The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-M-9-2025
30th CIPA Symposium “Heritage Conservation from Bits:
From Digital Documentation to Data-driven Heritage Conservation”, 25–29 August 2025, Seoul, Republic of Korea

D-TECH: An Open-Source Platform for Heritage Data Sharing and Collaborative Work

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Keywords: Heritage Data Sharing, Digital Twin, 3D Visualization, Semantic Ontology, Collaborative Platform, Augmented & Virtual Reality.

Abstract

This paper presents D-TECH, an open-source platform designed to support the documentation, visualization, and collaborative management of cultural heritage assets through a distributed, modular, and semantically driven environment. Developed under the D-TECH project and funded by the DTC Lazio initiative, the platform incorporates state-of-the-art technologies for 3D acquisition, Augmented Reality (AR), Virtual Reality (VR), and Geographic Information Systems (GIS), and ensures semantic interoperability aligned with ARCO standards. D-TECH addresses critical institutional challenges in the management and reuse of 3D heritage data, providing tools for storage, visualization, and sharing within a modular and federated environment. This platform enables public institutions to manage their digital assets in-house, ensuring full control, visualization, annotation, and dissemination through a federated network of nodes. The paper details the software architecture, data workflows, 3D visualization tools, and use scenarios, highlighting its role in facilitating collaborative heritage work and unlocking the potential of existing 3D data archives.

1. Introduction

In recent years, the digitization of cultural heritage has become a strategic priority for museums, conservation authorities, research institutions, and public administrations. Advances in technologies such as laser scanning, photogrammetry, AR/VR visualization, and spatial data infrastructures have enabled the creation of high-resolution digital twins of monuments, sites, and artifacts. These tools have transformed how heritage is documented, studied, and accessed by diverse user groups. Digital three-dimensional models, in particular, provide an essential contribution to the safeguarding and transmission of material heritage, enabling the preservation and accessibility of assets even in situations of risk, degradation, or limited access. Furthermore, digital twins allow for the reconstruction of museum environments and precise monitoring of the conservation status of artworks, facilitating the implementation of preventive maintenance strategies and integrated management (Mongelli, 2020). However, while the capacity to produce 3D data has grown significantly, the infrastructures for managing, sharing, and reusing these datasets remain fragmented and insufficiently developed.

The D-TECH project (Digital-Twin Environment for Cultural Heritage) was conceived to address this gap. Funded by the DTC Lazio and coordinated by Roma Tre University, D-TECH provides an open-source, modular, and federated digital platform designed as both a repository and an interactive environment for heritage data. Beyond simple storage, D-TECH serves as a flexible and scalable ecosystem, empowering institutions to autonomously manage their digital resources while benefiting from interoperability, semantic integration, and collaborative functionalities.

A key driver for D-TECH is its response to a widespread structural issue: both in Italy and internationally, public administrations often commission extensive 3D surveys of cultural assets but lack the necessary infrastructures or expertise to use and disseminate the resulting data effectively. As a consequence, publicly funded digital documentation often remains inaccessible, disconnected from research, conservation, and education processes. D-TECH addresses this challenge by enabling each institution to host its own platform node, maintaining full in-house control over the data lifecycle, from ingestion and archival to semantic enrichment, visualization, and selective sharing.

In comparison to the many existing Digital Twin platforms, the one proposed by the D-TECH project is not conceived as the result of the digitization of a specific collection of cultural assets. On the contrary, it positions itself as an open environment — a digital ecosystem designed to be progressively populated over time with data provided by all cultural heritage managers who wish to adopt the platform and contribute to the ongoing updating and enrichment of their respective assets.

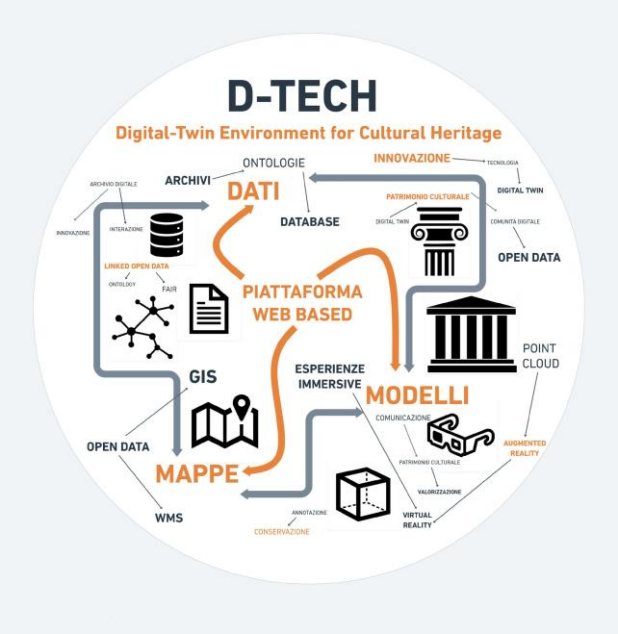

Figure 1. D-TECH infographic.

Technologically, D-TECH adopts a microservices architecture allowing modular deployment via containerized solutions like Docker. Each node can be customized and extended independently, adapting to institutional needs. Semantic structuring based on ARCO standards, combined with compatibility with Linked Open Data (LOD) frameworks, ensures dataset interoperability within the broader digital heritage ecosystem.

In addition to 3D model management and metadata curation, D-TECH integrates immersive visualization tools, including real-time AR/VR interfaces, multiresolution streaming, and collaborative annotation features—all accessible via an intuitive web interface designed for both specialists and the general public. The platform's tools and services (including 3D visualization and editing, AR, and VR) prove valuable in supporting the full production cycle of cultural content — the so-called "value chain" — by facilitating processes of knowledge development, diagnostics, conservation, and restoration. Moreover, D-TECH assists cultural heritage professionals in enabling access to digitized content for scholars and promoting the value of these resources through online dissemination of 3D models, meshes, point clouds, and multimedia content aimed at broadening the cultural offer for the general public.

This paper presents the conceptual framework, software architecture, and user scenarios of D-TECH, demonstrating its role in promoting a sustainable, collaborative, and inclusive future for digital cultural heritage management.

2. Methodology

As mentioned previously, the platform is built around a microservices architecture that facilitates modularity, deployment flexibility, and the integration of heterogeneous tools and data types. This approach allows for distributed development and institutional autonomy, while ensuring semantic and functional consistency across the entire system.
The methodology is structured into four primary architectural layers:

- Data Acquisition and Ingestion Layer
- Semantic Structuring and Knowledge Modeling Layer
- Visualization and Interaction Layer
- Service Orchestration and Collaboration Layer

2.1 Data Acquisition and Ingestion Layer

This layer is responsible for the structured intake of cultural heritage data. It supports the ingestion of various formats—ranging from textual descriptions, bibliographic records, and photographs to high-resolution 3D meshes, point clouds, and diagnostic reports. A suite of standardized data-entry forms is used to ensure consistency across datasets, based on categories aligned with the ARCO ontology (Architecture of Cultural Objects). These forms link each asset to metadata concerning typology, chronology, provenance, legal status, condition, survey method, and associated documentation. The platform aligns with the principles of data management planning (Bocconcino et al., 2023), ensuring that all digital heritage assets comply with FAIR guidelines and that their lifecycle is documented within an explicit DMP framework

2.2 Semantic Structuring and Knowledge Modeling Layer

Once data is ingested, it is semantically enriched through alignment with ontological models that structure relationships among people, institutions, places, objects, and documentation. The D-TECH platform leverages the ARCO ontology and its supporting modules (e.g., cultural event, conservation intervention, digitization activity) to represent the full lifecycle of heritage assets. This semantic backbone allows complex queries across time, space, and institutional domains, and enables integration with Linked Open Data (LOD).

2.3 Visualization and Interaction Layer

D-TECH incorporates a range of open-source visualization engines to enable user interaction with heritage datasets. These include 3DHOP for browser-based multiresolution 3D mesh visualization (Potenziani, M. et al. 2015), and ATON (Fanini, B. et al. 2021) for both 3D mesh visualization and immersive AR/VR environments via WebXR. All engines are accessible through a unified web interface, with responsive layouts optimized for desktop and mobile use. Interaction features include object-level metadata overlays, semantic annotations, spatial filtering, comparative views, and timeline-based visualizations. This layer also supports accessibility features, including language localization and assistive browsing modes.

2.4 Service Orchestration and Collaboration Layer

The final layer manages platform logic, user roles, collaborative workflows, and data access policies. It includes modules for user authentication, permissions management, project-based collaboration, annotation versioning, and content export. Importantly, it allows each institutional node to define its own visibility rules for datasets, supporting both open-access and restricted-use models. Through this orchestration layer, D-TECH promotes the secure and ethical sharing of cultural data, while also enabling distributed curation, collaborative research, and multi-user content generation.

This methodology ensures that D-TECH is not only a technical platform, but also a framework for digital sustainability, enabling institutions to autonomously manage their assets while participating in a shared, semantically coherent infrastructure. The layered structure is designed to evolve over time, supporting integration with emerging technologies such as AI-based feature detection, predictive maintenance analytics, and automated heritage risk assessments.

3. D-Tech Platform

The D-TECH platform was designed as a flexible, modular, and semantically enriched environment capable of supporting the complete digital lifecycle of cultural heritage data. The architecture is built around principles of decentralization, institutional autonomy, and sustainability, enabling individual institutions to host, visualize, and manage their heritage datasets while remaining fully interoperable within a larger, federated ecosystem. This section outlines the core functionalities and services provided by the platform, organized into four operational components: storage and ingestion, 3D model management, data enrichment, and immersive visualization.

3.1 Spatial Data Collection and Storage

One of the defining features of D-TECH is its flexible approach to storage architecture, which accommodates the diverse needs and technical capacities of cultural institutions. At present, the platform is configured to allow storage of 3D models and related assets directly within the servers of the institution that commissioned or owns the digital documentation. This strategy ensures that the intellectual ownership and operational control of

sensitive data remain firmly within the domain of the public body or heritage custodian. Institutions maintain full access to the raw and processed data, avoiding dependency on third-party platforms or proprietary systems.

However, the system is designed to be cloud-compatible and modular, supporting future integration with external storage infrastructures, including public or private cloud services and distributed object storage systems. This separation of the data layer (storage) from the visualization and management interface opens new scenarios for scalable deployments. For example, lighter nodes of the platform could rely on a centralized high-performance storage hub, while preserving local customization and access control. Conversely, large institutions with extensive archives could opt for hybrid solutions, combining local backups with cloud redundancy.

The ingestion process is structured through a standardized interface that enables the import of multiple data types: 3D models (in formats such as OBJ, glTF, E57, LAS), point clouds, orthophotos, panoramic imagery, high-resolution photography, diagnostic reports, and metadata documents. The platform supports the creation of relationships between digital assets and their analog counterparts, allowing each digital twin to be connected to its physical reference and historical documentation. Every object ingested is tracked with provenance metadata, including the method of acquisition, the team responsible, the purpose of the survey, and the associated project or funding source.

3.2 3D Model Management and Interaction

Once stored and indexed, 3D models can be visualized, explored, and managed through an integrated interface that includes various open-source rendering engines. The system allows institutions to upload, organize, annotate, and curate large collections of 3D data without the need for specialized technical staff or complex installations.

The platform integrates a range of visualization engines, including 3DHOP and ATON, enabling web-based 3D rendering, immersive AR/VR navigation, and interactive model annotation, as detailed in the visualization layer description.

Each model can be tagged with metadata, segmented into components, annotated with comments and links, and cross-referenced with other database entities (e.g., events, people, or locations). This allows users not only to view models in high detail, but to embed them in semantic workflows such as restoration planning, phase analysis, or condition monitoring. The interface supports comparison of different acquisition phases, enabling heritage professionals to document transformations and degradation over time (temporal "4D" visualization).

3.3 Assets, Metadata, and Ontology-Based Structuring

A core strength of D-TECH lies in its use of a semantic data layer built around the ARCO ontology. Each asset—whether a 3D model, image, or document—is embedded within the knowledge graph, which encodes its relationships to places, historical contexts, institutions, and people. In the next future this allows for advanced querying, semantic browsing, and linked open data interoperability.

The metadata forms follow a modular design inspired by international standards such as CIDOC CRM, Dublin Core, and the Europeana Data Model, but specifically tailored to the Italian national context through the ARCO framework.

The metadata fields managed by the platform are structured according to the ARCO ontology and are distributed across four interconnected databases: individuals, organizations, cultural assets, and digital copies. For cultural assets, fields include the cultural entity type (e.g., standalone asset, part of a larger asset, or derivative work), classification as movable or immovable heritage, and typology (archaeological, architectural/landscape, historical/artistic). Detailed descriptors also capture ownership, institutional responsibilities, catalog identifiers, geographic coordinates, institutional affiliations, and preview imagery.

For digital copies, the platform records the type of file (basic or advanced model), 3D data format (point cloud or mesh), acquisition context, original purpose of the investigation and the digital copy, licensing regime (Creative Commons options), data operator, scientific lead, commissioning body, acquisition date, presence of texture and colour data, and technical characteristics such as file format (PLY or glTF). These fields allow comprehensive classification, versioning, and contextualization of the digital representation of heritage objects.

Although not yet implemented, the development roadmap includes the potential integration of a semantic backbone based on RDF triples and SPARQL query capabilities. This potential extension would pave the way for cross-domain research and facilitate automated metadata enrichment through AI-driven tools for entity recognition, multilingual tagging, and semantic inference.

3.4 4D Visualization and Immersive Environments (AR/VR)

Leveraging engines like ATON, D-TECH offers immersive AR/VR capabilities directly via web browsers, allowing users to explore digital twins in augmented and virtual environments, with functionalities already detailed in the visualization layer.

The visualization layer builds upon state-of-the-art approaches for 3D and 4D web-based visualization of cultural heritage, similar to solutions adopted in projects like METEORA (Ioannidis et al., 2020), which pioneered LoD management and web AR visualization for complex heritage landscapes. In augmented reality, users can overlay 3D models onto real-world scenes using smartphone cameras or AR headsets. This functionality is particularly effective not only for storytelling and visitor engagement —such as visualizing architectural reconstructions, missing elements, or the chronological evolution of a monument— but also for on-site technical discussions. Viewing the object at 1:1 scale, heritage professionals can collaboratively evaluate conservation strategies, interpret structural features, or simulate potential restoration scenarios directly in the spatial context of the monument.

In virtual reality, users can enter fully reconstructed environments, navigating freely and interacting with rich contextual media. Beyond its value for education and public outreach, VR also becomes a remote meeting space where professionals can share the same model in a real-time virtual session, examining it from multiple angles and discussing its features collaboratively, as though gathered in the same physical room. This facilitates interdisciplinary dialogue, decision-making, and long-distance review sessions across institutional boundaries.

To complement the immersive experience, D-TECH includes tools for:

- curating narrative paths through annotated 3D environments;
- integrating multilingual voiceovers, subtitles, and infographics;
- logging user interaction for educational or scientific analysis;
- and exporting immersive content to digital exhibitions, interactive websites, or e-learning platforms.

These services are particularly valuable for public outreach, digital tourism, and museum education, but also support technical collaboration and research. Importantly, all AR/VR content is dynamically linked to the platform’s semantic backend, ensuring that immersive experiences are not only visually engaging but also epistemologically grounded and data-driven, fostering a comprehensive and informed understanding of cultural heritage assets.

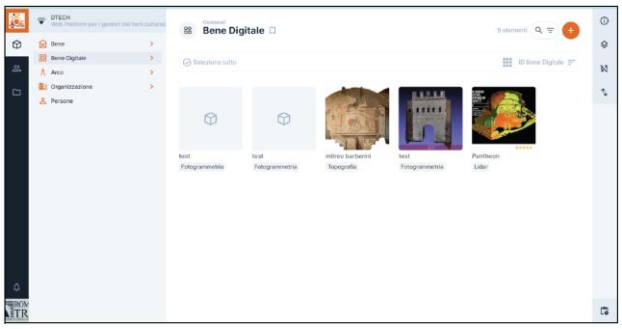

Figure 2. D-TECH platform landing page.

4. User Scenarios

4.1 Cultural Expert Use: Documentation, Maintenance, and Protection of Heritage Assets

The D-TECH platform was conceived first and foremost for the managers of cultural heritage assets—museums, superintendencies, regional authorities, and other public bodies responsible for documentation, protection, conservation, and enhancement. These institutions face increasing pressure to not only safeguard physical heritage but also manage its digital transformation, including the storage, structuring, and reuse of 3D data.

D-TECH provides an operational environment that supports:

- Progressive documentation updates, linking technical conservation records to 3D assets;
- Monitoring of the state of conservation, including condition reports over time;
- Risk and emergency management;
- Informed decision-making, through comparative analysis of models and versions;
- Remote collaboration, allowing multidisciplinary teams to inspect, annotate, and discuss the same digital twin synchronously, using AR/VR environments.

Each heritage authority can deploy its own autonomous instance of the platform, ensuring digital sovereignty: data does not need to be transferred to external providers. This “node-based” architecture allows for the internal management of heritage models, fully under the institution’s control. The adoption of a Master Data Management (MDM) logic, as discussed by Spettu in the Sacri Monti case (Spettu et al. 2024), also informs the structuring of D-TECH’s data versioning and institutional control mechanisms. Following methodologies adopted for heritage at risk platforms (Raco, 2022), D-TECH incorporates historical evolution visualizations, and tools to support risk assessment and disaster management strategies.

4.2 Scientific Use: Cross-Disciplinary Research and Education

The platform provides advanced functionalities that support scholars across a wide spectrum of disciplines—architecture, archaeology, art history, engineering, digital humanities, and more.

- Architects and archaeologists can inspect textured 3D models, perform comparative typological studies, annotate layers of construction, and access stratigraphic interpretations.
- Engineers and conservation scientists can work with metric point clouds or polygonal meshes for structural simulations, deformation tracking, or environmental monitoring.
- Historians and curators can enrich 3D objects with archival documents, iconographic parallels, or narrative timelines.
- Educators and academic institutions can design didactic modules, interactive lectures, and immersive research environments, integrating storytelling and multilingual accessibility.

The platform's semantic framework allows the creation of structured queries across assets using filters such as historical period, material, function, or geographic distribution. This makes D-TECH a powerful tool for cross-domain research, facilitating novel insights and thematic aggregations not possible in traditional catalogue systems.

4.3 Business Use: Enabling Innovation in Cultural Services

While D-TECH is primarily designed to serve cultural heritage institutions and research communities, it also offers the potential to foster innovation in the creative and cultural industries, should public administrations choose to make specific datasets accessible for external use. If and when a public institution decides to share 3D models or other digital heritage assets, the platform can support controlled, ethical, and institutionally governed collaboration with third parties, such as tourism operators, digital content creators, or technology providers.
In this scenario, creative industries could leverage the availability of shared datasets to develop value-added services that enhance public engagement and cultural dissemination (Canciani and Saccone, 2020).

Possible applications include:

- Embedding interactive 3D content, narrative timelines, or annotated models into institutional websites, mobile apps, or digital visitor guides;
- Developing AR-based interpretative routes and location-based storytelling for on-site smart tourism experiences;
- Creating serious games, virtual reconstructions, or mixed reality narratives grounded in authentic and institutionally validated datasets;
- Designing immersive installations, exhibitions, or interactive showcases for museums, fairs, expos, and public cultural events.

Any such external use would be subject to institutionally defined access policies and licensing agreements, ensuring that data integrity, ownership, and cultural responsibilities remain with the public institution. Creative content generated by third parties could, in turn, be reintegrated within the D-TECH platform, expanding the digital ecosystem around the heritage asset and enriching the narrative and educational resources available to users.

This open but controlled model of data sharing is fully aligned with European frameworks on open access and digital cultural reuse, promoting responsible innovation while safeguarding cultural heritage protection, data security, and institutional autonomy.

4.4 Cultural Heritage Valorization: Enhancing Visitor Experience

Finally, D-TECH supports audience engagement and heritage valorisation before, during, and after the visit, creating a continuous digital relationship with cultural sites. In terms of public outreach and digital storytelling, D-TECH takes inspiration from international initiatives like UNESCO’s Dive into Heritage platform (Vileikis et al., 2023), focusing on user-centered narrative paths and multi-device accessibility.

Before the visit, users can explore virtual tours, preview exhibitions, or reconstruct ancient architectures through historical phases. Interactive filters allow for customized itinerary planning, increasing cultural awareness and motivation to visit lesser-known heritage.

During the visit, the platform powers augmented reality features through mobile devices. By pointing their phones at monuments or artworks, visitors can access overlaid reconstructions, audio-visual guides, and contextual layers—transforming the site into a living narrative.

After the visit, users can revisit content from home, share curated experiences, or dive deeper into educational layers. The platform supports a model of “augmented tourism”, extending access to remote, damaged, or closed heritage sites, and promoting inclusive cultural participation.

This multi-layered approach to public engagement reflects the broader mission of D-TECH: to ensure that cultural heritage, once digitized, is not only preserved—but also activated, interpreted, and made meaningful for all.

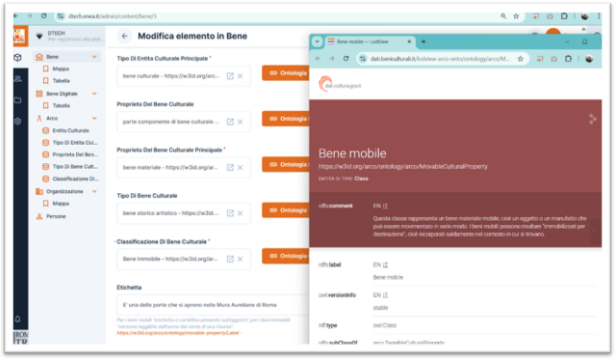

Figure 3. Metadata aligned with the ARCO ontology using standardized vocabulary.

5. Conclusions and Future Work

D-TECH offers a comprehensive and modular digital ecosystem for managing, sharing, and enhancing cultural heritage data through a combination of open-source technologies, semantic modelling, and immersive visualization tools. It addresses a well-recognized structural gap in the heritage sector: the growing disconnection between the increasing number of commissioned 3D documentation campaigns and the limited institutional capacity to store, manage, and reuse the resulting data in a meaningful way.

By enabling institutions to host and manage data independently within a federated network, D-TECH actively prevents the marginalization of valuable documentation assets and promotes data reuse across disciplines and audiences. Its node-based architecture ensures that each institution maintains sovereignty over its datasets while remaining interconnected within a larger semantic infrastructure. Its semantic alignment with ARCO standards guarantees data consistency, interoperability, and long-term sustainability.

Looking ahead, several key development directions have been identified to further enhance D-TECH’s capabilities and strategic relevance. A significant potential evolution involves the implementation of a semantic backbone based on RDF triples stored in a SPARQL-compliant triplestore. This would allow for cross-institutional queries, enabling users to retrieve, aggregate, and analyse data across different nodes and external heritage repositories. Such an enhancement would facilitate alignment with international linked data resources like Wikidata, GeoNames, Europeana, and ICCROM, laying the foundation for cross-domain research, semantic reasoning, and automated metadata enrichment through AI-based tools. This semantic layer would also support multilingual metadata management and the generation of contextual knowledge graphs, broadening the scope of heritage data interoperability.

Another important area for future development concerns the integration of optimized 3D viewers tailored to specific data types. D-TECH plans to incorporate a dedicated BIM viewer for managing complex architectural models in IFC format, enabling users to explore geometric, material, and parametric information within the platform. Building on recent experiences of BIM-GIS integration for cultural heritage maintenance like the MAIN10ANCE project (Colucci et al., 2023), D-TECH plans to introduce dedicated viewers and data layers for planned conservation workflows. In parallel, an advanced point cloud viewer will be introduced, offering multi-scale rendering, classification tools, and interactive analysis of high-density 3D survey data. These new viewers will complement existing tools like 3DHOP and ATON, providing users with a specialized interface for handling both building information models and large-scale spatial datasets.

Given the current efforts by the Italian Ministry of Culture to develop national-level services for 3D data storage, D-TECH will evolve to ensure full compatibility and integration with such external infrastructures. This will allow institutions to separate the storage layer from the visualization and management interface, adopting a hybrid architecture where metadata and interactive tools remain hosted on D-TECH nodes, while raw 3D data can reside on national or cloud-based storage services. This approach will align with emerging national strategies for the centralized preservation of cultural heritage digital assets, offering scalability, resilience, and compliance with public data governance frameworks.

Finally, future work includes the implementation of API and framework modules that will allow heritage managers and public bodies to embed D-TECH content directly into their institutional websites. This functionality will enable external portals to dynamically retrieve and display 3D models, semantic metadata, and AR/VR experiences developed within D-TECH. By exposing specific datasets or curated content through customizable endpoints, institutions can offer direct access to their digital heritage resources, enhancing visibility, public engagement, and educational outreach while maintaining full control over data dissemination policies.

Through these future developments, D-TECH aims to reinforce its role as a strategic enabler for digital transformation in the heritage sector, ensuring that investments in 3D documentation translate into sustainable, accessible, and interoperable knowledge resources. By combining technological innovation, semantic rigor, and institutional empowerment, D-TECH is well-positioned to support the next generation of cultural heritage management practices.

Acknowledgements

DTECH Research group:

- Marco Canciani, Project Coordinator, Department of Architecture, Roma Tre University
- Giovanna Spadafora, Deputy Project Coordinator, Department of Architecture, Roma Tre University
- Carla Masetti, Department of Humanities
  Marialuisa Mongelli, ENEA, Division for Systems Development for IT and ICT (DTE-ICT)
- Mauro Saccone, research fellow on contract, Department of Architecture, Roma Tre University
- Marco Puccini, research fellow on contract, ENEA

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