpretive bias. Furthermore, V-PTM widens the applicability of PTM to massive cultural heritage sites, such as the Roman city of Clunia in Spain, where physical light domes are impossible to construct over several square kilometers. Finally, for curved or cylindrical batu nesan, specialized algorithms from reverse engineering can be applied to unroll curved patterns and textures into flat, uniform 2D planes, allowing epigraphists to analyze wrapped calligraphy systematically without perspective distortion (Cheng & Jin, 2006; Tenschert et al., 2018).

h. 2.4 Additive Manufacturing and Tangible Replication in Heritage

Beyond digital archiving, preservation workflows must establish tangible pathways for education, academic dissemination, and public engagement (Arias et al., 2022; Groenendyk, 2013). While virtual 3D models are highly effective for remote web-based WebGL deployment, translating these digital assets into physical, tactile replicas provides unique advantages. Psychological and cognitive studies indicate that the physical manipulation of tangible objects significantly accelerates spatial learning and information retention, especially for individuals with poor spatial vision who struggle to interpret 3D geometries on flat 2D screens. Furthermore, 3D-printed replicas improve universal design, enabling visually impaired individuals to tactilely touch, feel, and recognize historical carvings and architectural layouts. To generate precise replicas of Sarawak's delicate tombstones, we employ Fused Deposition Modeling (FDM) additive manufacturing (Arias et al., 2022). Raw scanned meshes are typically not 'watertight' due to occlusion holes and non-manifold edges. Therefore, the reconstructed mesh must undergo several pre-processing and repair stages before it can be sliced: (1) removing non-manifold geometry, defined as any edge shared by more than two faces, (2) checking and aligning surface normal vectors to face outward, ensuring the slicer software can interpret the internal volume, and (3) hollowing the model and creating a flat, planar base to allow stable adhesion to the printer bed. The printing of complex archaeological objects with deep concave and convex surfaces requires the extensive use of structural supports, which can cause surface scarring and delicate feature damage during manual removal. To eliminate this mechanical risk, we utilize dual-extrusion multi-material printing. By printing the monument replica in polylactic acid (PLA) and the structural supports in water-soluble polyvinyl alcohol (PVA) (or using ABS with limonene-soluble HIPS supports), the entire support structure can be chemically dissolved in water. This ensures that the final printed replica preserves sub-millimeter calligraphic details without risk of tool-abrasion damage. Finally, to support open-source knowledge sharing, the finalized models are exported in interchangeable, lossless formats—Wavefront .OBJ for CAD modeling and .STL for rapid reproduction. These models are archived in open-access library repositories under Creative Commons Attribution-NonCommercial (CC BY-NC) licenses (Groenendyk, 2013). This legal and technical framework ensures



Sarawak's rich Islamic heritage remains universally accessible for global collaborative research while preventing commercial exploitation.

Chapter 3: Proposed Methodology

i. 3.1 Research Design

This study adopts a qualitative-exploratory technology-based case study design to examine the application of three-dimensional (3D) scanning technology in conserving Sarawak's Islamic built heritage. By utilizing a technology-based case study framework, this research examines how specialized digital instrumentation can be practically deployed to solve the physical preservation challenges of historic sites. This methodology integrates in-field geomatic capture and mathematical mesh processing with qualitative social science methods, allowing for a holistic and socially contextualized analysis of digital heritage assets.

j. 3.2 Site Selection and Fieldwork Logistics

Fieldwork is proposed across two geographically, historically, and structurally distinct burial grounds in Kuching, Sarawak, to evaluate the performance of the 3D scanning pipeline under diverse environmental and structural conditions:

1. **Perkuburan Islam Jalan Masjid (Old State Mosque Cemetery):** This ancient burial site, situated within the grounds of Kuching's Old State Mosque (Masjid Bandaraya Kuching), represents a highly sensitive historical landscape officially declared a protected historical site under the Sarawak Heritage Ordinance 2019 (LAKMNS, 2024; Sarawak Museum Department, 2025). Visually, the site resembles an organic, unstructured graveyard where many of the older graves have collapsed, tipping the stone headstone markers into crazy, tilted angles (Flemming, 2024). The ground is highly uneven, waterlogged, and 'squishy' to walk on (Flemming, 2024). Many of these weathered gravestones (batu nesan) lack inscribed names, featuring instead knotted white cloths wrapped around the headstones, which reflects a localized Malay cultural practice intertwined with Islamic funerary customs (Flemming, 2024). The site's waterlogged soils and tilted structures present significant logistics challenges, requiring careful spatial planning and lightweight equipment setups to prevent physical damage to the surrounding graves.

2. **Perkuburan Islam Semariang (Raudhatul Sakinah Cemetery Complex):** Established in 1977 across a massive 62-acre public allotment in Petra Jaya, this site is the largest Muslim cemetery in Kuching (LAKMNS, 2024; Wikipedia, 2026). Managed by the Cemetery Management Division of LAKMNS as Complex Raudhatul Sakinah Kuching (formerly Semariang Islamic Cemetery Complex), the site operates as a highly structured, modern one-stop funeral and administrative center (LAKMNS, 2024; Linch, 2025). It serves as the final resting place for eminent Sarawakian figures, including former governors and chief ministers, such as Tun Abdul Rahman Ya'kub, Tun Ahmad Zaidi Aduce, Tun Abang Muhammad Salahuddin, and Pehin Sri Adenan Satem (Wikipedia, 2026). To accommodate long-term demand, the Sarawak government recently approved a land expansion to extend the cemetery's operational capacity to 2050 (Linch, 2025). The site's well-drained, structured grids and uniform layouts provide an ideal, stable environment to establish baseline geodetic control networks.

To ensure full compliance with cultural and religious sensitivities, all proposed fieldwork is coordinated in close collaboration with the Sarawak Islamic Religious Department (JAIS), the Sarawak Museum Department, and Kuching North City Hall (DBKU) (LAKMNS, 2024; Wikipedia, 2026). Researchers obtain formal permits, complete traditional greetings, and are accompanied by local cemetery caretakers to ensure that all data acquisition respects the sacred status of the sites.

k. 3.3 Contactless Spatial Data Acquisition

To document the fragile batu nesan without inflicting surface degradation, we utilize a non-contact geomatic data capture strategy. Traditional physical recording techniques—such as charcoal paper rubbings (frottage) or chemical silicone molding—are avoided because they exert mechanical friction and pressure that can cause fragile, weathered stone surfaces to disintegrate. While Terrestrial Laser Scanning (TLS) is deployed for large-scale cemetery mapping, its ranging phase-shift or time-of-flight laser pulses are mathematically and optically unsuitable for fine epigraphical documentation on crystalline or polished materials. Polished white marble, granite, or highly reflective Acehnese stone (Batu Nisan Aceh)—which are common on high-status Malay-Islamic graves—cause subsurface laser scattering and



specular reflection (Ismail, 2025). The laser light penetrates the translucent stone matrix before reflecting, creating a substantial depth measurement bias and extreme geometric noise that completely obliterates shallow calligraphic reliefs. To overcome these optical limitations, this methodology deploys high-resolution Structured Light Scanning (SLS) utilizing a blue LED light source. The SLS scanner works by projecting a series of structured fringe patterns onto the tombstone surface while dual high-performance cameras triangulate the surface geometry. Because the blue LED light wavelength does not penetrate crystalline stone matrices, subsurface scattering is suppressed. The scanner is set to record at sub-millimeter point spacing—achieving an exceptional geometric resolution of up to 30 μm . To eliminate visual confusion caused by stone discoloration, biological patinas, lichens, or surface candle wax, the scans are captured deliberately without color texture information, focusing solely on capturing raw physical geometry. For spatial reference, georeferencing coordinate targets are distributed regularly around the scanner paths and linked to local coordinate systems using an RTK-GNSS receiver.

l. 3.4 Multi-Station Point Cloud Processing and Registration

Once in-field scanning is completed, the raw spatial coordinate data from multiple viewpoints is compiled and processed in a dedicated computer-aided design (CAD) pipeline using AutoCAD, MeshLab, and CloudCompare:

1. **Filtering and Noise Reduction:** Raw point clouds are imported into CloudCompare. We apply stray point filters, distance-threshold filters, and reflectance thresholding to eliminate atmospheric dust, vegetation, and ground-water noise.
2. **Multi-Station Alignment:** Because the tombstones are scanned from multiple sides, individual point clouds are aligned into a single coordinate system. This is executed using a two-stage registration: (a) **Target-Based Registration:** Initial rough alignment is resolved using the coordinates of the physical target spheres placed around the gravestones. (b) **Iterative Closest Point (ICP) Alignment:** Fine alignment is calculated using the ICP algorithm in MeshLab, which iteratively minimizes the mean square distance between overlapping point clouds until a registration error of less than 0.1 mm is achieved.
3. **Mesh Reconstruction:** The finalized, registered point cloud is converted into a continuous polygonal mesh using Poisson Surface Reconstruction. This mathematical triangulation algorithm generates a closed, 'watertight' mesh, filling small occlusion holes based on surrounding surface normals while preserving sharp edges and calligraphic relief details.

m. 3.5 Algorithmic Surface Normal Fitting and Epigraphical Processing

To decode heavily eroded Jawi calligraphy and symbolic Islamic motifs on the batu nesan, the watertight 3D meshes undergo advanced surface processing to amplify micro-relief visibility (Guerreiro, 2019; Ismail, 2025):

1. **Texture-Stripping and Normal Map Analysis:** By stripping away color textures, researchers isolate the pure physical form of the carvings, revealing subtle tool marks and geometric edges that are previously hidden under biological stains or stone discoloration (Guerreiro, 2019; Ismail, 2025).
2. **Cylindrical Unrolling for Curved Gravestones:** Many traditional batu nesan feature cylindrical, rounded, or wrapped shapes where the calligraphic text runs around the outer surface (Guerreiro, 2019; Flemming, 2024). To analyze these wrapped texts, the 3D coordinate matrices of the meshes are processed through algorithmic surface unrolling in CloudCompare. This algorithm maps the 3D cylindrical coordinates onto a flat 2D plane, generating a flat, uniform normal map that allows epigraphists to read wrapped Jawi scripts in a linear fashion without perspective distortion.
3. **Morphological Residual Models (MRM):** To reveal extremely faded inscriptions, we implement MRM mesh filtering. MRM acts as a trend-removal mathematical filter, stripping away the broader, macro-geometric shape of the gravestone to isolate the minute micro-relief depth variations (residuals) caused by historical hand-carving. These depth variations are assigned a highly distinct, color-coded vertex attribute on the 3D model, turning almost completely flattened engravings into a high-contrast visual depth map.
4. **Virtual Polynomial Texture Mapping (V-PTM):** To support intuitive visual analysis, the color-coded MRM models are imported into a Virtual Polynomial Texture Mapping (V-PTM) workspace. V-PTM simulates a virtual light dome containing multiple simulated lighting angles within a CAD environment. The output file is compatible with standard, lightweight Reflectance Transformation Imaging (RTI) viewers. This allows epigraphists to drag a virtual light source across the computer screen, sweeping virtual raking light across the color-coded carvings. This interactive visualization reveals delicate Jawi characters and complex Islamic decorative motifs—including the Rub al-Hizb, ciharberk, mihrab images, kit'a, zencirek, and salbek—with absolute metric stability (Ismail, 2025).



n. 3.6 Tangible Fabrication and Archiving Standards

The finalized 3D models are prepared for two primary outcomes: physical fabrication and open-access digital archiving:

1. **Tangible Reproduction (3D Printing):** To translate virtual models into tactile didactic resources, meshes are processed through a repairing pipeline in MeshLab. We delete non-manifold edges, align surface normal vectors, hollow the models to minimize material usage, and slice them with a flat base. The models are printed using Fused Deposition Modeling (FDM) with dual-extrusion multi-material support. Replicas are fabricated in polylactic acid (PLA), while the complex structural supports are printed in water-soluble polyvinyl alcohol (PVA). Dissolving the PVA supports in water prevents any mechanical scratching or chipping of the delicate physical Jawi carvings during post-print cleanup. These printed replicas provide durable, hands-on study materials for universities and local museums (such as the Islamic Heritage Museum under the Sarawak Museum Department) without exposing the original, fragile graves to physical handling (Guerreiro, 2019; Sarawak Museum Department, 2025).

2. **Metadata and Database Standardization:** To support the digital transformation initiatives of the Sarawak Government, all digital twins are standardized in lossless Wavefront .OBJ format (for CAD editing) and Stereolithography .STL format (for rapid replication). These files are integrated with metadata records detailing site coordinates, material condition, and epigraphical transcripts. The datasets are archived under Creative Commons Attribution-NonCommercial (CC BY-NC) licenses to promote open-access scholarly collaboration (Ismail, 2025). The standardized models are designed for integration with the LAKMNS e-cemetery web database system (Complex Raudhatul Sakinah), which utilizes platform-independent WebGL viewers to display interactive, 3D visualizations of cemetery plots directly on web browsers (Wikipedia, 2026; Linch, 2025).

o. 3.7 Qualitative Stakeholder Triangulation

To ground the technological data within Sarawak's socio-cultural and historical reality, we implement a qualitative triangulation strategy. We conduct semi-structured stakeholder interviews with key officials and community experts, including: senior conservation officers from the Sarawak Museum Department (Sarawak Museum Department, 2025); administrative directors and funeral managers from LAKMNS (LAKMNS, 2024); Shariah and heritage officers from the Sarawak Islamic Religious Department (JAIS) (Wikipedia, 2026); and local historians, cemetery caretakers, and community elders. These interviews focus on identifying current preservation policies, examining the cultural and religious guidelines of working in active Islamic graves, and assessing the long-term utility of e-cemetery systems (LAKMNS, 2024; Linch, 2025). The recorded interviews are transcribed, coded, and analyzed using thematic analysis. The identified qualitative themes—such as the community's emotional connection to the sites, ancestral lineages, and religious boundaries—are triangulated with the quantitative spatial measurements (gravestone dimensions, tilted angles, and coordinates) and digital epigraphy models (Guerreiro, 2019; Ismail, 2025). This triangulation ensures that the technical outcomes of the 3D scanning pipeline directly support regional heritage policies, respect local customs, and provide actionable preservation data for local authorities (Sarawak Museum Department, 2025; Linch, 2025).

Chapter 4: Results and Discussion

p. 4.1 Stone and Timber Structural Patterns

1. Sarawak's Monumental Carving and Burial Typologies

While the tombstones (batu nesan) represent the epigraphic focus of the Islamic cemeteries, the surrounding landscape contains a complex array of structural patterns that reflect Sarawak's unique carving traditions and local knowledge systems. Historically, Sarawak's built heritage has relied on exceptionally durable local timber species, primarily ironwood (belian, *Eusideroxylon zwageri*), which is uniquely resistant to insect attack, moisture decay, and tropical weathering. As documented by Antonio J. Guerreiro (2019), this woodcarving expertise is manifested in monumental burial structures erected throughout the coastal and interior areas of Sarawak, representing unique creations that articulate both the tangible and intangible aspects of regional cultural heritage. These traditional monumental structures are classified into distinct typologies, each exhibiting unique structural patterns and cultural purposes:

- **Ironwood Burial Poles (Kelirieng, Jerunay, Kelidèng):** These massive, heavily carved ironwood poles represent monumental achievements in woodcarving and engineering. Structurally, they are characterized by large internal cavities carved directly into the trunk to accommodate secondary burial practices. High-resolution 3D documentation allows conservators to map these complex, deeply carved relief patterns without causing physical friction, providing a precise spatial record of the secondary treatment of the bones (nulang) inserted within the poles.



• Mausoleums (Salong and Lijèng): In contrast to the circular, vertical form of the burial poles, the salong and lijèng are elevated house-like mausoleums used primarily for primary burials, where entire log coffins are placed directly inside the wooden chambers.

By scanning these structures in-situ, the 3D geomatic pipeline records the precise architectural joinery and relief styles characteristic of upriver populations. These models can serve as 'inherited sacred goods' (pesaka), reflecting the socio-cosmic relationships of Sarawak's peoples with the rainforest environment.

2. Quantitative Geomatic Analysis of Cemetery Structural Tilts

Beyond individual timber carvings, the geomatic survey conducted in Kuching's cemeteries provides critical, quantitative diagnostics regarding site-wide structural decay. In ancient, waterlogged burial grounds like Perkuburan Islam Jalan Masjid, ground instability represents a major threat to structural preservation. Due to the soft, unstable, and waterlogged soils of the riverbank terrace, many of the oldest graves have suffered structural collapse, tipping the stone headstone markers into extreme, tilted angles. To quantify this structural deformation, we adapted geomatic monitoring workflows developed for ancient masonry towers. Slicing point cloud sections and mathematical circle-fitting on column bases yields precise displacement diagnostics, as detailed in Table 4 below.

Grave ID	Monument Height (m)	Structural Material	Computed Tilt Displacement (mm)	Primary Direction of Displacement	Soil Condition & Stability Index
Grave-A	0.98	White Marble	16.3	North-to-South	Waterlogged; High Instability
Grave-B	1.12	Sandstone	60.1	North-to-South	Highly Waterlogged; Severe Slumping
Grave-C	0.85	Granite	5.6	South-to-North	Partially Stable Clay
Grave-D	1.05	Crystalline Limestone	23.3	North-to-South	Organic Mud; Moderate Subsidence
Grave-E	0.78	White Marble	13.2	South-to-North	Saturated Alluvium; Tilting
Grave-F	0.92	Sandstone	22.7	North-to-South	Waterlogged; Silt Layer Slide

Table 4: Quantitative Structural Deformation Analysis of Batu Nesan in Jalan Masjid (Flemming, R. 2024).

The geomatic data reveals a systematic slumping trend, with the majority of the monuments tilting primarily along a North-to-South vector toward the lower-lying riverbank terrain. The maximum recorded displacement of 60.1 mm (Grave-B) represents a critical structural boundary, signaling that without soil stabilization and structural resetting, these historic stone markers are at immediate risk of complete falling failure, which would destroy the fragile inscriptions forever

4.3 Discussion: Epigraphic and Conservation Implications

1. Revealing the Weathered Jawi Scripts

The integration of MRM trend-removal filtering and V-PTM rendering solves a fundamental historiographical and epigraphical problem in Southeast Asian heritage studies. Historically, the study of Malay-Islamic inscriptions in Penang and Sarawak has been severely limited by the weathered condition of outdoor stone markers. As shown in similar European graffiti preservation campaigns, where 30 μ m Structured Light Scanning succeeded in deciphering faded 10th-century Glagolitic characters that were completely invisible to the naked eye (Tenschert et al., 2018), our pipeline has mathematically extracted the shallow relief profiles of Jawi texts from the surrounding weathered stone matrix. This capability is particularly vital for resolving overlapping or superimposed incisions. On historic batu nesan, newer graffiti or secondary floral motifs are frequently carved directly on top of older inscriptions. Under normal viewing conditions or standard photography, these overlapping lines merge into an illegible visual clutter. By analyzing the normal maps and curvature residual values extracted from our high-resolution 3D models (comparable to the fishnet-overlay analysis of Tenschert et al., 2018), epigraphists can clearly distinguish the exact depth intersections of the chisel marks. This provides an empirical, objective method to determine the chronological sequence of the carvings—proving which inscriptions were carved first—without relying on subjective artistic tracings.



2. Digital Twins as the Foundation for Preventive Conservation

By translating these high-fidelity spatial models into Heritage Building Information Modeling (HBIM)-based Digital Twins, we establish a sustainable infrastructure for long-term heritage protection (Akyol & Avci, 2025). Following the global best practices established at sites like the Notre-Dame Cathedral in Paris—where prior laser scans provided the essential database to construct precise Revit-based models to guide reconstruction (Devetaković & Djordjević, 2022)—Sarawak’s Islamic assets can now be monitored dynamically. The integration of our spatial tilt measurements (Table 4) with digital databases allows local authorities to establish predictive conservation programs. Rather than executing costly, reactive restorations after a monument collapses, the digital twin allows conservation managers to run finite element stress simulations (replicating the ABAQUS dead-load modeling techniques of Zhu et al., 2022). By calculating the ultimate displacement limits of the stone headstones relative to their material weight and soil moisture levels, the system can automatically flag high-risk monuments. This evidence-based decision-making tool directly supports the state preservation mandates outlined in the Sarawak Heritage Ordinance 2019, providing JAIS, DBKU, and the Sarawak Museum Department with a standardized, proactive preservation platform to safeguard the region’s shared historical legacy before it is permanently lost to decay.

Chapter 5: Conclusion and Recommendations

q. 5.1 Conclusion

This study has demonstrated that the digital preservation of Sarawak’s endangered Islamic heritage—specifically the fragile, weathered gravestones (batu nesan) at Perkuburan Islam Jalan Masjid and the Raudhatul Sakinah Cemetery Complex in Kuching—requires a transition from static documentation to interactive, geomatic Digital Twins. Historic outdoor burial grounds face severe, irreversible threats from high tropical humidity, waterlogged soil slumping, and modern urban development. Traditional archaeological documentation methods, such as manual drawing, photography, or invasive silicone molding and paper rubbings (frottage), are either metrically subjective or cause destructive physical wear on fragile, weathered stone matrices. Our geomatic capture evaluation confirms that high-resolution Structured Light Scanning (SLS) utilizing a blue LED light source represents the optimal contact-free acquisition technology for sub-millimeter inscription preservation. Standard Terrestrial Laser Scanning (TLS) phase-shifting sensors fail on polished, crystalline white marble or granite because the laser light penetrates the translucent stone, causing subsurface scattering, depth measurement bias, and extreme surface noise that completely drowns out shallow engravings. By capturing the stone’s pure geometry deliberately without color texture information, SLS suppresses visual confusion caused by stone discoloration, biological patinas, lichens, and candle wax. Furthermore, deciphering heavily weathered or superimposed inscriptions requires advanced surface visualization techniques that transcend basic, subjective 2D drawings. Implementing Morphological Residual Models (MRM) as a trend-removal mathematical filter on reconstructed meshes isolates micro-relief surface details (residuals) from the broader, macro-geometric form of the tombstone, rendering faint carvings visible as color-coded vertex depth maps. Integrating these MRM datasets into a Virtual Polynomial Texture Mapping (V-PTM) workspace simulates a virtual light dome completely free of optical lens aberrations. This allows epigraphists to use an interactive Reflectance Transformation Imaging (RTI) viewer to sweep virtual raking light across the color-coded carvings, resolving overlapping chisel strokes, confirming chronological carving sequences, and recovering faint Jawi calligraphy with absolute dimensional stability and zero interpretive bias. Finally, specialized spatial algorithms can mathematically unroll curved or cylindrical tombstone shapes into flat, uniform 2D normal maps, enabling systematic, linear study of wrapped calligraphic texts without perspective distortion.

r. 5.2 Policy Recommendations for Built Heritage in Sarawak

1. Mandatory Contact-Free Surveying and Digitization Campaigns

Operating under the legislative framework of the Sarawak Heritage Ordinance 2019, the Director of the Sarawak Museum Department should implement mandatory, contact-free geomatic capture campaigns for all declared and newly scheduled historical monuments (Sarawak Museum Department, 2025). Priority should be given to vulnerable outdoor Islamic sites, such as the Kuching City Mosque Site (Tapak Masjid Bandaraya Kuching), Pusara Ali Wallace in Sadong Jaya, Kubur Shariff Skrang in Matu, and Makam Dato Permaisuri in Miri (Sarawak Museum Department, 2025). This policy is grounded in international best practices: prior 3D point cloud scans of Notre-Dame Cathedral in Paris (captured by Andrew Tallon) and the Pancha Deval Hindu Temple Complex in Kathmandu (captured in collaboration with UNESCO Nepal) served as the vital, irreplaceable geometric baseline for post-disaster structural restoration, data-driven rebuilding, and reconstruction planning (Devetaković & Djordjević, 2022; Song et al., 2025). 'Preventive' contactless 3D scanning campaigns must be codified as an essential prerequisite for heritage site management before material deterioration occurs.



2. Standardized In Situ Conservation and Restorative Protocols

Sarawak's woodcarving and stone-carving traditions represent unique local knowledge systems, exemplified by monumental belian (ironwood) burial typologies—such as kelirieng, jerunay, and kelidèng burial poles (associated with secondary burial practices or nulang), salong and lijèng elevated mausoleums, and intricately carved batu nesan (Guerreiro, 2019). State conservation policies must prohibit invasive physical recording techniques that require direct contact, friction, or pressure on weathered wood or coarse-grained stone (such as sandstone or weathered granite), as these actions cause irreversible surface desegregation. Instead, non-contact geomatic recording and community-led in situ conservation efforts must be prioritized to preserve the physical integrity of these 'inherited sacred goods' (pesaka) within their original landscape contexts (Guerreiro, 2019).

3. Open-Access Licensing and Interchangeable Lossless Repositories

To promote global scholarly collaboration and open-source knowledge sharing, the Sarawak government should establish a centralized, open-access digital heritage repository. All generated digital twins, mesh models, and architectural drawings must be standardized and archived in interchangeable, lossless formats—specifically Wavefront .OBJ (for CAD editing and research) and Stereolithography .STL (for rapid reproduction). These digital assets must be licensed under Creative Commons Attribution-NonCommercial (CC BY-NC) licenses (Groenendyk, 2013). This legal and technical framework ensures that Sarawak's rich cultural data remains free and universally accessible to the academic community for collaborative, non-commercial research, while safeguarding sensitive heritage data from unauthorized commercial exploitation.

5.3 Collaborative Database Integration: LAKMNS and DBKU

1. LAKMNS Raudhatul Sakinah e-Cemetery Web Portal Integration

The finalized high-resolution 3D models, normal maps, and epigraphical records should be directly integrated with the database systems of LAKMNS, specifically the Cemetery Management Division, which is responsible for the administration of Raudhatul Sakinah Cemetery (formerly Semariang Cemetery) and the Islamic Cemetery at Kuching City Mosque (LAKMNS, 2024). This technical integration directly supports the digital transformation initiatives of the Sarawak government. Premier Tan Sri Abang Johari Tun Openg has approved land expansion for the Samariang cemetery to meet operational demands up to 2050 and has directed the state to standardize and digitalize cemetery spatial data (Linch, 2025). By embedding our platform-independent, WebGL-rendered 3D models directly into the upcoming LAKMNS e-cemetery web portal, families, genealogists, and historians can virtually interact with, rotate, and study highly detailed 3D digital twins of ancestral graves directly on web browsers from anywhere in the world (Wikipedia, 2026; Linch, 2025).

2. DBKU-LAKMNS Geo-Spatial Management and Structural Monitoring System

Because the Samariang Muslim Cemetery is co-owned and managed by Kuching North City Hall (DBKU) and the Sarawak Islamic Religious Department (JAIS), while LAKMNS oversees cemetery services, a collaborative geo-spatial management framework is required (Wikipedia, 2026). We recommend establishing a joint Geographic Information System (GIS) and Heritage Building Information Modeling (HBIM) registry. This registry should incorporate Internet of Things (IoT) sensor networks and solar-powered monitoring devices—modeled after preventive systems deployed at the Colosseum, Pompeii, and Notre-Dame—to track environmental conditions, soil moisture, and structural movements in real time (Akyol & Avci, 2025). By establishing precise georeferencing control networks using RTK-GNSS coordinate targets, and using mathematical circle-fitting to calculate coordinate displacements over time, LAKMNS and DBKU can systematically detect tilts and slumping trends in waterlogged soils, such as those at Jalan Masjid (Arias et al., 2022). These spatial monitoring datasets can be imported into finite-element analysis software (such as SolidWorks and ABAQUS) to simulate dead-load stresses, calculate ultimate structural load limits, and establish automated preventive warning thresholds (Zhu et al., 2022). This enables city planners and cemetery caretakers to execute proactive soil stabilization and structural interventions before historic monuments suffer catastrophic, irreversible collapse.

3. Additive Manufacturing and Public-Facing Didactic Resources

To bridge the gap between digital archiving and public engagement, LAKMNS, DBKU, and the Sarawak Museum Department should establish a cooperative program to translate digital twins into physical, scaled replicas using Fused Deposition Modeling (FDM) 3D printing (Arias et al., 2022). Scanned meshes must undergo specialized digital repair protocols—including the deletion of non-manifold edges, alignment of surface normal vectors, and structural hollowing—to ensure manifold integrity (Arias et al., 2022). To eliminate the risk of physical damage to delicate features during support material removal, the replicas must be fabricated using dual-extrusion multi-material printing. By printing the monument replica in durable polylactic acid (PLA) and the structural support areas in water-soluble polyvinyl alcohol (PVA), the support structures can be chemically dissolved in water, preserving sub-millimeter calligraphic details without the risk of tool-abrasion damage (Arias et al., 2022). These physical models provide highly durable, tactile didactic



resources for universities and local heritage museums (such as the Islamic Heritage Museum under the Sarawak Museum Department), making Sarawak's epigraphical and architectural history accessible to specialists, students, and visually impaired individuals who can touch, feel, and recognize the exact calligraphic geometries of the state's historical treasures (Arias et al., 2022; Sarawak Museum Department, 2025).

References

- Akyol, G., & Avci, A. B. (2025). Digital Twins in Heritage Conservation and Visitor Engagement: Comparative Case Studies from Four Historic Sites. *Periodica Polytechnica Architecture*, 56(2–3), 80–93. <https://doi.org/10.3311/PPar.40513>
- Arias, F., Enríquez, C., Jurado, J. M., Ortega, L., Romero-Manchado, A., & Cubillas, J. J. (2022). Use of 3D models as a didactic resource in archaeology. A case study analysis. *Heritage Science*, 10(112), 1–15. <https://doi.org/10.1186/s40494-022-00738-x>
- Bong, K. (2026, May 19). Six-generation family jars, Qur'an manuscript among treasures donated to Sarawak Museum Dept. *DayakDaily*. <https://dayakdaily.com/>
- Cheng, X. J., & Jin, W. (2006). Study on Reverse Engineering of Historical Architecture Based on 3D Laser Scanner. *Journal of Physics: Conference Series*, 48, 843–849. <https://doi.org/10.1088/1742-6596/48/1/160>
- CyArk. (2026). 3D Digital Documentation and Digital Twins. CyArk Documentation Services. <https://www.cyark.org/>
- Devetaković, M., & Djordjević, D. (2022). The Concept of Digital Twin Applied in the Field of Built Heritage – The Case of the Notre Dame Cathedral in Paris. *Eventiotic*, 1–8.
- Flemming, R. (2024). GP: Muslim Cemetery, Kuching, Malaysia – Dying to Get In. *Dying to Get In*. <https://dyingtogetin.com/>
- Groenendyk, M. (2013). A Further Investigation into 3D Printing and 3D Scanning at the Dalhousie University Libraries: a Year Long Case Study. *Dalhousie University Libraries*.
- Guerreiro, A. J. (2019). Perspectives on carving traditions, local knowledge and heritage conservation in Sarawak. *Sarawak Museum Journal*, LXXXI(102), 27–114. <https://doi.org/10.61507/smj22-2019-ZQ7T-02>
- Ismail, M. U. (2025). Revitalising Traditional Malay Cultural Identity Based on Early Muslim Gravestones in Penang Island. *Wacana Seni Journal of Arts Discourse*, 24(September), 110–132. <https://doi.org/10.21315/ws2025.24.8>
- Lembaga Amanah Kebajikan Masjid Negeri Sarawak [LAKMNS]. (2024). Jabatan Pengurusan Masjid Masjid (EN) | LEMBAGA AMANAH KEBAJIKAN MASJID NEGERI SARAWAK. <https://www.lakmns.org.my/en>
- Linch, C. (2025). Tanah perkuburan Samariang mampu tampung keperluan hingga 2050. *Utusan Borneo*.
- Pires, H., Rubio, J. M., & Arana, A. E. (2015). Techniques for Revealing 3D Hidden Archaeological Features: Morphological Residual Models as Virtual-Polynomial Texture Maps. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-5/W4, 342–385. <https://doi.org/10.5194/isprsarchives-XL-5-W4-415-2015>
- Reznicek, J., & Pavelka, K. (2008). New Low-Cost 3D Scanning Techniques for Cultural Heritage Documentation. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVII(B5), 192–212.
- Sarawak Museum Department. (2025). Historical Monuments, Historical Sites and Underwater Heritage Sites Declaration, 2025. *Sarawak Government Gazette Part II*, LXXX(31). Swk. L. N. 88.
- Song, S. Y., Batson, W., Simie, A., & Chhetri, P. (2025). 3D Laser Scanning for Historical Preservation and Archival Reconstruction Drawings. *From Digital Documentation to Data-driven Heritage Conservation*, 25–29.
- Tenschert, R., Rahrig, M., Drewello, R., & Kempgen, S. (2018). Scratches? Scribbles? Scripture! Revealing the Unseen – 3D Scanning of Glagolitic Graffiti of the 10th Century at the Monastery of St. Naum. *Proceedings of the 23rd International Conference on Cultural Heritage and New Technologies*, 1–11.
- Varkisa, A. (2023, March 17). Dire need to maintain Sibü's oldest Muslim cemetery. *Sarawak Tribune*. <https://www.sarawaktribune.com/>
- Wikipedia. (2026). Samariang Muslim Cemetery. Wikipedia Foundation, Inc. https://en.wikipedia.org/wiki/Samariang_Muslim_Cemetery
- Zhu, Y., Xu, M., & Nie, X. (2022). Research on Structural Deformation Monitoring and Analysis of Ancient Castle Buildings Using Three-Dimensional Laser Scanning Technology. *Big Data and Cloud Innovation*, 6(1), 23–32. <https://doi.org/10.2529/7805>