A²I: A Cognitive Intelligence Framework for Archaeological Digital Twins

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***Abstract*— The increasing adoption of Digital Twins, Artificial Intelligence, semantic technologies, and immersive environments is transforming archaeological research and cultural heritage management. However, most AI applications in archaeology remain focused on isolated tasks such as artefact classification, image analysis, predictive modelling, and digital documentation. This paper introduces Artificial Archaeological Intelligence (A²I), a novel framework that conceptualizes archaeological intelligence as a collective phenomenon emerging from the interaction among human experts, archaeological evidence, knowledge graphs, Digital Twins, intelligent agents, and Large Language Models. Rather than automating interpretation, A²I aims to create cognitive ecosystems that support the continuous generation, validation, and evolution of archaeological knowledge. The proposed framework is applied to the House of Apollo Citharist in Pompeii, where archaeological data, historical sources, semantic representations, and AI services are integrated into a unified Digital Twin environment. Within this perspective, the Digital Twin evolves from a geometric model into an intelligent knowledge space capable of supporting contextual interpretation, conservation, and public engagement. To validate the proposed approach, the reconstructed house is made accessible through a Pocket Archaeological Metaverse, enabling immersive Augmented Reality experiences directly on standard smartphones. The paper argues that A²I represents a shift from digital archaeology toward cognitive archaeology, where archaeological sites become living knowledge environments supporting both scholarly research and visitor experience.**

Keywords*— *Artificial Archaeological Intelligence, Digital Twin, Cultural Heritage, Knowledge Graphs, Large Language Models, Pompeii, Apollo Citharist, Archaeological Reasoning

I. INTRODUCTION

Archaeology has always been a discipline centred on interpretation. Archaeological knowledge does not emerge directly from artefacts, structures, inscriptions, or excavation records. Rather, it is generated through the continuous interpretation of fragmented evidence within broader historical, cultural, social, environmental, and spatial contexts. During the last two decades, digital technologies have profoundly transformed archaeological practice. Laser scanning, photogrammetry, Building Information Modelling, Geographic Information Systems, Internet of Things infrastructures, Digital Twins, Artificial Intelligence, and immersive environments have dramatically increased both the quantity and complexity of available information [1][2][3]. Nevertheless, the production of archaeological knowledge remains fundamentally dependent on human expertise. Existing Artificial Intelligence applications primarily address narrowly defined tasks, including image analysis, object recognition, predictive modelling, or information retrieval. While these approaches have demonstrated significant value, they rarely address the central challenge of archaeology: contextual interpretation. The discovery and interpretation of the statue of Apollo Citharist of Pompeii (R.I.4.5) provides a paradigmatic example. Since its discovery in 1853, the statue has generated more questions than answers. Scholars have debated its chronology, artistic lineage, original appearance, symbolic meaning, and relationship with the surrounding architectural space. Recent studies suggest that understanding the statue requires simultaneously considering archaeological context, domestic cult practices, Roman cultural ideology, Greek artistic traditions, historical documentation, and centuries of scholarly interpretation. Such complexity cannot be represented adequately through conventional databases or isolated Artificial Intelligence systems. This observation motivates the introduction of Artificial Archaeological Intelligence (A²I), a framework designed to transform archaeological sites into collective cognitive ecosystems where archaeological knowledge and reasoning emerge from the continuous interaction among human expertise, archaeological evidence, semantic knowledge structures, and intelligent computational systems. Artificial Archaeological Intelligence is based on a simple assumption: Archaeological intelligence is not located within a single individual, dataset, algorithm, or technological platform. It emerges from the continuous interaction among humans, data, knowledge structures, digital representations, and intelligent computational systems. Within A²I, archaeological sites are conceived as living knowledge ecosystems composed of six interconnected dimensions:

- Physical archaeological evidence;
- Historical and documentary sources;
- Semantic knowledge structures;
- Digital Twin representations;
- Artificial Intelligence agents;
- Human expertise.

The objective is not to replace archaeologists with intelligent systems but to create environments where collective archaeological reasoning can emerge and evolve.

II. THE A²I ARCHITECTURE

The architecture consists of seven interconnected layers..

2.1 Data Acquisition Layer

This layer collects heterogeneous information from:

- archaeological excavations;
- historical archives;
- laser scanning campaigns;
- photogrammetric surveys;
- drone inspections;
- environmental monitoring systems;
- conservation records;
- visitor interaction data;
- geospatial repositories.

Together these components form the sensory infrastructure of the archaeological ecosystem.

2.2 Archaeological Data Lake Layer

The Archaeological Data Lake Layer provides the data foundation of the A²I ecosystem. It integrates heterogeneous archaeological resources, including excavation records, historical archives, photogrammetric surveys, laser scanner acquisitions, geospatial datasets, conservation reports, environmental monitoring data, and multimedia content. The layer supports interoperability, metadata management, provenance tracking, and FAIR-compliant principles, ensuring the long-term accessibility and reuse of archaeological information. Acting as a federated repository, the Data Lake enables the integration of datasets generated by different disciplines and institutions, providing the basis for semantic modelling, Digital Twin generation, and AI-driven services.

2.3 Semantic Knowledge Layer

At the core of A²I lies a semantic infrastructure based on ontologies and knowledge graphs. Buildings, rooms, artefacts, inscriptions, stratigraphic units, historical periods, materials, restoration interventions, environmental variables, and conservation states are represented as interconnected semantic entities. The knowledge graph acts as the collective memory of the ecosystem, preserving provenance information, evidential relationships, uncertainty levels, expert annotations, and alternative interpretations.

2.4 Multi-Agent Intelligence Layer

Specialized AI agents contribute domain-specific expertise. Examples include
:

- Artefact Analysis Agent;
- Epigraphy Agent;
- Remote Sensing Agent;
- Conservation Agent;
- Structural Monitoring Agent;
- Environmental Risk Agent;
- Historical Reconstruction Agent;
- Visitor Behaviour Agent.

The collective interaction among these agents generates emergent archaeological intelligence
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2.5 Digital Twin Layer

Within A²I, the Digital Twin is not merely a three-dimensional model. It becomes a dynamic cognitive environment where geometry, semantics, monitoring data, historical knowledge, archaeological interpretation, and conservation information coexist. Each archaeological entity evolves continuously through the integration of new evidence and scholarly contributions.

2.6 LLM-Augmented Cognitive Layer

Large Language Models act as cognitive augmentation systems connected to knowledge graphs, scientific literature, excavation reports, monitoring infrastructures, and Digital Twins. Their role is not to generate archaeological knowledge autonomously but to support:

- contextual interpretation;
- narrative generation;
- multilingual explanations;
- evidence synthesis;
- hypothesis exploration;
- educational storytelling.

2.7 Collective Intelligence and Decision Support Layer

The highest layer supports interaction among archaeologists, conservators, architects, historians, engineers, heritage managers, visitors, and AI systems. Through dashboards, GIS platforms, Extended Matrix, immersive environments, collaborative workspaces, and natural language interfaces, all stakeholders contribute to the continuous evolution of archaeological knowledge. Within A²I, intelligence is therefore not centralized in algorithms but emerges from the interaction among humans, machines, data, and digital environments. Archaeological knowledge continuously evolves through this interaction.

III. The House of Apollo Citharist as a Living Archaeological Intelligence Environment

To demonstrate the feasibility of the proposed framework, this paper identifies the House of Apollo Citharist in the Archaeological Park of Pompeii as a pilot implementation scenario (RI.4.5). The House of Apollo Citharist constitutes an ideal experimental environment due to the availability of heterogeneous information sources including archaeological documentation, excavation reports, historical archives, historical photos, photogrammetric surveys, laser scanner acquisitions, geospatial datasets, conservation records, and contextual archaeological knowledge. Within the A²I framework, all these resources are integrated into a unified cognitive ecosystem. The Digital Twin of the house acts as the central knowledge environment. Rooms, walls, decorative apparatuses, inscriptions, architectural elements, archaeological finds, and conservation interventions become interconnected semantic entities represented within the knowledge graph. Each component of the Digital Twin can continuously evolve through the integration of new discoveries, expert annotations, environmental observations, monitoring data, and scholarly interpretations. Large Language Models further enrich the Digital Twin by generating contextual descriptions, excavation narratives, conservation summaries, interpretative reports, and educational content grounded in validated archaeological evidence. For example, a room of the House of Apollo Citharist can be represented not only through its geometric reconstruction but also through its historical evolution, functional interpretation, decorative characteristics, conservation state, bibliographic references, and relationships with other spaces of the domus. The proposed implementation also introduces a collective intelligence dimension. Archaeologists, conservators, architects, historians, engineers, and digital heritage specialists actively contribute to the evolution of the knowledge ecosystem by validating interpretations, adding evidence, documenting interventions, and proposing new hypotheses. In this perspective, the House of Apollo Citharist becomes a Living Archaeological Intelligence Environment where archaeological knowledge is continuously generated, validated, enriched, and reinterpreted through the interaction among human expertise, digital infrastructures, semantic representations, intelligent agents, and generative artificial intelligence systems.

IV From Digital Twins to Pocket Archaeological Metaverses

Traditional Digital Heritage initiatives have primarily focused on the geometric reconstruction of archaeological contexts, aiming to digitally preserve and visualize buildings, artefacts, and historical landscapes. While these approaches have significantly improved documentation and accessibility, they often remain limited to the representation of physical structures and spatial relationships. Within the proposed A²I framework, we introduce the concept of Cognitive Reconstruction, extending the notion of reconstruction beyond geometry and appearance. The objective is not only to recreate how an archaeological environment looked in the past, but also to reconstruct the knowledge, interpretations, relationships, and cultural meanings associated with it. In this perspective, archaeological entities are no longer treated as isolated objects. Buildings, rooms, decorative apparatuses, artefacts, inscriptions, excavation records, historical sources, conservation interventions, and scholarly interpretations become interconnected components of a shared cognitive ecosystem. To validate this approach, the House of Apollo Citharist was selected as a pilot implementation scenario. Starting from archaeological documentation, laser scanner surveys, photogrammetric acquisitions, historical sources, and recent archaeological studies, a comprehensive Digital Twin of the domus was developed. The reconstructed environment reproduces the architectural configuration of the house while integrating contextual information concerning the Apollo statue, domestic religious practices, decorative programs, conservation history, and archaeological interpretations. Through semantic representations and knowledge graph technologies, each element of the Digital Twin is associated with provenance information, evidential relationships, uncertainty levels, and alternative interpretative hypotheses, transforming the reconstruction into a dynamic knowledge environment. A distinctive aspect of the proposed implementation is its accessibility. Rather than relying on expensive Virtual Reality equipment, dedicated immersive installations, or head-mounted displays, the reconstructed environment has been designed according to the concept of a Pocket Archaeological Metaverse. This paradigm enables visitors to access immersive archaeological experiences directly through standard mobile devices such as smartphones and tablets, transforming everyday technologies into gateways to archaeological knowledge. Through Augmented Reality techniques, digital reconstructions are superimposed onto the existing archaeological remains, allowing users to explore ancient spaces, visualize lost architectural elements, access contextual information, and interact with AI-enhanced narratives directly within the site. Visitors can continuously compare the current state of preservation with the hypothesized ancient appearance of the house while simultaneously accessing historical, archaeological, and interpretative information generated within the A²I ecosystem. In this perspective, the Digital Twin evolves from a static three-dimensional model into an intelligent and immersive cognitive environment where physical remains, semantic knowledge, archaeological evidence, and digital narratives coexist within a unified space. The Pocket Archaeological Metaverse extends the traditional concept of Digital Twin by making advanced

archaeological intelligence portable, ubiquitous, and immediately accessible. Smartphones become cognitive interfaces capable of connecting users with knowledge graphs, contextual information, immersive reconstructions, and AI-driven interpretative services. The proposed solution demonstrates how Artificial Archaeological Intelligence can move beyond purely visual reconstruction toward a new generation of mobile, immersive, and context-aware archaeological experiences, where archaeological knowledge is not simply represented but actively explored, interpreted, and shared. In this vision, the entire archaeological ecosystem can literally fit into the visitor's pocket.

CONCLUSIONS

Artificial Archaeological Intelligence represents a new paradigm for digital archaeology. By integrating semantic infrastructures, Digital Twins, multi-agent systems, environmental monitoring technologies, and Large Language Models, archaeological sites evolve from static repositories of information into dynamic collective intelligence environments. The House of Apollo Citharist demonstrates how archaeological interpretation can be supported through the continuous interaction among evidence, experts, computational systems, and digital representations. The future of archaeology is not simply digital: it is cognitive, collaborative, explainable, and continuously evolving. Artificial Archaeological Intelligence provides a first step toward this future. We argue that the future of archaeological Digital Twins lies not in increasingly accurate geometric reconstructions, but in the creation of intelligent cognitive ecosystems capable of connecting archaeological evidence, scholarly interpretation, Artificial Intelligence, and public engagement within a unified knowledge environment.

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