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Digital Twin 4.0: Semantic 3D Documentation and Analysis of Jewish Sepulchral Heritage

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KEY WORDS: cultural heritage, 3D laser scanning, photogrammetry, semantic modelling, point cloud processing, Linked Open Data, Jewish cemeteries.

ABSTRACT:
In this paper we introduce and report on the project *"Steinerne Zeugen digital – German-Jewish Sepulchral Culture between the Middle Ages and Modernity. Space, Form, Inscription."* A project report on the first years of the project will be given, with a focus on the design and implementation of interdisciplinary, digitally integrated workflows. We will present and compare different technical and methodological approaches applied to three cemeteries and analyse the challenges encountered at the interface of interdisciplinary collaboration, particularly regarding data interoperability, semantic consistency, scalable data processing, and long-term preservation of complex 3D datasets. An outlook on future developments and specific research questions in geomatic engineering will be given, addressing automated feature extraction, advanced spatio-semantic querying, and FAIR-compliant data infrastructures for sustainable digital heritage documentation and analysis within this long-term project.

1. INTRODUCTION

In this paper we introduce and report on the research project *"Stone Witnesses Digital"* with a focus on the design and implementation of interdisciplinary, digitally integrated workflows.

The technical innovation and added value of the project lie in the development of a semantic Digital Twin 4.0 for Jewish sepulchral heritage. High-resolution 3D data acquisition methods (including image-based and range-based surveying) are combined with spatial referencing, semantic enrichment, and ontology-based data modelling. This enables the structured integration of geometric, topological, material, and epigraphic information within a unified, machine-readable framework (Talabardon and Hess, 2025).

We will present and compare different technical and methodological approaches applied to three cemeteries and analyse the challenges encountered at the interface of interdisciplinary collaboration, particularly regarding data interoperability, semantic consistency, scalable data processing, and long-term preservation of complex 3D datasets.

An outlook on future developments and specific research questions in geomatic engineering will be given, addressing automated feature extraction, advanced spatio-semantic querying, and FAIR-compliant data infrastructures for sustainable digital heritage documentation and analysis within this long-term project.

2. THE PROJECT "STONE WITNESSES DIGITAL"

The project, "Steinerne Zeugen Digital [Stone Witnesses Digital] – German-Jewish Sepulchral Culture between the Middle Ages and Modernity. Space, Form, Inscription." (Project team 'Steinerne Zeugen digital', 2025) was funded since 2023 as part of the research program of the German Academies of Sciences and Humanities and is supervised by the North Rhine-Westphalian and Bavarian Academies. At the Steinheim Institute in Essen and the University of Bamberg, researchers are working on an interdisciplinary basis to analyse and edit data acquired from Jewish cemeteries dating from the 16th century in German speaking countries (Steinerne Zeugen digital, 2026).

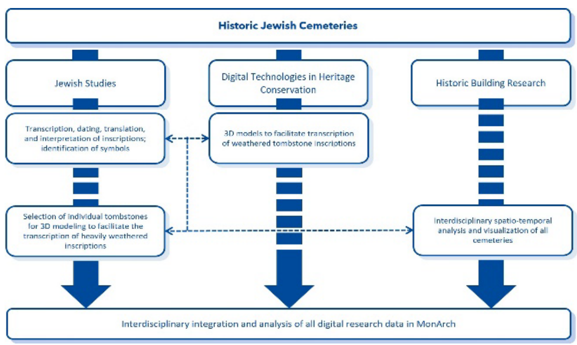

Figure 1. Workflow of different disciplines working together to create a new corpus of Jewish sepulchral culture in Germany.

The aim is to create a comprehensive digital dataset that documents the inscriptions as well as the spatial and structural characteristics of the gravestones, secures them permanently and makes them accessible for further scientific research. The project involves the disciplines of Jewish Studies, Digital Technologies in Heritage Conservation and Building Research (Figure 1).
In this way, the gravestones of the selected cemeteries, their inscriptions, their design and construction, their materiality and preservation as well as their spatial arrangement can be systematically analysed synchronically and diachronically, creating a valuable new source of data on the German-Jewish history of the pre-modern period.

Within this multi-institutional framework, 35 cemeteries containing more than 34,000 gravestones and 20,000 inscriptions are being recorded through a fully digital workflow. The project is long-term and has been funded for 24 years.

3. STATE OF THE ART - COMPARABLE SURVEY AND DOCUMENTATION PROJECTS

A few international projects provide relevant points of reference for the digital surveying and documentation of cemeteries and sepulchral heritage, employing different combinations of geomatic, archaeological, and digital humanities methodologies.

One frequently cited example is the Mueschke Cemetery project (Houston, USA). This project applied Terrestrial Laser Scanning (TLS) in combination with Ground-Penetrating Radar (GPR) to identify grave locations and subsurface structures. Its strength lies in the integration of high-resolution surface geometry with geophysical data, enabling archaeological interpretation of burial patterns without invasive methods. The project demonstrates the suitability of TLS-based terrain documentation for cemetery contexts and subsequent analytical workflows (Aziz *et al.*, 2016).

Another relevant group of projects focuses on UAV- and GIS-based cemetery documentation, such as those involving the Váraszó and Istenmezeje cemeteries in Hungary (Pál and Hajdú, 2024). Here, unmanned aerial vehicles (UAVs) were used to generate orthomosaics and digital surface models (DSM), which were subsequently processed through automated vectorization and integrated into GIS environments. These approaches are particularly notable for their efficiency in documenting large cemetery areas and are well suited for small municipalities with limited resources. The resulting workflows are highly transferable, especially

Project	UAV/Drone (SfM/LiDAR)	TLS	MLS	Close-Range Photogrammetry/ SfM	GNSS/ Geo-referencing	Semantic Annotation/ Ontology	GIS-Integration	AI/ML Pattern Analysis
Mueschke Cemetery (Houston, USA)	✕	✓	✕	✕	✓	✕	✕	✕
Váraszó & Istenmezeje (Hungary)	✓ (SfM)	✕	✕	✓	✓	✕	✓	✕
East End Cemetery (Richmond, USA)	✓ (SfM)	✕	✕	✓	✓	✕	✓	✕
Julfa Cemetery Digital Repatriation (Armenian)	✕	✕	✕	✓	✕ (Reconstruction)	✕	✕	✕
Bellu Cemetery (Romania)	✕	✕	✕	✓	✕	✕	✓*	✕
STECCI (Stone Epitaphs)	✕	✓	✕	✓	✓*	✓	✓*	✕
Steinerne Zeugen digital	✓ (SfM)	✓	✓	✓	✓	✓	✓	✓

Table 1.: Comparison of data acquisition and documentation methods used in selected cemetery projects and in *Steinerne Zeugen digital*.

Legend: ✓ = method applied; ✕ = method not applied; ✓* = method applied in specific contexts or partially.

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for grave mapping, spatial analysis, and the creation of structured spatial databases (Pál and Hajdú, 2024, pp. 8–12).

A comparable UAV-centered approach was applied at East End Cemetery (Richmond, Virginia, USA) by (Spera *et al.*, 2022). Small UAVs were used to acquire high-resolution imagery, which was then integrated into a GIS framework. This project illustrates how drone-based image acquisition can support the digital accessibility and spatial organization of historical cemetery data, particularly where traditional archival documentation is incomplete or fragmented (Spera *et al.*, 2022, pp. 1126–1129).

In contrast to physically extant cemeteries, the Julfa Cemetery Digital Repatriation Project (Armenia) addresses the documentation of a largely destroyed cemetery (Short, Crispin, and Drew Baker, 2017). Using historical photographs and 3D visualization techniques, the project reconstructs gravestones and spatial configurations virtually. Its relevance lies less in surveying technology and more in demonstrating how archival sources, 3D reconstruction, and digital dissemination can be combined to preserve and communicate lost sepulchral heritage.

A further example is the project Digitized Funerary Artworks from Bellu Cemetery (Romania), which concentrates on the digital documentation of funerary art and monuments. The emphasis is placed on cultural-historical interpretation and public engagement through digital platforms rather than on metric surveying accuracy. Nevertheless, it highlights the potential of digital documentation for heritage mediation and interdisciplinary research. (Angheluță and Tănașcu, 2025, p. 1915)
Beyond cemetery-specific projects, transferable methodologies can also be found in the documentation of other religious and cultural burial landscapes, such as Buddhist architecture (Li *et al.*, 2021) as well as within the broader field of spatial humanities and medieval heritage research. These approaches demonstrate how spatial analysis, semantic enrichment, and digital visualization can be applied to burial sites regardless of religious or cultural context.

From a technological perspective, existing projects show a heterogeneous use of sensing technologies. Several initiatives primarily rely on UAVs combined with GIS, while others complement aerial data with Terrestrial Laser Scanning (TLS) or, more rarely, Mobile Laser Scanning (MLS). Some projects use TLS exclusively for high-precision documentation, whereas others integrate TLS and MLS to capture both static monument geometry and broader spatial context. Stal et al. (2014) present an early approach combining UAV-based imagery with GIS to efficiently document large-scale heritage sites, albeit with limited geometric detail compared to ground-based sensing. Salerno et al. (2017) and Demir and Yogeswaran (2018) demonstrate that augmenting UAV data with TLS enables high-precision documentation of static monument geometry, compensating for the limitations of purely aerial methods. Downs et al. (2020) employ TLS as a standalone sensing technology to produce highly detailed and metrically reliable 3D documentation of individual heritage objects, with less emphasis on broader spatial context. Badillo, Myers and Peterson (2020) integrate TLS and MLS to capture both fine-grained architectural details and the monument's spatial embedding within its surrounding environment. Lee et al. (2025) showcase a multimodal framework that fuses UAV, TLS, and MLS data to generate scalable, context-rich digital twins of historical sites. Zachos and Anagnostopoulos (2024) highlight the efficiency of MLS for capturing extended spatial context around monuments, while TLS remains the primary tool for high-resolution documentation of static structures.

A particularly relevant reference for object-centered documentation is the STECCI project (Stone Epitaphs: Textual, Cultural and Contextual Information) ('STECCI', 2026). STECCI is an interdisciplinary digital heritage initiative dedicated to the high-resolution 3D documentation, analysis, and semantic enrichment of grave inscriptions. Its core objective is to link geometry, text, materiality, and contextual information within a coherent digital framework. Technically, STECCI combines TLS for precise geometric acquisition with image-based photogrammetry (SfM) to enhance texture detail, micromorphology, and inscription legibility. Semantic annotation and GIS/database integration are used to contextualize inscriptions spatially and typologically. The project is explicitly object-focused, concentrating on individual gravestones and epitaphs rather than entire cemetery landscapes, and does not employ UAV-based acquisition (Drešković and Radulović, 2024).
Nevertheless, its workflows are highly transferable to cemetery-scale projects, particularly in the areas of epigraphic analysis, material and weathering documentation, and semantic 3D modelling. Overall, the reviewed projects demonstrate a broad spectrum of established methodologies for cemetery documentation, ranging from UAV–GIS mapping to TLS-based object recording and archival 3D reconstruction. However, they also reveal a gap in fully integrated, multi-scale approaches that systematically combine UAV, TLS, MLS, GIS, and semantic modelling within a unified digital twin framework for cemeteries as complex spatial and cultural systems.

Table 1 shows a comparison of the technological approaches used in the relevant projects named above.

4. METHODOLOGY - RECORDING OF SPACE, FORM, INSCRIPTION

The primary aim of the project is to compile a comprehensive and systematically structured corpus of German-Jewish sepulchral heritage, enabling both qualitative and quantitative analyses as well as data correlation across multiple sites. The resulting datasets are intended for research use, Open Access dissemination, and public engagement (Liu, Hindmarch and Hess, 2023). This corpus encompasses not only gravestone inscriptions but also architectural and decorative features within their topographic landscape context, including information on stone types, damage patterns, and long-term observations of changes resulting from climatic factors or other human and environmental interactions. (Talabardon and Hess, 2025)

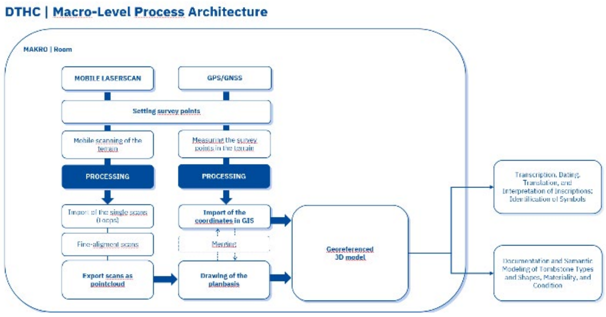

Figure 2. Macro-Level process architecture and workflow integrating mobile laser scanning and GPS/GNSS

4.1 Multi-Scale 3D-Imaging Workflows

To achieve this, we developed a metrology-guided 3D imaging approach with multiple workflows tailored to diverse data types at different scales, which we classify as macro, meso, and micro levels. The macro scale (Figure 2) captures cemetery layouts and topography, the meso scale focuses on groups of gravestones and their spatial relations, and the micro scale documents individual gravestone geometry and inscriptions. These workflows are currently being refined and are intended for routine application across multiple sites (Puglisi and Hess, 2025).

For data acquisition, the project employs high-resolution terrestrial and mobile laser scanning (TLS, MLS, Figure 3), structured-light or close-range 3D scanning, and GNSS-based georeferencing (Figure 4) and close-range photogrammetry (Figure 5). These techniques allow the capture of cemetery layouts, gravestone geometries, and surface inscriptions with sub-millimetric accuracy. While alternative methods such as drones (both LiDAR and SfM) or tachymetric surveying were tested, they proved either insufficiently metric or less reliable for the high-precision documentation required for inscriptions of upward standing gravestone.

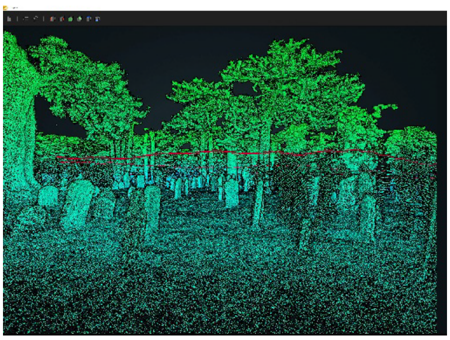

Figure 3. Image of 3D mobile laser scanning in operation, Jewish Cemetery Walsdorf in Franconia, Germany.

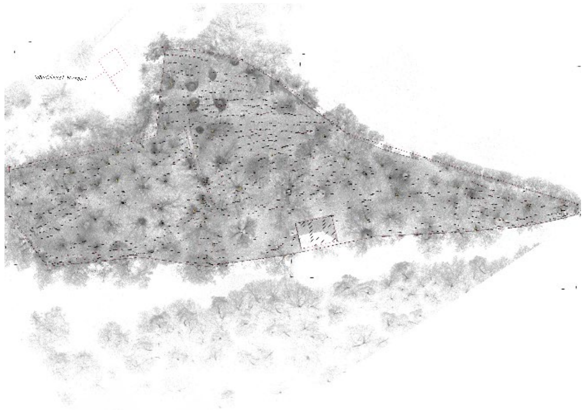

Figure 4. Extraction of a plan from 3D mobile laser scanning from the topographic terrain model with gravestones for an accurate representation of topography and spatial arrangement of gravestones, Jewish Cemetery Walsdorf.

4.2 Semantic Annotation and Data Integration

After acquisition, the datasets are semantically annotated in the *MonArch* data management environment using controlled vocabularies and OWL-based ontologies, (Stenzer, Woller and Freitag, 2011) and (Arera-Rütenik, 2018). This ensures interoperability and enables cross-disciplinary analyses that integrate spatial, material, and textual data. Preparing the datasets for *MonArch* involves standardizing metadata, harmonizing grave identifiers, and verifying geometries, ensuring that the datasets are fully queryable and reusable.

The resulting semantic 3D models do more than reconstruct geometric and morphological relations among gravestones; they also integrate epigraphic and archival information, aiming to create a sustainable "digital twin" of endangered cemeteries. Such digital twins support 4D monitoring of conservation states, allow comparative analyses across sites, and provide a framework for research in architecture, history, and digital heritage.

4.3 First Results and Observations

Initial fieldwork and data processing have produced several preliminary outputs:

- Gravestone counts and inventories per cemetery.
- Topographic and locational groupings, enabling analysis of spatial distribution patterns.
- Documentation of damage and weathering on individual stones.
- Plans and preliminary 3D models for Bayerisches Landesamt für Denkmalpflege (BLfD).

The combination of TLS, MLS, and close-range photogrammetry, alongside GIS integration, has proven sufficient to generate metric, semantically annotated datasets, while avoiding the limitations of less precise techniques. These first results confirm the feasibility and transferability of the workflows and highlight the value of integrating multi-scale geometric data with semantic and archival information to create dynamic, analysable digital representations of Jewish sepulchral landscapes (Puglisi and Hess, 2025).

Figure 5. Textured and untextured 3D model of a gravestone from photogrammetry to enable better reading of Hebrew text and inspection of architectural forms, Jewish Cemetery Walsdorf.

4.4 Research Questions and Workflow Refinement

To refine the workflows, several key research questions are being explored:

- Automatic segmentation and classification: Can multi-scale point clouds be automatically segmented and linked to the semantic database, reducing manual processing?
- AI-driven architectural interpretation: Can AI identify and classify gravestone decorative and architectural features across sites and periods?
- AI-assisted epigraphy: Can machine learning reliably extract Hebrew inscriptions, even on damaged, weathered, or overgrown stones?

While the project produces information-rich, semantically annotated 3D models—a “digital shadow” of the cemeteries—the feasibility of real-time updates for monitoring environmental or human-induced changes remains an open question.

Through iterative trials over the first five years, including changes in sensors and acquisition methods (Pavlovskis *et al.*, 2020), it has become clear that long-term sustainability is a major challenge in this 24-year project. Careful metadata planning and structured data management are essential to ensure datasets remain interpretable and reusable for future researchers.

Finally, balancing interdisciplinary goals across heritage science, digital humanities, and epigraphy continues to shape the project’s scope and workflow refinement. These reflections inform both the practical implementation and long-term value of the digital documentation approach (Figure 6).

Figure 6. Collaborative work for the interpretation of text and symbols on a gravestone, alongside the digital model.

5. CHALLENGES

The development of the project workflows follows an agile and iterative approach, allowing methodological steps to be continuously refined in response to practical experience in the field and interdisciplinary feedback. Rather than applying a fixed, linear workflow, data acquisition, processing, semantic enrichment, and evaluation are repeatedly tested and adapted across different case studies. This approach is essential given the heterogeneity of cemetery sites, historical sources, and disciplinary requirements.

Several recurring challenges were identified during the initial project phases. One major issue concerns the source situation, particularly the existence of inconsistent or historical numbering systems for graves and monuments across archival records, cemetery plans, and on-site markings. Achieving internal consistency and traceability therefore requires the development of harmonization strategies and cross-referencing schemes rather than simple standardization.

Environmental conditions also pose significant challenges. Weather, seasonal vegetation, and lighting conditions directly affect data acquisition, especially for photogrammetric and UAV-based surveys. Dense vegetation, limited accessibility, and restricted working windows complicate comprehensive coverage. Additionally, fallen or fragmented gravestones require adapted documentation strategies, as they often no longer reflect their original spatial context and may exist only as partial objects.

Equally important are ethical and behavioural considerations. All fieldwork is conducted in accordance with a strict code of conduct for work in cemeteries, respecting religious traditions, the dignity of the site, and local community expectations. These considerations influence not only field practices but also decisions regarding data publication and visualization.

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5.1 Data Publication, Access, and Sustainability

Data publication and access represent a central strategic component of the project. Given the rapid pace of technological renewal, particular emphasis is placed on sustainable data formats, modular system architectures, and documentation that allows future reuse and reinterpretation.

The project follows an open access principle wherever legally and ethically possible, while acknowledging disciplinary differences in publication cultures, especially between international journal-based research and German-language book chapters or edited volumes. Dissemination strategies therefore include open access publications, curated digital platforms, and targeted disciplinary outputs.

A core element of data access is the development of a web-based interface, building on systems such as *MonArch,* which allows differentiated access to spatial, geometric, and semantic information. This raises fundamental questions regarding data granularity: whether a lean, publicly accessible version of the data should be provided, whether full-resolution raw data should be accessible to all users, and how different user groups (researchers, heritage institutions, the public) can be addressed appropriately.

5.2 Copyright, Stakeholders, and Governance

All data handling and dissemination activities are governed by copyright regulations and stakeholder agreements, including contractual arrangements between the project partners and the responsible academic institutions. These agreements define ownership, usage rights, and responsibilities and are essential to balancing openness with legal and ethical obligations.

5.3 Interpretation, Evidence, and Expectations

The project explicitly addresses the tension between qualitative interpretation and quantitative, metric evidence. While high-resolution spatial data enable numerical analysis and reproducibility, historical and cultural interpretation remains essential and cannot be reduced to measurable parameters alone. Managing expectations—both within the academic community and among external stakeholders—is therefore a critical task.

A clear delimitation of project scope is necessary. The project is not a hands-on conservation or restoration initiative, nor a commercial surveying undertaking. It does not replace monument preservation measures, which are often constrained by time, funding, and legal responsibilities. Instead, it provides digital documentation and analytical frameworks that can inform, support, and potentially catalyse conservation and heritage management activities.

5.4 Added Value and Consequences

The added value of the project lies in its ability to create a sustainable, semantically enriched digital record of Jewish sepulchral heritage that is at risk of deterioration and eventual disappearance and would otherwise remain inaccessible. By making spatial, formal, and epigraphic data systematically available, the project contributes to long-term research, education, and heritage awareness. While digital documentation alone cannot change the physical condition of cemeteries, it can fundamentally alter the knowledge base, visibility, and decision-making context surrounding them, thereby enabling informed future actions beyond the project's immediate temporal and financial scope.

6. CONCLUSION

Ultimately, the primary scope of this project is to develop practical, robust, and transferable workflows for the documentation and analysis of cemeteries and sepulchral contexts. These workflows are designed not only for the specific case studies within this project but are also intended to be applicable and adaptable to other sites, enabling the systematic collection of high-quality data across diverse heritage contexts.
A key objective is to integrate advanced sensing technologies—including UAVs, terrestrial laser scanning and mobile laser scanning - with semantic web standards and structured metadata, ensuring that the resulting datasets are interoperable, machine-readable, and suitable for long-term reuse.
Moreover, the project emphasizes the creation of informative Open Access outputs, making high-resolution, semantically enriched data accessible to researchers, heritage professionals, and the wider public, thereby enhancing transparency, scholarly exchange, and educational outreach.

The project "Stone Witnesses Digital" aims to demonstrate the potential of digital twins as analytical, interpretative, and communicative tools in heritage research. By transforming conventional static documentation into dynamic, interconnected, and intelligent datasets, digital twins enable new modes of exploration, comparison, and visualization.

This approach not only preserves Jewish sepulchral heritage in its spatial, formal, and textual dimensions but also allows it to be reinterpreted within broader frameworks, including digital humanities, heritage science, and Jewish studies. In doing so, the project establishes a model for the systematic integration of technological innovation, semantic enrichment, and scholarly interpretation, illustrating how digital approaches can enrich both the documentation and the analytical potential of cultural heritage assets.

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