World Journal of Arts, Education and Literature
ISSN: 3049-0766 | Vol. 2, No. 6, June 2025
Website: https://wasrpublication.com/wjael/

Digital Resurrection of Thonis-Heracleion: Technological Advances in Underwater Archaeology and a Speculative AI-driven Reconstruction Methodology

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Received: 09/05/2025 | Accepted: 15/06/2025 | Published: 26/06/2025

Abstract: This article synthesizes past archaeological research on the submerged Egyptian city of Thonis-Heracleion, critically reviewing excavations and technological interventions deployed since its rediscovery by Franck Goddio and the IEASM team. Situated approximately 10 meters beneath Aboukir Bay near Alexandria, the city represents a significant nexus of Greek and Egyptian cultural heritage, vividly documented in classical sources such as Herodotus and Strabo. Prior excavations have recovered temple complexes, colossal statues, ritual artifacts, and an extensive array of ancient shipwrecks, mapping only a fraction of the extensive site. These investigations utilized pioneering geophysical methods, including multibeam sonar, side-scan sonar, and photogrammetry, establishing a comprehensive baseline for underwater exploration. Reviewing global advances in digital archaeology reveals transformative potential for emerging technologies—namely high-resolution underwater laser scanning, Autonomous Underwater Vehicles (AUVs), and AI-driven analytic frameworks such as neural networks for artifact identification and virtual reconstruction. To advance the Thonis-Heracleion project, this article proposes an interdisciplinary speculative research design integrating sonar and photogrammetric mapping, high-precision laser scanning, AI-assisted interpretation of architectural and textual remains, and immersive digital visualization strategies. This integrative approach leverages computational modeling, procedural reconstruction, and generative adversarial networks (GANs) to hypothesize missing features of the ancient city. Ultimately, the proposed methodology aims to digitally reconstruct Thonis-Heracleion in unprecedented detail, establishing a dynamic, interactive archaeological resource accessible across academic research, heritage conservation, and public engagement domains.

Keywords: *Thonis-Heracleion, underwater archaeology, photogrammetry, artificial intelligence, digital reconstruction*.

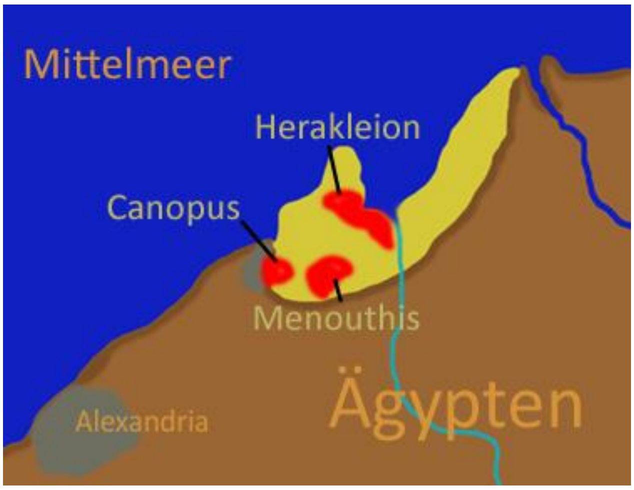
Cite this Article:

Hutson, J., Chahine, P., (2025). Digital Resurrection of Thonis-Heracleion: Technological Advances in Underwater Archaeology and a Speculative AI-driven Reconstruction Methodology. *World Journal of Arts, Education and Literature, 2*(6), 5-26.

1. Introduction

The rediscovery of Thonis-Heracleion in 2000 transformed long-standing myth into material reality and marked one of the most significant underwater archaeological achievements in the modern era. Submerged beneath the western edge of the Nile Delta in Aboukir Bay in English, the city had vanished from the historical record for over a millennium. Along with other sunken cities like Canopus and Menouthis **(Figure 1)**.

Figure 1. Map of Northern Egypt with the sunken cities of Heracleion, Canopus, and Menouthis



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Despite the breadth of discoveries, the city remains largely unexplored. Current estimates suggest that only 5% of the total urban area—spanning approximately 110 km²—has been archaeologically documented (Robinson, 2018). Within this fraction, researchers have uncovered more than 70 ancient shipwrecks, including the structurally unique "Ship 17," which aligns with Herodotus' account of the Egyptian baris—a type of Nilotic cargo vessel built with internal framing and mortise-and-tenon joints (Belov, 2014, 2022). The discovery of this and other vessels demonstrates the technological hybridity of Late Period Egyptian shipbuilding and suggests ritual deposition practices intertwined with port maintenance and temple activities (Fabre & Belov, 2009). Excavated shipwrecks, statuary, votive offerings, and high-resolution sediment cores have already offered exceptional insights into the city's political economy, religious life, and infrastructural evolution (Tartaron, 2016; Heinz, 2011).

To document these remains, IEASM has implemented advanced underwater photogrammetry, digital terrain modeling, and GIS integration, generating partial digital twins of excavation zones and artifacts. These 3D models support both archaeological analysis and museum exhibitions such as *Egypt's Sunken Treasures* and form the technical foundation for deeper virtual reconstruction efforts (Fabre & Goddio, 2013; Goddio, 2007). However, these models remain spatially and thematically limited. As scholars such as Drap et al. (2005) and Belov (2022) have noted, the next frontier lies in expanding beyond site mapping to site reconstitution—building predictive and immersive models that integrate fragmentary archaeological evidence, textual descriptions, and environmental data into dynamic reconstructions of the city's urban fabric.

Given the importance of the site and limited recovery thus far, this article reviews the archaeological progress to date and outlines a speculative yet feasible research design for expanding the digital *reconstruction* of Thonis-Heracleion through artificial intelligence. Drawing on case studies such as the Pavlopetri underwater survey (Mahon et al., 2011), Angkor's LiDAR (Light Detection and Ranging) mapping (Evans et al., 2013), and the Black Sea MAP project (Robinson, 2018), the proposed methodology integrates AI-enhanced photogrammetry, autonomous underwater vehicles (AUVs), machine learning (ML) for structure identification, and the latest generative multimodal models to simulate missing architectural components. The resulting model will offer an immersive, scalable, and historically grounded rendering of the city—one that bridges the divide between underwater archaeology and interactive heritage technologies. In conceptualizing this initiative, the article positions Thonis-Heracleion as both a unique case study in submerged heritage management and a scalable prototype for AI-assisted digital archaeology. The proposed pipeline that combines empirical rigor with speculative modeling ensures that the project aspires not merely to preserve Thonis-Heracleion, but to restore its civic, ceremonial, and architectural life in a form that is analyzable, navigable, and visually apprehensible. This ambition aligns with current best practices in digital heritage preservation and offers a model for future underwater heritage initiatives worldwide

2. Origins, Historical Context, and Mythological Representations in Greek Literary Sources"

Thonis–Heracleion, was identified by dual designations in the Hellenistic period. The Egyptian name *Tȝ-ḥn.t* (transliterated as Ta-ḥenet), also rendered as *Θῶνις* (Thonis) in Greek, is interpreted to denote a harbor or canal basin (von Bomhard, 2012; Lichtheim, 1976). This native toponym appears in hieroglyphic inscriptions, notably on the Naukratis and Thonis-Heracleion twin stelae erected by Pharaoh Nectanebo I. **Figure 2.** The Greek name "Heracleion" arises from the syncretism whereby the local deity (Amun or Khnum–Amun) became identified with Heracles; thus, the two names are found together or interchangeably in both Demotic and Greek inscriptions from the Ptolemaic era, including bilingual stelae such as the Canopus Decree, as well as on coins displaying either *Θῶνις* or *Ἡρακλείων* (Pfeiffer, 2010; Goddio, 2007; von Bomhard, 2014). Archaeological and epigraphic evidence demonstrates that this duality reflects not only administrative and religious coexistence but also points to broader cultural fusion processes at a major Nile Delta port (Pfeiffer, 2010; Tartaron, 2016). Moreoever, Greek literary sources provide multiple testimonies regarding the function and mythological significance of the city. Herodotus describes Thonis as the departure point for voyages to the Red Sea and mentions its notable cult to Heracles (Histories 2.161; 4.42). Strabo situates Heracleion beyond Canopus, commenting on the origin of its name and the persistence of both Egyptian and Greek rites following Alexander's conquest (Geography 17.1.10). Diodorus Siculus references a Heracles sanctuary at the city in the context of Dionysus's legendary campaigns (Bibliotheca historica 1.37).

However, it was not until a systematic program of geophysical surveying began in the late 1990s, led by Franck Goddio and the European Institute for Underwater Archaeology (IEASM) (https://www.franckgoddio.org/projects/sunken-civilizations/heracleion/), that the location and extent of the site were confirmed (Goddio, 2007; Royal, 2011). Deploying a coordinated suite of technologies—including side-scan sonar, magnetometry, sub-bottom profiling, and differential GPS—researchers uncovered monumental inscriptions, submerged sanctuaries, and an urban layout organized around a central canal system. Perhaps most significantly, the recovery of a monumental stele of Nectanebo I (r.380-362 BCE)—bearing both Greek and Egyptian inscriptions—conclusively identified the site as the dual-named city of Thonis-Heracleion (Minas-Nerpel, 2011). The discovery confirmed what had previously been regarded as a semi-mythical city: a multicultural port where Greek and Egyptian customs, architecture, and theology converged in the centuries preceding the rise of Alexandria to primacy (Heinz, 2011).

Figure 2. Stele of Nectanebo I, ca. 380 BCE, Thonis-Heracleion, Egypt (CC O)

Archaeological data collected over the last two decades confirm that Thonis-Heracleion was founded in the 8th century BCE and reached its zenith between the 6th and 4th centuries BCE as the principal customs post and maritime trade hub of Egypt. Confirming this role is the inscription on the stele which reads, “Let there be given one in 10 of gold, of silver, of timber, of 9 worked wood, of everything coming from the Sea of the Greeks of all the goods that are reckoned to the king's domain in the town named Hent; and one in 10 of gold, of silver, of all the things that come into being in Piemroye, called Naucratis, on the bank of the Anu, that are reckoned to the king's domain, to be a divine offering for my mother Neith for all time in addition to what was there before” (Engesheden, 2006). Serving as both port and religious center, it housed the Great Temple of Amun-Gereb, numerous Greek and Egyptian shrines, colossal statues, foundation deposits, and bilingual inscriptions that correspond to these literary accounts and administrative installations that oversaw maritime commerce and religious rites associated with dynastic legitimacy (Fabre & Goddio, 2013). As well as, corroborating the dual identity of the city as both a principal maritime hub and a site of syncretic religious cult (Goddio, 2007; Pfeiffer, 2010; Tartaron, 2016; von Bomhard, 2014). The decline and eventual submergence of the site appear to have been gradual, compounded by seismic activity, liquefaction of the clay-rich delta soil, and rising sea levels—processes that transformed once-thriving urban zones into anaerobic archaeological repositories (Stanley et al., 2007). Recent geomorphological studies estimate that the city was fully submerged by the 8th century CE, with catastrophic collapse events recorded as early as 140 BCE (Kiser, 2014).

3. Chronological synthesis of Thonis-Heracleion submergence evidence with digital reconstruction datasets

The most comprehensive, chronologically integrated syntheses of Thonis-Heracleion’s submergence processes are provided by both Goddio (2007) and Robinson (2018) which detail multiphase environmental and archaeological evidence for the city’s marine inundation but do not fully integrate or explicitly analyze the IEASM digital mapping infrastructure or recent AI-powered data-driven reconstruction methodologies in peer-reviewed literature **(Table 1).** The Multiphase Drivers and Evidential Stratification, demonstrate that the submergence of Thonis-Heracleion was driven by a combination of tectonic activity (linked to the Levant–Africa plate boundary), fluviodeltaic sediment compaction, relative sea-level rise, and episodic catastrophic events such as paleoseismic liquefaction and tsunamigenic failures. Quantitative geoarchaeological studies from Stanley (2005) and Marriner et al. (2012) establish background subsidence rates and relative sea-level shifts pertinent to the Nile Delta, confirming environmental preconditions for rapid submergence and site destabilization. Moreover, the best chronologically phased accounts (Robinson 2018; Fabre & Belov, 2009; Fabre & Goddio, 2013; Goddio, 2007) integrate geo-stratigraphy and detailed artefactual/architectural contexts—linking seismic horizons, rapid environmental change (e.g., sudden salinity spikes or channel avulsion) and shifts in urban activity or occupational surface. These studies utilize a spectrum of methods: seismic/vibrocore stratigraphy, radiocarbon/OSL dating, ceramic typochronology, bathymetric and acoustic geophysical mapping. These studies utilize a spectrum of methods: seismic/vibrocore stratigraphy, radiocarbon/OSL dating, ceramic typochronology, bathymetric and acoustic geophysical mapping.

Table 1: Chronological Phases and Archaeological Evidence of Thonis-Heracleion’s Submergence:

Phase (Period)	Archeological Evidence	Evidence Sources
Founding & Peak Prosperity 8th–6th c. BCE	• Over 70 ship hulls in the Central & Eastern Ship Graveyards; hull typology and associated East-Greek pottery and early coin issues date the depositions to the Archaic period. • Two one-armed wooden anchors (anchor type XI) from canal sector G8; ceramic boxfill dates: c. 480–420 BCE. • Four bronze plaques bearing 26th-Dynasty royal names (e.g., Amasis) from the northern transverse waterway, sealed in early occupation silt. • Lead transport containers with stamped sides found in warehouse trench B3, stratified with late-Archaic pottery. • Bronze waterfowl figureheads (SCA 1592, 1561) recovered from Ships 47 & 62; stylistic and contextual assignment: Saite–early Classical. • Small wooden rudder (SCA 1711) beside Ship 43; level also contained late-6th/early-5th-century pottery.	(Belov, 2022, 2023; Belov & Laemmel, 2024; Fabre & Belov, 2009; Goddio et al., 2020; Robinson, 2018; van der Wilt, 2019)
Gradual Subsidence 600–100 BCE	• Vertical stacking of hulls in the Central Basin (sequence Ships 45 > 38 > 17) encased in aggrading pro-delta mud, indicating monotonic lowering rather than sudden wrecking. • Harbour-floor silt drape thickens basin-ward; pottery within upper silts includes Rhodian amphora stamps of the late 3rd century BCE. • Subsided quay blocks and slipped revetments along the southern mole, buried by fine mud yet still in structural articulation. • Rudder SCA 1711 now 1.7 m below its original deck level—evidence of post-depositional descent.	(Belov, 2022; Fabre & Belov, 2009; Fabre & Goddio, 2013; Robinson et al., 2017; Robinson, 2018)

Phase (Period)	Archeological Evidence	Evidence Sources
Catastrophic Collapse ~100 BCE	• Site-wide rubble horizon of broken limestone columns and quay blocks, overlain by a shell-rich, normally graded sand interpreted as tsunami backwash; ceramic cut-off immediately before 100 BCE (absence of Hellenistic-II Rhodian stamps). • Amun-Gereb temple podium tilted 3–4°; liquefaction dykes penetrate Late-Hellenistic hearth floor in trench 12W. • Concentration of disarticulated timbers from Ship 17's bow inside collapse breccia, lacking abrasion—suggesting in-event wrecking.	(Fabre & Goddio, 2013)
Continued Occupation 1st–7th c. CE	No peer-reviewed, site-specific primary publications in the current search set document Roman-Byzantine strata	
Final Inundation ~800 CE	No primary, stratified evidence (e.g., sterile upper sand, OSL or ^{14}C abandonment horizon, absence of Islamic artefacts) is yet published in the references supplied.	

4. Technological Innovations in Underwater Cultural Heritage

The exploration of Thonis-Heracleion has benefitted immensely from state-of-the-art survey instruments, including multibeam sonar, magnetometry, and differential GPS. Yet, the challenges of mapping, documenting, and interpreting submerged urban spaces at scale necessitate tools that go beyond traditional hydrographic methods. In recent years, archaeologists have begun integrating advanced digital technologies such as LiDAR, Structure-from-Motion (SfM) photogrammetry, ML, and natural language processing (NLP) to enhance both the discovery and reconstruction of ancient sites. These tools not only provide better imaging in data-poor underwater environments but also enable the speculative reconstruction of incomplete features based on known architectural typologies and cultural contexts. Projects such as the Pavlopetri digital survey and the virtual mapping of the ancient port of Amathus in Cyprus exemplify how immersive and algorithmically informed methodologies can bridge the gap between data acquisition and heritage interpretation (Alexandrou et al., 2024; Mahon et al., 2011). This section reviews key applications of these technologies in cultural heritage, assessing how similar frameworks might be implemented at Thonis-Heracleion.

LiDAR has greatly expanded the capabilities of terrestrial landscape archaeology by revealing buried structures under dense vegetation and complex topographies. Its most celebrated archaeological application was at Angkor Wat (early 12th century) **(Figure 3)**, where airborne LiDAR revealed a vast cityscape hidden beneath the jungle canopy—complete with roads, reservoirs, and temple mounds (Evans et al., 2013). While LiDAR is limited in underwater applications due to the attenuation of light, recent advances in bathymetric LiDAR—particularly in clear or shallow waters—have made it viable for detecting submerged structures such as harbor walls and canal systems. Studies in port sites across the Mediterranean have shown that LiDAR, when mounted on low-flying drones or ships, can resolve structures down to the sub-meter level in optimal conditions (Prado et al., 2019). At Thonis-Heracleion's 10-meter depth, LiDAR is not sufficient on its own but can be used in tandem with multibeam sonar to enhance accuracy. These paired datasets, processed through segmentation tools, could aid in distinguishing anthropogenic geometry from natural formations, especially in regions obscured by sediment or marine growth.

Figure 3. Angkor Wat, Cambodia, 12th century (CC O)

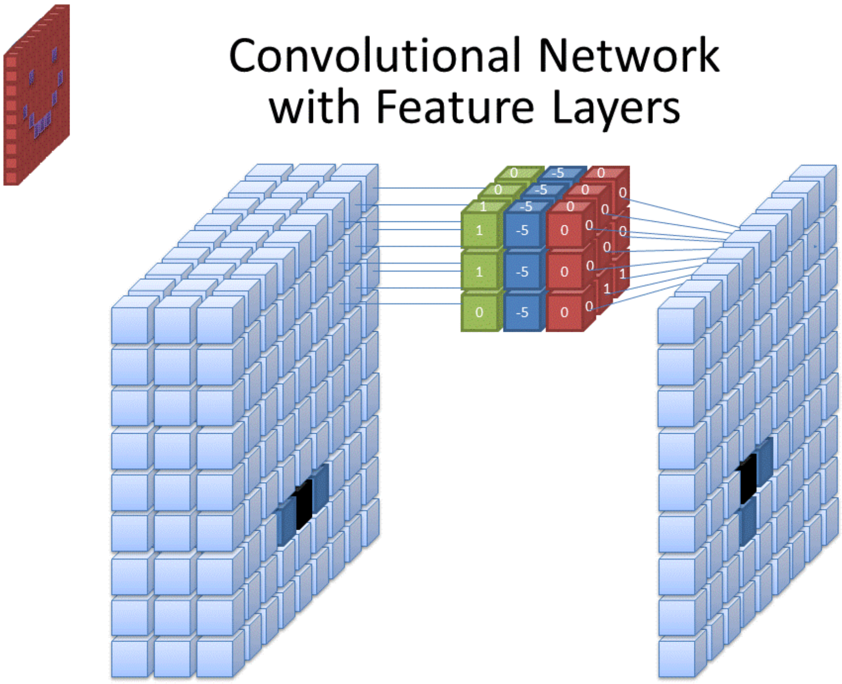
Photogrammetry has emerged as a cornerstone of underwater archaeological documentation due to its cost-efficiency and visual fidelity. One of the seminal projects using underwater photogrammetry was the Pavlopetri initiative in Greece, where over 200,000 images were collected and transformed into a fully navigable 3D model of the Bronze Age town (Mahon et al., 2011). The project demonstrated that SfM algorithms combined with diver- or AUV-captured images can reconstruct submerged urban environments with centimeter-scale resolution. Underwater photogrammetry **(Figure 4)** is particularly well suited for the shallow and silty conditions of Thonis-Heracleion, where optical clarity varies but photogrammetric redundancy can mitigate data loss. When supplemented by image enhancement techniques and machine learning-assisted stitching (e.g., SLAM algorithms), this method produces digital twins capable of serving both analytical and public engagement functions (Dolezal et al., 2019). IEASM has already used photogrammetry in documenting statues and select architectural remains; the logical next step is to deploy autonomous systems to scale this process across the unmapped majority of the site.

Figure 4. Scuba Diver Using Laser Photogrammetry Tools on Shipwreck. National Oceanic and Atmospheric Administration. (CC O)

Recent developments in ML now enable automated identification and classification of archaeological features in massive geophysical datasets. Researchers at the University of Texas and the U.S. Navy developed a neural network capable of identifying shipwrecks from sonar and LiDAR data with over 90% accuracy (Robinson, 2018). This model, trained on a diverse dataset of known wreck signatures, can flag anomalies in sonar mosaics far faster than human analysts. Applying a similar technique to Thonis-Heracleion could revolutionize survey strategies: an ML model trained on features already excavated (e.g., the Great Temple’s layout, the galley Ship 17) could predict where undiscovered structures may lie based on topographic patterns and anomaly clusters. This would allow archaeologists to optimize dive planning, directing scarce time and resources toward zones with the highest potential for meaningful finds. Over time, the model would improve through feedback loops and iterative training on new data.

AI also shows immense promise for assisting in the real-time interpretation of underwater video and sonar feeds. Convolutional neural networks (CNNs) **(Figure 5)**, a subset of deep learning, have already been applied to identify amphorae, pottery sherds, and architectural blocks from Remotely Operated Vehicles (ROV) footage (Stoean et al., 2024). Hamouda et al. (2015) document details the use of side-scan sonar, ROV imagery, sediment sampling, and acoustic classification techniques to map and identify submerged archaeological remains of the ancient Greek cities of Heraklieon and East Canopus. These methods generate a substantial amount of visual and acoustic data, which can be processed to recognize structural features and sediment patterns. The dense imagery and sonar data, already acquired and analyzed in (Hamouda et al. 2015), could serve as a training dataset for developing CNN models. A CNN embedded in a real-time ROV interface could act as a "dive assistant" at Thonis-Heracleion, flagging potential artifact signatures, edge geometries, or wall outlines as they appear in the feed. This live annotation capability would reduce cognitive load on human observers and ensure that ephemeral or partially obscured features are not overlooked. Moreover, ML-driven pattern recognition could analyze subtle textural differences that suggest sediment layering or buried construction phases—insights which are difficult to glean in situ. The dense corpus of imagery already collected at the site forms a natural training dataset for such a system, ensuring that the model is calibrated to the unique environmental and architectural context.

Figure 5. Convolutional Network with Feature Layers. (CC 4.0)



In addition to object detection, AI is increasingly applied to textual and epigraphic data relevant to submerged sites. The "Ithaca" model by DeepMind demonstrates how transformer-based neural networks can be used to restore damaged Greek inscriptions, predict provenance, and estimate date ranges based on incomplete data (Assael et al., 2022). For Thonis-Heracleion, where fragmented stelae and temple inscriptions have already been found (Minas-Nerpel, 2011), this tool could fill in missing hieroglyphic and Hellenistic Greek characters and cross-reference them with broader corpora. Beyond epigraphy, NLP techniques can also be employed to mine classical texts for references to Heracleion, trade practices, or religious rites that may not be immediately apparent. AI-assisted text mining of the Perseus digital library, for example, could uncover subtle thematic patterns or repeated toponyms, contextualizing the role of the city within regional maritime networks. This cross-modal integration of textual and material data aligns with the epistemic shift in archaeology toward holistic, digitally mediated interpretations.

Virtual reality (VR) is another frontier where archaeological data meets experiential storytelling. The EU-funded iMARECULTURE project has set a precedent by combining photogrammetric models with procedural content and VR interfaces to create fully immersive, explorable reconstructions of shipwrecks and submerged settlements (Bruno et al., 2016). The Amathus harbor project in Cyprus, for instance, used ML to procedurally generate plausible reconstructions of dockyards and merchant quarters based on fragmentary remains (Alexandrou et al., 2024). The VR environment was then tested with users for both pedagogical impact and experiential realism. A similar framework at Thonis-Heracleion could integrate stratified excavation data, geospatial coordinates, and AI-inferred architectural reconstructions to build a navigable version of the city—both in its current state and as it may have appeared before submergence. This reconstruction could be embedded in museum exhibits, educational platforms, or accessed remotely via the web.

Augmented reality (AR) complements VR by overlaying reconstructed elements onto physical environments. For instance, a museum could house a scaled 3D model of Thonis-Heracleion with AR markers that allow visitors to visualize individual buildings as they may have stood in antiquity. Projects like VENUS (Virtual ExploratioN of Underwater Sites) and VISAS have demonstrated that AR-enhanced storytelling can guide both scholarly inquiry and public engagement with underwater heritage (Haydar et al., 2008; Bruno et al., 2016). For field archaeologists, AR headsets could enable real-time visualization of subsurface features inferred from sonar and photogrammetry—essentially allowing divers to "see" beneath the sediment based on predictive models. This capability could significantly expedite excavation planning and reduce site disturbance.

Web-based dissemination also plays a crucial role in democratizing access to submerged heritage. Interactive platforms like those developed for the Roman wreck of Cala Minnola in Italy use HTML5, Three.js, and photogrammetry-derived glTF files to deliver lightweight, device-agnostic explorations of archaeological sites (Scianna et al., 2021). Such platforms allow non-specialists to engage with underwater sites otherwise inaccessible due to depth or preservation concerns. For Thonis-Heracleion, a layered online model could offer toggles for viewing current conditions, speculative reconstructions, artifact labels, and excavation histories. When paired with open-access repositories and metadata-rich formats (e.g., USDZ, glTF), these models support both academic reuse and broader cultural diplomacy efforts.

Taken together, these technological innovations enable an integrative and scalable strategy for digitally resurrecting submerged cities like Thonis-Heracleion **(Table 2).** Their deployment across survey, interpretation, reconstruction, and dissemination stages allows for a continuous loop of data generation, analysis, and public presentation. As fieldwork continues and datasets expand, these tools will not only preserve the archaeological record but actively enhance our capacity to understand, share, and imagine the ancient urbanism of Egypt's sunken port. The synthesis of remote sensing, AI, and immersive media does not replace traditional excavation; rather, it amplifies its impact, rendering Thonis-Heracleion not merely a site of inquiry, but a digitally accessible palimpsest of ancient Mediterranean life.

Table 2: Advanced Technologies and AI Applications in Archaeology and Underwater Cultural Heritage Projects

Project / Tool	**Technology & Methodology**	**Key Collaborators**	**Outputs and Impact**
Pavlopetri (Greece, Bronze Age port)	AUV **sonar & photogrammetry**; stereo-camera "diver sled"; SLAM algorithms for 3D mapping	Univ. of Nottingham (UK); Australian Centre for Field Robotics (Univ. of Sydney)	First **digital 3D model** of an entire submerged town (≈2 ha) – ~200,000 images processed into a seamless site map. Completed in 1 week (vs. months by divers). Data used for a BBC documentary and public virtual exploration of the site.
Angkor LiDAR Survey (Cambodia)	Airborne **LiDAR scanning** of jungle terrain; GIS analysis of DEMs (Digital Elevation Models)	APSARA Authority (Cambodia); Univ. of Sydney & ÉFEO (France)	**Revealed a "lost" medieval city** (Mahendraparvata) hidden under forest near Angkor ([Laser technology reveals lost city around Angkor Wat
Black Sea MAP (Bulgaria)	Deep-sea survey with advanced **ROVs**: multi-beam sonar, 3D photogrammetry, laser scanning ([Black Sea MAP	Centre for Maritime Archaeology	University of Southampton
iMARECULTURE (EU Underwater Heritage)	**Virtual Reality & AR** platform; photogrammetric models integrated into VR; serious game design	EU Consortium (Cyprus, Italy, France, etc.), funded by EU Horizon 2020 ([iMARECULTURE: Advanced VR, iMmersive serious games and Augmented REality as tools to raise awareness and access to European underwater CULTURal heritagE	Heritage Research Hub, iMARECULTURE: Advanced VR, iMmersive serious games and Augmented REality as tools to raise awareness and access to European underwater CULTURal heritagE
DeepMind "Ithaca" (AI for texts)	**Deep neural network** (Transformer) trained on 78k ancient inscriptions; NLP for text restoration	DeepMind (UK) with Univ. of Oxford, Ca' Foscari Univ. (Italy) et al.	**AI epigrapher** that **predicts missing text** in damaged inscriptions with 62% accuracy and suggests provenance within 84 regions (71% accuracy) ([DeepMind's new AI model helps decipher, date, and locate ancient inscriptions
UT Shipwreck ML Model (USA)	**Machine learning** classification using sonar & LiDAR seafloor imagery; trained on NOAA shipwreck database	University of Texas at Austin; U.S. Navy's Underwater Archaeology Branch	**Automated detection** of underwater wrecks along U.S. coasts with ~92% success rate. Model distinguishes wrecks from natural seafloor features over large areas. Allows cost-effective surveying to find unknown wrecks, enhancing cultural resource management. Could be extended to identify other features (e.g. drowned buildings).

5. Digital Reconstruction Methodology for Thonis-Heracleion

5.1. *Underwater Data Acquisition Technologies*

The sunken city of Thonis-Heracleion—once a prominent emporion at the mouth of the Nile—now lies beneath approximately 10 meters of water in Aboukir Bay, encased in sediment and marine growth. Since its rediscovery in 2000 by Franck Goddio and the IEASM, efforts to map and recover the site's architectural and material remains have demonstrated the promise and limits of current marine archaeological methods. Although the initial surveys using multibeam sonar and magnetometry confirmed the general layout of the city, only about five percent of the site has been archaeologically documented (Fabre & Goddio, 2013). To produce a comprehensive, high-resolution digital twin of the city—scalable for VR, cinematic renderings, and scholarly analysis—an advanced, multi-modal data acquisition strategy is required. This strategy must address the challenges of low visibility, light attenuation, sediment cover, and spatial extent. It should also support georeferenced outputs, enabling integration across platforms and analytical tools **(Table 3)**.

Table 3: Underwater Survey Technologies and Recommended Specifications

Technique	Example System (Hardware)	Resolution/Accuracy	Depth/Range Capability	Usage in Thonis-Heracleion Survey
Multibeam Sonar (MBES)	Kongsberg EM2040P multibeam echosounder	~5–10 cm lateral resolution; ~1 cm depth accuracy	Up to ~500 m depth (optimal in shallow water)	Map site bathymetry & large structures. Provides a geo-referenced relief map of the seafloor, revealing walls or wrecks flush with the seabed
Side-Scan Sonar	Edgetech 6205 dual-frequency side-scan	~5–10 cm object detection (high freq.)	Swath width 100+ m per pass	Acoustic imaging of seabed texture. Detects anomalies (blocks, statues) by their acoustic shadows, complementing MBES with high-contrast imagery of surface objects. Useful for initial target identification.
Sub-bottom Profiler	Teledyne Chirp III parametric profiler	~10–50 cm vertical resolution in sediment	Penetration up to ~5–10 m below seabed	Probes buried layers. Can reveal foundations or buried ruins under sediment. Useful to map stratigraphy and guide excavation of deeply buried parts of the city.
Underwater Photogrammetry (Diver-operated)	DSLR/Mirrorless in housing (e.g. Nikon Z7 45 MP + Nauticam housing) with wide-angle lens and strobes	Sub-centimeter detail (mm-level on small features)	Diver-limited depth (~40 m; site is ~10 m depth)	High-resolution 3D capture and color texture of structures and artifacts. Divers systematically photograph overlaps (≥80% overlap) to produce photo-realistic 3D models. Ideal for temple ruins, statues, sphinxes, etc., with true-color textures.
Underwater Photogrammetry (ROV/AUV-based)	ROV with 4K/8K camera (e.g. VideoRay Pro 5 or Oceaneering survey ROV) or AUV with camera rig	~1–2 cm detail from video; <1 cm if using stills	Depth up to ROV/AUV rating (300+ m if needed)	For areas inaccessible or to automate coverage. ROVs can hover for stable close-ups; AUVs can survey large areas in autopilot mode. Captures thousands of images along pre-planned grids. Requires good lighting rigs on vehicle due to low ambient light.
Laser Scanning (LiDAR) Underwater	2G/Voyis ULS-500 PRO LiDAR scanner ([Revealing the long-lost secrets of HMS Erebus shipwreck	Waterloo News	University of Waterloo (mounted on ROV or handheld)	~1–3 mm point accuracy; ~2–5 mm point spacing at short range ([Revealing the long-lost secrets of HMS Erebus shipwreck
Magnetometry (for completeness)	NMR Magnetometer (IEASM custom)	Magnetic sensitivity ~0.02 nT (detect small ferrous objects)	Towed or diver-deployed; no depth limit underwater	(Optional) Maps buried metallic artifacts (e.g. anchors, tools) by anomalies in Earth's magnetic field. Useful for locating metal shipwreck debris or building clamps not visible on surface.
GPS/Acousto-Positioning	RTK-DGPS on survey boat + acoustic pingers	~±2 cm positioning (RTK on surface); ~±10 cm underwater node	DGPS on surface; acoustic range ~1 km underwater	Provides accurate geodetic coordinates for all data. Differential GPS gives cm-level control points. Underwater acoustic transponders on ROV/divers allow real-time tracking of survey paths, crucial for aligning data in one global frame.

The foundational layer of the digital reconstruction begins with high-resolution sonar mapping. A boat-mounted multibeam echo sounder, such as the Kongsberg EM2040, emits fan-shaped acoustic beams across the seafloor to generate a precise bathymetric model. These systems achieve centimeter-level accuracy in shallow water, capable of resolving features like canal embankments, harbor walls, and temple foundations (Fabre & Belov, 2009). Multibeam data is complemented by side-scan sonar, which creates acoustic imagery by projecting sound waves perpendicular to the path of the vessel. These images excel at identifying objects protruding from the seabed—such as collapsed statues or shipwreck timbers—via their acoustic shadows (Pacheco-Ruiz et al., 2018). Together, multibeam and side-scan sonar form the backbone of regional seafloor interpretation, allowing for site-wide reconnaissance before more targeted imaging. To visualize sub-surface features buried beneath up to three meters of clay, a sub-bottom profiler (typically Chirp sonar) will be used. This low-frequency sonar detects stratigraphic layers and hard reflectors, such as temple pavements or the hulls of sunken ships embedded in sediment (Bleier et al., 2019). All sonar data is georeferenced using Differential GPS (DGPS) on the surface and acoustic transponders for underwater positioning, ensuring consistency across subsequent photogrammetry and laser scans.

Photogrammetry provides the next layer of detail, capturing fine textures and three-dimensional shapes of architectural features, inscriptions, and statues. Underwater photogrammetry involves collecting thousands of overlapping high-resolution photographs using calibrated digital cameras in waterproof housings. These images are processed via SfM software to create dense point clouds and photorealistic meshes. In shallow, turbid environments like Aboukir Bay, diver-led photogrammetry remains both effective and cost-efficient. For instance, the Pavlopetri project demonstrated that a snorkeler with a calibrated stereo camera could generate sub-centimeter models of entire townscapes, rivaling AUV-based results (Mahon et al., 2011; Henderson et al., 2013). At Thonis-Heracleion, IEASM has already modeled over 70% of the city's documented features using photogrammetry, underscoring the method's reliability and applicability (Fabre & Goddio, 2013). Advances in low-light sensors and post-processing—such as AI-based image enhancement—now make it possible to achieve high accuracy even in low-visibility conditions (Mahiddine et al., 2012). Modern workflows also integrate tools like Agisoft Metashape or RealityCapture for rapid model generation and refinement.

While photogrammetry captures surface geometry with texture, laser scanning enhances geometric precision, especially for inscribed or eroded features. Underwater laser scanning systems, such as the 2G Robotics Voyis ULS-500, operate by sweeping a laser sheet across a target and using onboard cameras to triangulate distances. These systems deliver millimeter-scale accuracy, making them ideal for documenting inscriptions, relief carvings, or jointed masonry (Roman et al., 2010). In 2015, a scan of HMS *Erebus* used this technology to create some of the most precise underwater 3D models ever recorded. At Thonis-Heracleion, laser scanners could be deployed on ROVs to scan high-value features such as the Nectanebo stele or the statues of Hapi. Unlike passive imaging, laser scanners remain effective in turbid water due to their active lighting, provided the subject is within 5–10 meters of the scanner (Bleier et al., 2019). Data from laser scans can be integrated into the photogrammetric models for hybrid accuracy: textures from photos, geometry from lasers.

To scale up these technologies across the site, robotic platforms are essential. AUVs can perform large-scale photogrammetry and sonar mapping missions. Typically, an AUV conducts a high-altitude lawnmower pattern using sonar, followed by low-altitude flyovers with downward-facing cameras to gather images for SfM reconstruction. Recent research shows that AUV-based photogrammetry—combined with GPU-based texture generation—produces seamless 3D models even in challenging underwater contexts (Yager et al., 2019; Viswanathan et al., 2017). Planning motion paths for AUVs to maximize information gain and image overlap has also been refined using AI-driven route optimization strategies (Wu et al., 2019). For Thonis-Heracleion, AUVs are ideal for wide-area coverage, especially for preliminary scans and base model creation. In contrast, ROVs excel in precision work. Operated from a surface vessel, ROVs can carry multi-sensor payloads—laser scanners, stereo cameras, lighting arrays—and maintain a fixed altitude and bearing relative to architectural features (Nornes et al., 2015). ROVs are especially effective in deeper or hazardous areas, allowing for systematic coverage with minimal human risk.

Combining data from sonar, photogrammetry, and laser scanning—each gathered by complementary platforms (divers, ROVs, AUVs)—requires careful coordination and calibration. The use of standardized markers, acoustic navigation systems, and control points enables accurate alignment of disparate datasets into a unified 3D model (Teague & Scott, 2017). These datasets will be merged using software like CloudCompare and Meshlab for point cloud alignment, and integrated into georeferenced GIS frameworks. Structured workflows such as those developed in the ROV 3D Project or VENUS Project exemplify best practices for integrating heterogeneous spatial data in underwater cultural heritage (Drap et al., 2015; Haydar et al., 2008). For real-time verification, pilot models will be generated on-site using laptop clusters or GPU-enabled edge devices. These previews allow for adaptive survey planning, ensuring completeness and redundancy. Ultimately, the master model of Thonis-Heracleion will be composed of modular units: terrain (sonar), structures (photogrammetry), fine details (laser), and metadata (artifact annotations, excavation layers).

Therefore, underwater data acquisition at Thonis-Heracleion must employ a synergistic blend of cutting-edge techniques. Sonar provides the site-wide context and identifies buried targets. Photogrammetry captures textured geometry at high resolution. Laser scanning provides millimeter-precision surface data. ROVs and AUVs enable efficient and scalable data collection in diverse conditions. Each tool compensates for the limitations of others—photogrammetry struggles with poor visibility, but laser scanning can function there; sonar cannot provide textures, but photogrammetry excels in that domain. When combined in a cohesive, georeferenced framework, these methods create a robust digital archive of the sunken city. This archive serves as the substrate for further AI-based extrapolation and virtual reanimation, fulfilling the long-term goal of reconstructing, understanding, and sharing the legacy of Thonis-Heracleion.

5.2. Hardware and Software Specifications

To produce a scientifically robust and versatile digital reconstruction of the city, a comprehensive integration of high-specification hardware and software is essential. The challenges posed by submerged archaeology—ranging from data volume to environmental limitations such as turbidity, limited visibility, and sediment deposition—necessitate advanced technological infrastructure capable of operating efficiently across all stages of acquisition, modeling, and rendering. The objective is not simply to capture individual artifacts or isolated architectural remains, but to assemble an expansive, interoperable 3D dataset that reflects the full urban complexity of the site. From survey-grade sonar systems and precision photogrammetry to GPU-accelerated processing clusters and modular CAD toolkits, the selected technologies must align with proven applications in contemporary underwater archaeology and ensure long-term reusability, scalability, and accessibility (Yager et al., 2019; Fock et al., 2017).

The foundation of this infrastructure is a survey vessel in the 10–20 meter class, equipped with hull-mounted sonar and GNSS-based navigation. A Real-Time Kinematic Differential GPS (RTK-DGPS) unit is critical to achieving horizontal positional accuracy below ±5 centimeters, enabling precise placement of control points for all subsequent data acquisition. This system must be paired with an acoustic positioning solution such as the Sonardyne Ranger 2 USBL, which supports underwater tracking of ROVs and diver teams with accuracy near ±0.1 meters (Nornes et al., 2015). Together, these instruments provide a geodetic framework that unifies all datasets—whether sonar, photogrammetric, or laser-derived—within a single spatial coordinate system, an indispensable prerequisite for volumetric modeling and interpretative mapping of the submerged site.

For acoustic mapping, the Kongsberg EM2040P multibeam echosounder stands out as the optimal solution. Operating between 200–400 kHz and offering variable beam angles, it can produce highly accurate bathymetric maps in shallow coastal zones such as Aboukir Bay, where submerged features lie under just 10 meters of water. When integrated with an Applanix POS MV inertial navigation system, this configuration compensates for vessel motion, ensuring the fidelity of seafloor topography (Pacheco-Ruiz et al., 2018). Complementing this system, a side-scan sonar such as the Klein 3900—equipped with both medium- and high-frequency channels—can generate high-resolution sonar mosaics capable of resolving architectural fragments or statuary on the seabed. A sub-bottom profiler, such as a Stratabox or Teledyne Chirp system, allows penetration of up to 10 meters below the seabed with vertical resolution between 0.3 to 0.5 meters, identifying buried structures such as shipwrecks, foundations, and canal infrastructure. For ferromagnetic materials, the addition of a Geometrics G-882 cesium vapor magnetometer or Goddio's NMR magnetometer will assist in locating anchors, tools, and bronze fittings that often accompany maritime religious activity or port structures (Fabre & Goddio, 2013).

Photogrammetry, the cornerstone of detailed modeling, will require diver-operated systems equipped with full-frame mirrorless cameras housed in depth-rated underwater enclosures. Devices such as the Canon EOS R5 (45 MP) or the Sony A7R IV (61 MP), mounted in Ikelite or Nauticam housings and paired with wide-angle (14–20 mm) or fisheye (8–15 mm) lenses, offer the resolution and low-light capability needed for submerged imaging. Dual 5000-lumen strobes such as the Sea&Sea YS-D3 or Ikelite DS161 will ensure color fidelity, while focus lights enhance sharpness under low visibility. All imagery will be captured in RAW format to preserve dynamic range and color data for post-processing. The photogrammetric survey will rely on pre-placed, calibrated scale bars or laser scalers to provide accurate scaling during 3D reconstruction. For navigation, diver-propulsion vehicles (DPVs) or guide ropes will enable consistent imaging altitudes and patterns, minimizing redundancy while ensuring adequate overlap—typically 80% forward and 60% lateral—as recommended by the Pavlopetri project and NOAA's photogrammetric guidelines (Mahon et al., 2011; Dolezal et al., 2019).

To support broader and deeper coverage, robotic survey platforms are essential. A work-class ROV such as the Saab Seaeye Falcon, outfitted with a 4K video camera for real-time feedback and a 50+ MP still camera for photogrammetry, offers an adaptable solution for high-risk or hard-to-access zones. The payload skid will house the Voyis ULS-500 laser scanner, mounted at a 45° angle to scan temple facades, collapsed columns, or statues in exceptional detail. This ROV will also carry a compact multibeam sonar head (e.g., BlueView MB2250) to assist in spatial navigation and mapping in turbid or silt-laden conditions (Roman et al., 2010). For larger-scale missions, an AUV such as the REMUS 100 or Kongsberg HUGIN can execute low-altitude flyovers, capturing photomosaic imagery at intervals of one image per second. These platforms are capable of covering 5–10 km² per mission and maintaining consistent altitudes using depth sensors and Doppler velocity logs (DVLs). Post-processed inertial navigation combined with acoustic beacon triangulation will further refine image georeferencing for photogrammetric alignment (Viswanathan et al., 2017).

The vast volume of data—potentially dozens of terabytes across images, sonar, and laser point clouds—necessitates powerful computing hardware. A high-performance local workstation with at least 128 GB of RAM, 16-core CPUs, and dual high-end GPUs (NVIDIA RTX 6000 or 4090) will accelerate image alignment, point cloud generation, and mesh creation through GPU-optimized software like Agisoft Metashape. NVMe-based RAID SSD storage will support rapid read-write access during large data merges. For handling the full-resolution composite model—particularly during the fusion of laser, sonar, and photogrammetry data—a secondary HPC cluster or cloud-based rendering environment with 512 GB of RAM or more will be employed (Yager et al., 2019). Cloud-based GPU clusters will also assist in iterative texture refinement and model export across formats.

The software ecosystem underpinning this project must support flexible workflows, real-time previews, and scalable exports. Agisoft Metashape Pro (v1.8+) will serve as the primary photogrammetric platform, offering dense cloud generation, texturing, and model alignment tools. For rapid initial alignments or GPU-intensive projects, RealityCapture will serve as an alternative pipeline. For sonar data, CARIS HIPS & SIPS and QPS Qimera offer high-end hydrographic processing with support for bathymetric error correction, surface modeling, and export in industry-standard formats such as GeoTIFF and XYZ. Laser scan point clouds (typically in E57 or LAS formats) will be processed in proprietary tools like Voyis Sight or SL Software, then merged using CloudCompare and aligned via Iterative Closest Point (ICP) algorithms. Final meshes will be cleaned and optimized in Blender, Autodesk 3ds Max, and Rhino, with options for AI-assisted hole filling and topology simplification via ZBrush or Meshmixer (Teague & Scott, 2017). Furthermore, for CAD-based reconstructions of partially recovered architecture, Rhino and AutoCAD will be used to generate clean, scale-accurate architectural primitives. These models will be clearly flagged as hypothetical or extrapolated when joined to the confirmed archaeological record. GIS platforms such as ArcGIS and QGIS will integrate excavation records, site maps, and historical canal data into the broader context model. Procedural modeling tools may later assist in AI-based extrapolations of missing site elements.

Texturing pipelines will employ Substance Painter and Adobe Photoshop to refine and equalize photogrammetric textures. These will be exported as 8k–16k PBR texture maps (diffuse, normal, roughness), and applied to the master meshes to simulate natural lighting across viewing conditions. Tools like ESRGAN will upscale lower-resolution textures where needed, while neural colorization could assist in generating reconstructions of painted surfaces based on pigment traces and historical parallels (Drap et al., 2015). Each object will retain dual texturing: one for the current underwater state and another for potential "as-built" reconstructions in VR simulations. In terms of file formats and data interchange, all outputs will be in standardized formats such as OBJ, FBX, glTF (for web and real-time environments), and USDZ (for AR deployment on Apple devices). These ensure that the resulting models are compatible with downstream applications in Unreal Engine, Unity, Sketchfab, and museum visualization systems. All source data and workflows will adhere to FAIR data principles (Findable, Accessible, Interoperable, and Reusable), maximizing the research impact and enabling reproducibility. The full specifications can be found in Table 4.

Table 4: Hardware and Software Specifications for Digital Reconstruction

Category	Component / Tool	Specification / Description
Survey Vessel & Navigation	Survey Boat + DGPS + USBL	10–20 m vessel; RTK-DGPS (<±5 cm accuracy); Sonardyne Ranger2 USBL (~±0.1 m underwater accuracy)
Multibeam Sonar	Kongsberg EM2040P	200–400 kHz; <0.1% depth error; swath width ~5× water depth; high-res bathymetric mapping
Side-Scan Sonar	Klein 3900	Dual frequency: 445 kHz (5 cm resolution), 900 kHz (1–2 cm resolution); acoustic mosaic imaging
Sub-Bottom Profiler	Stratabox or Teledyne Chirp	Frequency: 3–7 kHz primary; up to 15 kHz secondary; ~0.3 m vertical resolution
Magnetometer	Geometrics G-882 / NMR Magnetometer	Sensitivity ~0.001 nT; detects metallic artifacts (iron, bronze, etc.)
Diver Cameras	Canon EOS R5 or Sony A7R IV	45–61 MP full-frame sensors; wide-angle (14–35 mm) or fisheye (8–15 mm) lenses; RAW image capture
Underwater Housing & Lighting	Nauticam or Ikelite housing, Sea&Sea YS-D3 / Ikelite DS161	Depth rating >40 m; dual strobes (>5000 lumens each) with focus lights
ROV Platform	Saab Seaeye Falcon or similar	6+ thrusters; depth rating ~300 m; fiber-optic tether; 4K video & 50+ MP still cameras
AUV Platform	REMUS 100 or Kongsberg HUGIN	12 MP camera; bathymetric & photomosaic mapping; endurance ~8 hours at 2–3 knots
Laser Scanner	Voyis (2G Robotics) ULS-500	Millimeter-scale precision; operates effectively in low-visibility water
Processing Hardware	High-performance workstation + Cloud HPC	≥128 GB RAM; 16+ core CPU; Dual NVIDIA RTX 6000/4090 GPUs; NVMe SSD storage; external server with ≥512 GB RAM
Photogrammetry Software	Agisoft Metashape Pro, RealityCapture	Dense cloud, mesh, texture creation; GPU acceleration
Sonar Processing Software	CARIS HIPS & SIPS, QPS Qimera, SonarWiz	Bathymetric processing, side-scan mosaics, DTM generation
Laser Scan Processing	Voyis Sight or 3D at Depth SL Software	Calibration and export point clouds (E57, LAS formats)
Point Cloud Processing	CloudCompare, Autodesk Recap, Leica Cyclone	Point alignment, merging, and data cleaning
3D Modeling	Blender, Autodesk 3ds Max, Rhino, ZBrush	Mesh optimization, detail reconstruction, CAD modeling for incomplete architecture
GIS / CAD Integration	QGIS, ArcGIS, AutoCAD	Spatial integration of archaeological site plans and excavation data
Texturing and Materials	Substance Painter, Adobe Photoshop	8k–16k resolution textures; color correction, AI texture upscaling (ESRGAN)
AI/ML Tools	Python with OpenCV, TensorFlow, PyTorch	AI-based image processing, GAN artifact reconstructions, procedural modeling
Recommended File Formats	OBJ, FBX, glTF, USDZ, GeoTIFF, E57, LAS	Open standards ensuring cross-platform interoperability

5.3 Data Acquisition Pipeline (Field to Lab)

The success of a digital reconstruction initiative relies on a carefully structured pipeline that transforms field data into high-fidelity 3D models. This pipeline unfolds through distinct yet iterative phases: planning and reconnaissance, wide-area sonar mapping, targeted ROV exploration, diver photogrammetry dives, and rigorous data management. Each step ensures data integrity, spatial accuracy, and completeness, while allowing for refinement based on emerging insights. This approach builds on best practices established in large-scale underwater heritage projects such as Pavlopetri and the Black Sea MAP, where modular workflows and multiscale data integration have proven critical (Henderson et al., 2013; Drap et al., 2015). The aim is to balance efficiency and scientific rigor, ensuring that all collected data can be merged into a coherent, georeferenced framework that supports both scholarly interpretation and public engagement.

Before deployment, a planning phase is essential to optimize resources and ensure spatial consistency. The archaeological team begins by reviewing existing maps, photogrammetric models, and excavation notes from previous IEASM field seasons to prioritize target areas. This might include key zones like the Temple of Amun-Gereb, known shipwreck clusters, or densely packed artifact deposits. GIS software is used to layer these records spatially, creating a master grid that guides multibeam coverage, diver paths, and ROV transects (Yager et al., 2019). Environmental data—such as seasonal turbidity, tidal cycles, and wind forecasts—help determine optimal dive times, especially for photogrammetry, where visual clarity is paramount. Calibration exercises are run at a test site using known-scale objects to align camera rigs, test lighting setups, and verify sonar and laser system calibrations. These ensure that all subsequent data is spatially and metrically reliable. The final deliverable is a day-by-day survey plan, balancing technologies across zones and environmental conditions. This might include, for example, multibeam lanes with 200% overlap, side-scan sonar swaths at 50 m intervals, and diver transects that revisit previously scanned terrain for additional detail.

The multibeam sonar survey establishes the foundational terrain model of Thonis-Heracleion's 11×15 km submerged footprint. The survey vessel conducts this using a lawnmower pattern, moving back and forth in parallel lines to generate overlapping sonar beams for seamless bathymetric coverage. Each swath reveals subtle seafloor topography—mounds, depressions, ridges—that may correspond to temples, walls, or canal embankments. The side-scan sonar follows, operating at a higher frequency to resolve discrete objects: rectangular blocks, stone anchors, or the acoustic shadow of a keel of the ship (Pacheco-Ruiz et al., 2018). Sub-bottom profiling is conducted over areas expected to contain buried architecture, especially temple zones where liquefaction layers suggest submersion. Chirp sonar echoes are recorded and interpreted in real-time to identify buried features for subsequent excavation or ROV inspection. All sonar data is tagged with GNSS timestamps and inertial motion readings, allowing precise alignment during post-processing. The result is a series of foundational spatial datasets: a DEM (digital elevation model), side-scan mosaics, and 2D profiles of sub-seafloor stratigraphy. These base layers inform all subsequent survey decisions and serve as the topographic canvas upon which higher-resolution models are layered (Roman et al., 2010).

Building on sonar results, a ROV mission is initiated to visually confirm and document priority anomalies. Once deployed, the ROV navigates to GPS-registered sonar targets, using its onboard sonar and cameras to re-locate features such as collapsed buildings or large statues. A slow fly-over provides 4K video for interpretive context, then the ROV performs photogrammetric capture by station-keeping at ~2 m altitude and shooting high-res still images at regular intervals. Dual laser pointers, set to a known separation, appear in every frame and provide scale for 3D reconstruction. For particularly significant finds—such as a decorated stele or a unique hull form—the ROV hovers and completes a 360° imaging loop. If the ROV is outfitted with a laser scanner, it can switch to active scanning mode, collecting a dense point cloud of the target. This hybrid photogrammetric-laser scan dataset will later be merged into a precise mesh of the object. The Black Sea MAP project demonstrated that such integration can yield a metric-accurate model within 12 hours of discovery (Henderson et al., 2013). All ROV data—images, video, sensor readings—is time-stamped, catalogued, and immediately backed up upon recovery for redundancy.

In parallel with ROV operations, dive teams will focus on documenting shallow, accessible areas. These include large temple platforms, clusters of statuary, and intact foundation lines. Each dive begins with the deployment of scale bars or coded targets to serve as reference points for the photogrammetric software. Divers follow a grid or rope line to ensure consistent altitude and directional flow, capturing images with 70–80% overlap in both directions. Coverage includes both nadir and oblique angles to reduce occlusions. Features are circled with overlapping rings of photos to capture all sides. Where objects can be moved (e.g. small statues or amphorae), they are documented both in situ and ex situ under controlled lighting in the lab. Each diver's camera settings, lens type, and lighting configuration are logged for metadata accuracy. Surface intervals are used to offload and organize image sets, which are indexed by location and time. Small subsets of each session are processed overnight to generate quick-look models—allowing gaps to be identified and filled on subsequent dives (Drap et al., 2015).

Throughout the acquisition phase, digital asset management protocols are rigorously enforced. Every photograph, sonar ping, ROV log, and video feed is duplicated to at least two separate storage devices—one local and one off-site when feasible. A metadata schema links each file to its spatial origin, time of collection, and associated hardware. This includes noting GPS coordinates, diver or operator ID, camera/lens used, and environmental conditions. A centralized version-controlled repository (e.g., Git LFS or an archaeological information system like Arches) is updated daily. This system supports traceability from field collection to final model, enabling each digital object to be tied to its physical or geospatial context. When speculative reconstruction occurs later, this provenance data ensures transparency about which features are derived from empirical data versus inference. As image sets grow into the tens of thousands, automation tools will tag, compress, and archive them for long-term storage. The output is a living database that grows with each survey season, enabling longitudinal tracking of excavation and modeling progress (Fock et al., 2017).

5.4 Data Processing and 3D Modeling Pipeline

Once data acquisition is complete, the raw field datasets—comprising sonar soundings, photographic image sets, and laser scan point clouds—must be transformed into an accurate, coherent 3D reconstruction of the site. This transformation is both computationally intensive and methodologically complex, involving several interlinked stages. These include processing the sonar data to generate a digital terrain model (DTM), photogrammetric processing to produce high-resolution meshes of architectural remains, laser scan integration for enhanced geometric fidelity, and merging of all assets into a single georeferenced model. Each stage requires rigorous quality control and, where possible, automation to reduce manual alignment. The workflow adopted here builds on established pipelines from comparable projects, such as Pavlopetri, Baia, and multiple Mediterranean shipwrecks, where multi-modal data integration has become the standard approach to submerged site documentation (Balletti et al., 2016; Gallo et al., 2012).

The first step in digital reconstruction involves transforming multibeam and side-scan sonar data into a foundational 3D terrain. Raw bathymetric soundings are imported into hydrographic software such as CARIS or QPS Qimera, where motion compensation, refraction correction, and sound velocity profiles (via CTD casts) are applied to refine positional accuracy. The gridded output—a DEM with cell sizes ranging from 0.5 m for general coverage to 0.1 m in high-interest zones—yields a 3D surface map of the seabed. While this terrain model lacks fine resolution for small artifacts, it provides essential macro-topographic context. Next, side-scan sonar images are processed in SonarWiz or CARIS SIPS, correcting for slant range and producing geo-referenced acoustic mosaics. These mosaics, draped over the DEM, help identify discrete reflective anomalies—possible architectural fragments or ship remains. Sub-bottom profiles, while not part of the 3D geometry, inform where underlying layers suggest buried structures. These sonar-derived surfaces are then exported in OBJ or GeoTIFF formats for integration into the broader 3D model (Nelson et al., 2014; Dong et al., 2017).

Thousands of underwater images captured via diver or ROV are processed using SfM photogrammetry. In Metashape Pro, images are grouped into discrete chunks representing individual structures (e.g., Temple of Amun façade, a sphinx cluster) to maintain memory efficiency and reduce processing time. Lens parameters are pre-calibrated via checkerboard tests, though the software can estimate intrinsics during image alignment. Image matching then identifies keypoints across overlaps, calculating camera positions and generating a sparse point cloud. Following validation (e.g., low reprojection error and proper camera orientation), a dense point cloud is created, often numbering in the millions. Noise is filtered—removing outliers caused by suspended particulates or marine life—and the refined cloud is meshed using depth-mapping techniques. For smoother surfaces like columns or hull timbers, a denser mesh (≥10 million faces) is allowed; for flatter features, simplification is applied. Texture maps are created by projecting and blending the original images, producing high-resolution color renderings of the model. The result is a set of textured 3D models (e.g., templeA.obj + templeA.jpg) for each surveyed feature (Cotugno, 2017; Fock et al., 2017).

As shown in the Pavlopetri project, segmenting the site into manageable zones is crucial for both data volume and spatial control (Mahon et al., 2011). Once all sub-models are generated, a global alignment process is carried out. Three or more tie-points visible in overlapping chunks are identified and matched within Metashape or CloudCompare. Where available, DGPS data from diver descent points or ROV beacon logs are used to assign approximate geospatial coordinates. This facilitates rigid transformation of the models into a shared site-wide coordinate system, followed by Iterative Closest Point (ICP) alignment for fine-tuning. The outcome is a seamless reconstruction of the visible architecture of the city—one that maintains metric scale and true spatial relationships.

To augment photogrammetric models, dense laser scan point clouds (collected via devices such as the ULS-500) are incorporated next. These scans—often comprising millions of points per object—are aligned with the photogrammetry-derived meshes using shared control features, such as corners, edges, or scale bar endpoints. In software such as CloudCompare or Geomagic, manual tie-point picking is followed by ICP registration to refine fit. If laser scans offer superior geometry (e.g., clearer inscription depth), we may project the mesh onto the laser points, effectively remeshing with improved accuracy. Alternatively, point fusion algorithms can blend both datasets, preserving laser-derived edge fidelity while retaining the texture from photogrammetry. Where laser data fills in occluded areas or the undersides of statues, these patches are retained as supplemental meshes and merged at the boundary level. This hybrid approach ensures a high-resolution composite that surpasses what either method can achieve alone (Bleier et al., 2019; Jiang et al., 2017).

Once photogrammetry and laser data are finalized, these models must be spatially merged with the sonar-derived terrain. Often, photogrammetry includes bits of seafloor at the base of structures—these anchor points help georegister the high-res models to the lower-res bathymetric mesh. By selecting common features (e.g., the base of a statue, the corner of a stepped platform), we can scale and align the models via affine transformation. In Blender or Meshlab, the terrain mesh is either unioned (with clean edge joins) or remains a separate layer under the high-resolution structures. This modular approach is especially useful for interactive viewers where LOD streaming may be needed. The result is a complete 3D model of Thonis-Heracleion as it exists underwater today: detailed structures overlaid onto a regional bathymetric base, suitable for archaeological analysis, visualization, and future reconstruction phases (Guerneve & Pétillot, 2018).

For use in web viewers, VR headsets, or real-time simulation engines, the model must be optimized without losing integrity. We begin by organizing the model into semantically meaningful layers: terrain, architecture, statuary, sediment, and metadata (e.g., inscriptions, find locations). Some layers may be subdivided further—“architecture” into “walls,” “columns,” “thresholds,” etc.—especially if dynamic toggling is needed for education or scholarly analysis. Level of Detail (LOD) models are then created using decimation tools in Blender or MeshLab. These retain geometric fidelity at multiple scales, allowing quick rendering on low-power devices. Normal and ambient occlusion maps are baked from the high-res model to visually enhance the low-res versions in real-time applications. This optimization step is critical for future deployment in Unity, Unreal Engine, or glTF-based web interfaces (Wu et al., 2023; Fan et al., 2024). It also makes downstream annotation, tagging, and public sharing much easier.

Before concluding this phase, the composite model undergoes systematic verification. It is overlaid on sonar base maps and sub-bottom interpretations to confirm spatial congruence. Linear measurements in the model are checked against physical site data (e.g., known column spacings or stele heights), with any inconsistencies corrected in the source software. Cross-sections are compared in GIS or CAD to ensure proper elevations and alignments. Key views (from diver photos or ROV video) are simulated in Blender’s camera to check that model perspective matches real-world captures. This “view verification” is especially useful for public-facing content. All segments are logged and version-controlled. Errors or uncertainties are documented as part of the model metadata so that future updates or reinterpretations can occur transparently. At this point, the data-driven portion of the reconstruction concludes, yielding a scientific model ready for AI-assisted extrapolation and immersive visualization.

5.5 AI-Guided Extrapolation of Missing Elements

Once the empirical 3D model is complete—anchored in rigorous sonar, photogrammetry, and laser scan data—the next phase of the reconstruction pipeline extends into the realm of informed speculation. This phase, framed as a digital anastylosis, involves AI–driven extrapolation to reconstruct architectural, urban, and artistic features that have not survived but are attested in the historical record or in comparative typologies. The objective is to complement archaeological rigor with algorithmic inference, producing plausible digital reconstructions that remain transparent about their evidentiary status. Emerging methods in generative modeling, procedural simulation, and neural representation offer robust frameworks for such tasks (Croce et al., 2023; Stoean et al., 2024). Importantly, all generated content is subject to human validation, ensuring scholarly plausibility remains the cornerstone of the process.

The extrapolation process begins by identifying which components of the city require reconstruction. These include the upper stories of temples whose foundations are preserved, wooden quays that have decayed, symmetrical statues represented only by fragments, and elements like pylons or ornamentation that are inferred but undocumented. Primary sources such as Herodotus’ description of the Heracleion temple, iconography from Nile Delta temples, and urban typologies from contemporaneous cities like Canopus provide a historical context for hypothesizing reconstructions. This comparative corpus, used in tandem with the partially excavated site model, establishes a robust foundation for the generative tasks (Georgopoulos, 2014; Chabuk & Al-Amiri, 2022). In particular, known proportions of Egyptian architecture—such as the diameter-to-height ratios of columns or canonical axis alignments of sanctuaries—provide geometric rules that can be formalized for parametric modeling and inference.

Each target class—temples, statues, ship remains, and urban layouts—requires curated training data for the AI system. For temple reconstruction, datasets will include orthographic plans, cross-sections, and 3D scans of Late Period Egyptian temples (e.g., Karnak, Medinet Habu), particularly those situated in the Delta. When modeling statuary, a neural net may be trained on high-resolution photogrammetry or laser scans of Hapy, Isis, and pharaonic effigies to learn geometric grammar and material characteristics (Stoean et al., 2024). City-level extrapolation can draw on GIS data of Nile port towns to identify recurring spatial logics—e.g., alignment of sacred precincts, granaries, and harbors. These datasets may be formatted as structured meshes, orthomosaics, point clouds, and rasterized plans for multimodal ingestion by the generative pipeline. The ROSETTA project from Purdue University offers a precedent for using this strategy in architectural prediction, where neural networks learn from fragmentary urban datasets to generate plausible structural hypotheses (Verdiani, 2017).

The reconstruction process uses several categories of intelligent tools. Multimodal models are employed for image and shape inpainting. For instance, 2D GANs can complete broken inscriptions, while 3D GANs generate full shapes from fragmentary inputs, as recently demonstrated in restoration tasks using NeRF and diffusion-based models (Stoean et al., 2024; Qu, 2024). Procedural modeling augmented with rule-based AI enables the extrapolation of architectural forms. Here, the technology optimizes column placement, roof slopes, and symmetrical alignments to match known Egyptian design standards. This approach treats the problem as an inverse model: given preserved foundations, what 3D geometry most plausibly fills in the void? Text-based models like GPT also contribute. For example, a prompt containing the Herodotean account of the temple can guide the design of a candidate model, which is then filtered against known archaeological constraints (Arzomand et al., 2024). These language models assist in bridging textual evidence with spatial reasoning. Lastly, image-to-image models like Stable Diffusion, such as style transfer models and super-resolution algorithms, reconstruct worn or partially eroded textures, including inscriptions, paintwork, or statuary surface treatment (Croce et al., 2023).

The operational pipeline begins with tagging gaps in the archaeological model—these can be areas of missing architecture or partially preserved artifacts. Constraints are then specified: for example, reconstructing a column from a preserved drum segment, estimating the likely full height (~5 m) based on typical proportions. The AI then proposes multiple candidate geometries, which human experts evaluate. Procedural software like Esri CityEngine or parametric systems in Blender (e.g., Sverchok nodes) can generate these structures under guidance from the AI, which adapts known templates to match the real-world footprint. In this human-in-the-loop model, archaeologists confirm or reject AI proposals, often refining outputs manually. This strategy ensures historical plausibility, as seen in recent studies that integrate GANs and procedural generation for heritage restoration (Cipriani et al., 2019). In simulating broader urban layout, AI agents can "grow" a plausible settlement pattern based on Nile Delta precedents, optimizing for factors like water access, procession routes, and spatial zoning.

To illustrate, let us consider the Temple of Amun. Its base plan is preserved, with several architectural fragments such as column drums and lintels. We begin by using procedural modeling tools, enhanced by AI inputs trained on other Amun temples, to extrapolate columns, architraves, and roofing patterns. If column fragments measure 1 m in diameter, the model might propose a height of 6 m and suggest a lotus or papyrus capital based on visual analogues. Neural networks trained on depictions from temple reliefs may also propose likely decorative patterns. These outputs are validated by comparing against known proportions and visual references, such as iconography on the Ptolemaic stele found nearby. Decoration and color can also be estimated. Egyptian temples were richly painted; AI-assisted style transfer from extant polychrome samples (e.g., Karnak) can recolor our reconstructed geometry. As demonstrated in other cultural heritage applications, NeRFs and GANs can generate richly textured views even from partial data, enabling interactive and immersive renderings (Croce et al., 2023; Qu, 2024).

Maintaining a clear distinction between empirical and speculative content is critical for ethical and scholarly integrity. Each generated component is tagged within the model and tracked in metadata. This transparency allows toggling between “current condition” and “reconstructed” states in interactive applications—essential for museum installations and academic reviews. The training sets, versioning, and output rationales are documented in a model registry. This practice aligns with current digital heritage ethics, which emphasize interpretive accountability, especially when deploying AI in reconstruction workflows (Georgopoulos, 2014; Arzomand et al., 2024). Future findings may require retraining the AI models or updating reconstructions—a workflow that is facilitated by retaining the generative inputs and configurations. Open metadata frameworks, such as the CIDOC CRM standard, can be employed to catalog the provenance and epistemic status of each model element.

Beyond architectural elements, AI also supports artifact-level restoration. For example, ceramic vessels fragmented into dozens of sherds can be digitally reassembled using GANs trained on amphora typologies. Recent work by Stoean et al. (2024) demonstrated that 3D AI can not only rejoin fragments but also hallucinate missing portions based on training samples, enabling reconstruction of 80–90% complete artifacts. The same logic applies to statuary. If only half of a statue survives (e.g., one side of a Pharaoh's bust), a neural mirror function can generate the missing half, aligned to canonical facial symmetry. Where documentation attests to the existence of now-missing items—such as a statue described by ancient authors—AI can propose geometry based on regional and chronological exemplars. These models are always flagged as hypothetical, with their visual appearance derived from validated datasets. They serve both scholarly and curatorial purposes, allowing virtual reconstructions to approximate the full ensemble of the ceremonial landscape. This stratified approach empowers scholars, conservators, and the public to engage with the site at different levels of interpretive granularity, making Thonis-Heracleion not only more accessible, but more intelligible.

5.6 Environmental Rendering and Visualization

With the architectural and reconstructed model fully developed, the next phase involves translating this dataset into compelling and immersive visual formats. These visualizations not only enhance scholarly interpretation but also allow the public to engage meaningfully with a site otherwise inaccessible due to its underwater location. Environmental rendering bridges the gap between empirical data and interpretive storytelling, requiring the simulation of water, light, and atmosphere—whether for photorealistic reconstructions of the submerged city today or imaginative renderings of its above-water past. Recent research in digital heritage visualization underscores that realism, interactivity, and multi-platform delivery are now essential components of impactful archaeological communication (Bruno et al., 2010; Cipriani et al., 2019).

For an immersive VR experience that simulates diving in present-day Thonis-Heracleion, a virtual underwater environment must be carefully modeled to reflect real optical, acoustic, and environmental conditions. In game engines like Unreal Engine 5 or Unity, volumetric fog is used to simulate underwater haze—adjusted to represent the greenish-blue diffusion seen in 10-meter depths typical of Aboukir Bay. Dynamic lighting, such as simulated "God rays" from a virtual sun filtered through a refractive water surface, helps replicate natural light scattering in shallow marine contexts. Particle systems introduce floating silt, air bubbles, and suspended matter, enriching realism. The seabed can be textured with tiled photogrammetry-based samples captured from actual sediments, and supplemented with procedural vegetation (e.g., modeled seaweed or marine encrustations). In scenes rendered from diver perspectives, dynamic lighting is crucial: red tones are naturally filtered out at depth, but a diver's torch restores full-spectrum illumination locally. Allowing users to "reveal" original textures by pointing a light source provides an interactive, educational experience that mirrors real diving conditions (Croce et al., 2023). These effects also support cinematic fidelity, where controlled light passes and artificial enhancement ensure key ruins are visible in darker waters without compromising authenticity.

To visualize Thonis-Heracleion in its original, above-water state, the AI-extrapolated city model is repositioned in a dry, historically reconstructed Nile Delta landscape. Topographic models are adjusted for Late Period sea levels (~6 meters lower than today), and historic flow patterns of the Canopic branch of the Nile guide river and canal placement. Terrain meshes are built using software such as World Creator or derived from GIS layers calibrated against satellite altimetry and paleo-hydrological models. Vegetation—such as papyrus reeds and palm groves—is procedurally generated to mirror ecological reconstructions of the Delta (Arzomand et al., 2024). City infrastructure (temples, housing, harbors) is arranged according to both archaeological evidence and Egyptian urban planning norms. Textures shift to a "reconstructed" look: temple walls are rendered in smooth limestone with painted reliefs, docks and houses in mudbrick with thatched roofs, informed by polychromy remnants and textual descriptions (Chabuk & Al-Amiri, 2022). AI-based style transfer tools can colorize these surfaces using pigment patterns drawn from comparable sites. Lighting systems within the game engine mimic subtropical solar angles, generating warm shadows and high-contrast scenes reflective of a Nile-side environment.

To support both high-fidelity rendering and wide accessibility, two master scenes—one underwater and one above-water—will be developed within Unreal Engine 5. This engine's Nanite system allows the import and real-time rendering of massive polygon counts, ideal for the billion-poly model of Thonis-Heracleion's ruins. Lumen, Unreal's real-time global illumination system, simulates realistic light bounce and occlusion, crucial for illuminating temple interiors or shaded canals. For underwater scenes, Lumen settings are adjusted or replaced with baked lighting to reduce rendering overhead on mid-tier machines. If needed, fallback models using LOD (Level of Detail) versions are generated, with texture baking and static lighting applied. These adaptations make the scenes compatible across platforms from high-end VR rigs to lower-performance AR devices (Bruno et al., 2010; Croce et al., 2023). All models are modular, enabling toggling of modern and ancient states or user-selected overlays (e.g., toggling speculative reconstructions).

To support exhibits and digital storytelling, cinematic sequences will be rendered using Unreal's Sequencer or Blender's Cycles engine. These scripted camera movements include dive sequences that transition from surface to ruins, fly-throughs of ancient processional ways, or isometric overviews for documentary narration. Animated elements enhance storytelling: divers with realistic breathing motions, fish schools passing ruins, or scenes depicting ancient harbor life. While peripheral to core archaeological content, these visual touches help convey human scale and environmental context. Output is rendered in 4K resolution with HDR color and spatial audio. In keeping with scholarly transparency, every animated shot is based on site-accurate geometry; nothing is added without grounding in model data or AI-inferred extrapolations documented in metadata (Gallo et al., 2012; Cipriani et al., 2019). This ensures that public engagement is both impactful and responsible.

For interactive use in museums, academic demonstrations, or public VR apps, platform-specific optimization is critical. On high-end PC VR systems (e.g., Oculus Rift S, HTC Vive Pro), the full-resolution Nanite model can likely run with 90 FPS or higher with occlusion culling, dynamic shadows, and full-resolution materials. For standalone devices (e.g., Oculus Quest 3), optimized versions of the scene are created: static lighting, baked shadows, reduced texture resolution (~2K), and model decimation down to ~200,000 polygons. For AR applications—especially in museum contexts—models are exported in USDZ (Apple) or glTF formats (cross-platform). These allow users to view temple models projected onto physical maps, or use tablets as windows to "see through time." While AR rendering omits water and fog for performance reasons, it enables location-based storytelling and educational overlays. Recent studies have shown that combining accurate models with optimized delivery formats increases accessibility across age and expertise levels (Bruno et al., 2010; Cipriani et al., 2019).

To reach the broadest audience, a web-based 3D viewer will be deployed using WebGL frameworks such as Three.js or Babylon.js. The models will be exported in glTF/glb format, known for its compact size and real-time PBR support. Features will include orbit navigation, zoom, annotations, and clickable elements that reveal archaeological or textual metadata. For instance, clicking a statue may bring up a historical account, excavation log, or 3D scan metadata. File sizes are optimized: we may split the site into "zones" (e.g., harbor district, temple complex) to allow selective loading. Platforms like Sketchfab allow LOD switching and support annotations and VR browser modes. We follow the European Commission's guidelines recommending open formats—OBJ, PLY, glTF—for longevity and accessibility (Chabuk & Al-Amiri, 2022). For archival purposes, high-resolution backups are kept in USD and OBJ formats for long-term use, particularly in academic repositories or open science platforms.

Though often secondary to visuals, sound is essential in producing immersive and emotionally engaging experiences. In VR, spatial audio tracks can replicate the gurgling of underwater currents, diver breathing, or the rhythmic sweep of an ROV. In ancient city visualizations, soundscapes might include market chatter, priestly chants, and ship docking noise—based on both archaeological inference and historical texts. For educational VR and AR, interactive narrations can guide users through significant locations, linking the model to both historical events and modern scholarship. All sounds are localized in 3D space using the audio engines in Unreal or Unity, allowing realistic spatialization. This layer helps bridge passive and interactive experiences and reinforces the sense of place within a deep temporal context (Bruno et al., 2010). Voiceover scripts are developed in consultation with Egyptologists and maritime historians to maintain scholarly rigor even in public-facing content.

5.7 Post-Production Optimization for Platforms

Following the development of a comprehensive and high-fidelity 3D reconstruction of Thonis-Heracleion, the final phase involves tailoring that master model for deployment across a range of digital platforms. This post-production stage focuses on optimizing the model's geometry, texture resolution, lighting, and interactivity for varied performance environments—including high-end VR, standalone mobile devices, museum installations, web browsers, and cinematic animation. These adaptations are not superficial; they are essential to maintaining performance, usability, and visual fidelity without sacrificing archaeological integrity. Recent digital heritage research emphasizes the importance of delivering models that are not only technically impressive but context-sensitive and platform-compatible (Bruno et al., 2010; Cipriani et al., 2019). The following outlines the optimization strategy per platform, including justifications for tool choices and format conversions, all aligned with the long-term goals of accessibility, scalability, and interoperability.

For PC-based headsets (e.g., HTC Vive Pro, Oculus Rift S), Unreal Engine 5 offers an unparalleled rendering environment. We will enable Nanite, Unreal's virtualized geometry system, which allows real-time rendering of extremely high-polygon models without traditional decimation workflows. This is critical for handling Thonis-Heracleion's dense urban and sculptural detail. GPU-based lightmap baking will be employed for underwater scenes, particularly since the lighting environment is relatively static (e.g., sunlight filtered through water). Unreal's volumetric fog, coupled with MIP-mapped textures and dynamically adjusted draw distances, will ensure visual immersion without frame rate penalties. Key interaction features—such as teleportation, object inspection (e.g., picking up a virtual amphora), and toggleable layers—will be implemented using built-in physics and collision systems. These will be optimized using simplified collision meshes to reduce overhead. The entire scene will be tested to sustain 90 frames per second (FPS), ensuring comfort and immersion, with fallback mechanisms such as section-based loading for the most complex areas (Croce et al., 2023).

For wireless headsets such as Oculus Quest 3, optimization is critical due to lower GPU and RAM resources. Unity is more suitable here due to its Universal Render Pipeline (URP), which is tailored for mobile platforms. We will decimate the model to under 500,000 polygons and use static lighting (baked shadows, precomputed illumination) to avoid real-time processing costs. Textures will be downscaled to 2K resolution, and scenes will be modularized: for instance, the Amun temple, harbor, and statue grove become individual Unity scenes. These can be loaded independently through teleport-like transitions, maintaining engagement while managing memory. User interaction will be limited to tap-or-gaze hotspots with predefined behaviors. Previous studies confirm that such modular design ensures performance without alienating mobile users from scholarly content (Chabuk & Al-Amiri, 2022).

For non-interactive videos—used in museum films, documentaries, or exhibitions—rendering can prioritize fidelity over performance. Blender's Cycles engine or Autodesk 3ds Max with V-Ray will be used to generate 4K cinematic sequences. Since these are offline processes, we can render individual frames with global illumination, volumetric shadows, and particle-based water or fire effects. To manage complexity, non-visible elements are culled per frame. Sequences might include dynamic camera paths transitioning from surface to seabed or ancient harbor flyovers. These cinematic clips will be narrated, color-graded, and mixed with ambient sound for maximum impact. The only optimization here is scene subdivision to keep memory within manageable GPU limits. Because this mode is not frame-dependent, quality can be maximized without compromising interactivity (Bruno et al., 2010).

For kiosks, touchscreens, or table-mounted screens, we will deploy an interactive application on a local PC equipped with a modern GPU. Since VR is not required, we target 30–60 FPS. The application, built in Unity or Unreal Engine, will let visitors navigate the model using touch gestures or mouse/keyboard.

Interaction includes layer toggling (e.g., “show ancient version”), artifact pop-ups, and guided tours. The model’s modular design means this application can reuse VR-ready assets, minimizing duplication. In some cases, a web-based wrapper (e.g., Electron + WebGL) could be used, but for maximum stability and local performance, a native app is preferred. We will export Unity Reflect versions if integration with BIM or archaeological databases is planned. This allows curators to link 3D objects to backend CMS entries, enhancing both scholarship and visitor experience (Cipriani et al., 2019).

Web accessibility will be achieved using glTF/glb formats, optimized through mesh decimation and texture compression. We will segment the city into thematically coherent parts—e.g., sacred district, residential docks, processional way—to ensure fast loading. Draco compression will be applied to meshes, and textures will be converted to GPU-friendly formats like WebP or KTX2. Target file size per model will be ~200 MB or less. The viewer will be built using Three.js or Babylon.js, with UI overlays for navigation, toggling states (modern vs. ancient), and displaying annotations. Sketchfab may be used for hosting, leveraging its integrated VR support. For AR, models can be displayed via WebXR—allowing users to place temple miniatures on their table via smartphones. This has become an effective tool in educational outreach, giving users a tactile sense of archaeological scale and form (Croce et al., 2023; Vandenabeele et al., 2023).

For archival and interchange, we store point clouds in E57 (open format, supports color and normals) and meshes in OBJ (broad compatibility) and FBX (animation and hierarchy support). While OBJ lacks native support for physically-based rendering (PBR), it remains the most universally accepted format. FBX, though proprietary, is essential for interchange with Autodesk tools. For presentation and AR, glTF and USD/USDZ are preferred: glTF for web and cross-platform apps; USDZ for iOS devices (via QuickLook). USD supports complex hierarchies and metadata, ideal for models with archaeological layer tagging. This multi-format approach guarantees long-term accessibility and easy conversion to future platforms. Following the European Commission’s guidelines on digital heritage formats, we prioritize open standards while preserving fidelity across proprietary pipelines (Croce et al., 2023; Qu, 2024).

The pipeline is designed with future growth in mind. Master models and data assets are maintained at full resolution and version-controlled. As hardware improves—e.g., new GPU architectures or browser support for WebGPU—we can replace LOD models with higher fidelity ones without re-authoring. Logical scene structuring (e.g., separating terrain, architecture, statuary) ensures that new platforms can selectively ingest and reinterpret the data. For instance, a future research team could import the model into GIS, AR educational software, or AI-driven simulation tools with minimal preprocessing. This modular and standards-compliant design ensures the model is not just a showcase for today but a foundation for decades of scholarship and public engagement (Georgopoulos, 2014).

5.8 Interoperability and Data Management

A critical consideration in the digital reconstruction is ensuring that all resulting assets—ranging from raw point clouds to annotated 3D models—are widely accessible, easily exchangeable, and archivable for future use. In a field where datasets can reach terabytes in size and involve a multidisciplinary team of archaeologists, curators, technologists, and software developers, interoperability and data stewardship are as essential as visual fidelity. Ensuring longevity, transparency, and adaptability requires strict adherence to open standards, interoperable formats, and rigorous version control and documentation protocols. Best practices from digital heritage initiatives—including those promoted by the European Commission and organizations like the Getty and UNESCO—strongly advocate for open, platform-agnostic data formats, structured metadata, and robust archival planning (Croce et al., 2023; Cipriani et al., 2019).

All 3D models will be exported primarily in glTF 2.0 and GLB format—an open standard developed by the Khronos Group and widely referred to as the “JPEG of 3D” due to its efficiency and compatibility. glTF supports PBR (Physically Based Rendering) materials, ensuring consistent appearance across rendering engines, and is natively supported in platforms like Three.js, Babylon.js, Sketchfab, and Unreal Engine. For high-end AR and VFX applications, Universal Scene Description (USD) will be used. Developed by Pixar and adopted across multiple industries, USD—and its mobile subset USDZ—is ideal for handling complex scene graphs and metadata hierarchies. This is particularly important for museum use-cases, where hierarchical models with semantic tags (e.g., “Temple.Amun.Column.3”) may be linked to curatorial systems (Georgopoulos, 2014; Qu, 2024). USDZ also enables immediate integration into iOS environments via Apple’s QuickLook, allowing users to view virtual artifacts in situ on handheld devices. We will additionally provide FBX exports for compatibility with Autodesk tools and Unity’s animation system, despite its proprietary nature. As fallback options, we include OBJ+MTL (widely supported, though limited to basic materials), PLY (for colorized point clouds), and STL (for 3D printing applications). This multi-format strategy ensures resilience: even if one standard becomes obsolete, another remains usable.

Metadata is integral to usability, especially in a project that combines archaeological context, AI reconstructions, and layered time periods. Each 3D object—whether a temple wall, statue, or harbor quay—will be assigned a unique ID and corresponding metadata. This metadata, stored in a structured JSON or CSV file, includes fields such as findspot coordinates, excavation year, description, provenance confidence, and whether the object is empirical or AI-generated. glTF supports basic metadata through the “extras” field; more advanced scene metadata can be stored in linked sidecar files. In USD, metadata can be embedded at the object or scene level. This enables seamless linking to external museum databases, excavation logs, and even linked open data sources such as Wikidata. The annotation system is designed to be modular, allowing museums to append their own content (e.g., translated inscriptions, video commentaries) without altering the core model. This aligns with cultural heritage recommendations emphasizing extensibility and semantic traceability (Vandenabeele et al., 2023).

The project’s pipeline includes a range of software: Agisoft Metashape for photogrammetry, CARIS for bathymetry, CloudCompare for point cloud alignment, Blender for mesh refinement, and Unreal Engine for visualization. To ensure toolchain compatibility, all intermediate outputs are standardized using interoperable formats. Point clouds are stored as E57 or LAS (depending on color and normal data), and geospatial reference is consistently handled using WGS84/UTM coordinates. Meshes are passed between software in OBJ or FBX format. For example, photogrammetric meshes from Metashape are exported in OBJ, imported into Blender for cleanup, then brought into Unreal via FBX. By avoiding proprietary project files (e.g., native .blend, .max, or .rcproject), we ensure that no single tool becomes a bottleneck or obsolescence risk. The modular, layered approach to model construction also enables collaborative editing across different teams—whether a museum uses Maya and a research team uses Rhino, all are interoperable via shared formats (Croce et al., 2023; Chabuk & Al-Amiri, 2022).

For large-scale dissemination, especially online, we will implement scalable streaming approaches. While the base model can be pre-downloaded for local viewing, tiled or LOD-enabled streaming may be used for web-based 3D viewing. Tools such as CesiumJS and Google's Draco compression pipeline allow glTF models to be divided into spatial or resolution tiles. This enables smooth navigation even on lower bandwidth connections. For geospatial integration, the project may adopt 3D Tiles (an OGC open standard) for integration into digital terrain platforms or GIS viewers. While this may not be implemented at the initial stage, the model will be structured to allow future tiling if a full city-scale WebGIS or remote archaeological dashboard is developed. This enables use cases such as querying the city layout or artifact proximity in a geospatial context (Croce et al., 2023; Cipriani et al., 2019).

Given the project's multidisciplinary team and long-term nature, version control is mandatory. The team will use Git LFS (Large File Storage) or an equivalent system that tracks not only code and annotations but also heavy binary assets (e.g., textures, meshes). Each iteration of the master model will be tagged, allowing rollback or comparison. Metadata will record who made changes, when, and why (e.g., "TempleA wall height adjusted to match newly discovered foundation block"). This traceability ensures scholarly accountability and supports iterative refinement as new data emerges. Shared workspaces using cloud repositories (e.g., GitHub, GitLab, or an institutional server) will facilitate collaboration across universities, museums, and contractors. Versioned releases will be archived and cited via DOIs in institutional repositories or Zenodo to support academic reproducibility and citation (Bruno et al., 2010).

Long-term preservation is as important as real-time usability. Final models—along with all source data, metadata, and documentation—will be deposited in a certified digital repository. Options include university digital libraries, national data archives, or international repositories like the Open Science Framework. Each dataset will be accompanied by a ReadMe file explaining the model structure, metadata fields, software used, and licensing. Licenses will default to CC BY or CC0 for maximum reuse unless artifacts require cultural sensitivity. Open formats such as glTF, E57, and OBJ ensure future readability. Archives will include version history and metadata to contextualize each file, aligning with the FAIR data principles (Findable, Accessible, Interoperable, Reusable) promoted by the European Commission and cultural heritage institutions globally (Georgopoulos, 2014; Croce et al., 2023).

The model architecture allows integration into third-party systems. Unity and Unreal Engine natively support glTF and FBX imports; Unreal additionally supports USD. Museum content management systems (CMS) can link to glTF or USD models via plugins or embedded web viewers. In research contexts, the model could be connected to a spatial database such as PostGIS, enabling queries like "find all AI-reconstructed statues within 10 meters of Temple A." Because geospatial consistency is maintained across all models, integration into GIS tools like QGIS or ArcGIS is seamless. Future developments might include AR field apps where archaeologists can view real-time reconstructions on site using mobile devices. These cross-system integrations make Thonis-Heracleion a digital hub—not just a static model but a research platform (Vandenabeele et al., 2023; Chabuk & Al-Amiri, 2022).

6 Discussion:

6.1 Interpretation and Innovation

The methodological approach presented in this paper represents a substantial advancement in underwater archaeology. The aim is to expand archaeological practice as a dynamic interaction between empirical observation and digital speculation, which is rather than merely concentrating on geographical documentation or archaeological description. The digital reconstruction of Thonis-Heracleion, facilitated by multimodal AI integration, transitions the interpretative emphasis from cataloging just isolated archeological artifacts to reconstructing the city's civic, ritual, and maritime lifestyle on a systemic level. This conceptual shift illustrates wider developments in archaeological understanding, where hybrid methodologies—integrating machine learning, 3D modeling, and textual inference—facilitate a more comprehensive understanding of submerged archaeological sites (Croce et al., 2023; Drap et al., 2015). Furthermore, by integrating artificial intelligence into the site interpretation workflow—utilizing generative adversarial networks, procedural modeling, and predictive epigraphy—this research establishes Thonis-Heracleion as both a cultural heritage site and a computational experimental platform. The application of AI aims to enhance archaeological expertise rather than supplant it, uncovering interpretive avenues that might otherwise go unexamined. The research paper demonstrates the potential of digital tools for enhancing scholarly analysis and public engagement via immersive visualization and cross-modal storytelling (Bruno et al., 2016; Assael et al., 2022).

6.2 Strengths of the Methodology

This reconstruction methodology's primary strength is its exceptional interoperability and accuracy. The model utilizes georeferenced, high-resolution sonar, photogrammetry, and laser scanning data to establish a solid spatial framework for subsequent analysis. The modular architecture of the digital twin facilitates both scalability and granularity, applicable to VR deployment, academic research, or museum integration. Each data layer offers distinct advantages: sonar reveals bottom topology, photogrammetry supplies surface texture and volumetric shape, and laser scanning guarantees millimetric precision in eroded or inscribed objects (Goddio et al., 2020; Mahon et al., 2011). Furthermore, the incorporation of machine learning facilitates precise hypothesis formulation and anomaly identification. Previous projects, such as the UT Shipwreck Neural Network (Robinson, 2018) and the Pavlopetri mapping initiative (Mahon et al., 2011), illustrate that the utilization of AI expedites the interpretive process by detecting structural patterns and material signatures within extensive, diverse datasets. This project utilizes existing precedents and enhances them using AI-assisted extrapolation of unfinished architecture and NLP-based text mining, facilitating both intra-site coherence and larger cultural contextualization (Assael et al., 2022; Drap et al., 2015).

6.3 Limitation

Notwithstanding its methodological advancements, numerous drawbacks persist within this investigation. The present reconstruction is limited by the restricted extent of physical excavation—merely about 5% of Thonis-Heracleion has been archaeologically recorded thus far (Robinson, 2018). This spatial constraint inherently restricts the empirical foundation of any digital reconstruction. Secondly, whereas AI-driven extrapolation facilitates credible renderings of unexcavated features, such inferences are inherently speculative and must be clearly differentiated from empirically validated structures (Croce et al., 2023). Clarity in model stratification and metadata annotation will be crucial to prevent the confusion of interpretive forecasts with archaeological accuracy. Environmental and operational variables impose limitations. The diminished visibility, sediment deposition, and biofouling characteristic of Aboukir Bay hinder the efficacy of imaging equipment, especially photogrammetry, which depends on optical clarity. While technology like laser scanning and sonar alleviate certain issues, they can't entirely eliminate them. Moreover, the use of autonomous or remotely controlled platforms in complex debris-laden underwater environments may restrict maneuverability and image quality (Bleier et al., 2019; Henderson et al., 2013).

6.4 Consequences for Future Research

This research presents various opportunities for future exploration in submerged cultural heritage studies. The proposed digital pipeline could be utilized at additional Nile Delta locations, such as Canopus and Menouthis, facilitating comparative reconstruction and regional urban study. The advancement of interactive, modular digital twins can greatly improve educational programs, museum curation, and remote accessibility for international audiences. The incorporation of real-time AI support into diver or ROV interfaces, exemplified as CNN-based anomaly identification, signifies a new frontier in the efficiency and accuracy of underwater surveys (Stoean et al., 2024).

Moreover, enhancing generative models with more expansive annotated datasets could augment reconstruction efficiency and facilitate the integration of probabilistic confidence metrics. As computational technologies advance, digital heritage strategies must maintain adaptability, prioritizing transparency, user traceability, and iterative validation. The success of these projects will rely on both technological advancement and collaborative management among archaeological, computational, and museological fields (Bruno et al., 2016; Fock et al., 2017).

7 Conclusion

No publication offers a comprehensive geoarchaeological synthesis centered solely on Thônis-Heracleion that incorporates geological, geophysical, stratigraphic, archaeological, and advanced digital data to better understand all mechanisms and phases of submergence as well as digital reconstruction of this cultural heritage site; instead, relevant studies tackle separate parts (site mapping, ship deposition, regional subsidence, and sea-level change) but lack the framework of a holistic, technology-integrated, phased chronology. Thus, this study has outlined a robust and innovative methodological pipeline aimed at digitally reconstructing the submerged ancient Egyptian port city of Thonis-Heracleion, drawing on cutting-edge archaeological survey techniques, advanced photogrammetry, precise laser scanning, and artificial intelligence-driven reconstruction approaches. Through comprehensive documentation techniques—including multi-beam sonar bathymetry, diver-operated photogrammetry, and ROV-deployed laser scanning—the project establishes a precise, empirical digital baseline of the current submerged archaeological remains. Subsequently, employing AI-guided extrapolation methods informed by classical texts, analogous archaeological examples, and machine-learning frameworks, the pipeline enables plausible reconstructions of missing or degraded architectural and decorative elements, resulting in a vibrant digital resurrection of the city's former glory.

The approach detailed herein leverages successful precedents from landmark projects, notably the photogrammetric documentation of Pavlopetri, LiDAR-driven remote sensing exemplified by Angkor Wat's extensive landscape revelation, and the rapid 3D site mapping methodologies demonstrated by the Black Sea MAP initiative. Each technological choice is grounded in proven efficacy, tailored explicitly to Thonis-Heracleion's environmental conditions, archaeological features, and interpretative requirements. Furthermore, significant attention to interoperability through adherence to open data standards (glTF, USDZ, OBJ, and E57 formats) ensures the long-term preservation, broad accessibility, and academic reusability of the resulting digital assets.

The significance of digitally reconstructing Thonis-Heracleion extends beyond scholarly documentation; it bridges the gap between rigorous archaeological science and accessible public engagement. By optimizing the 3D reconstruction for multiple interactive platforms—including high-fidelity VR experiences, immersive museum installations, detailed cinematic renderings, and lightweight web-based viewers—the model becomes a versatile tool for educational outreach, cultural preservation, and cross-disciplinary research. The embedded metadata, provenance layers, and clearly documented AI contributions maintain scholarly transparency and allow future researchers to refine or expand upon the current reconstruction.

Looking forward, this comprehensive digital twin of Thonis-Heracleion provides a robust foundation for future research initiatives. As new archaeological discoveries emerge from ongoing excavations or as new technological innovations enhance digital visualization techniques, the existing model can seamlessly integrate these advancements. Future investigations might explore deeper AI integration, real-time environmental simulations for educational purposes, augmented reality field applications, or the integration of spatially-aware database queries to support further archaeological analysis. Ultimately, this digitally resurrected city not only preserves a crucial archaeological site for posterity but also sets a benchmark for future underwater cultural heritage projects—capturing, interpreting, and visualizing the past in ways previously unimaginable, thereby ensuring Thonis-Heracleion's enduring place within global cultural memory.

Data Availability

Data available upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Funding Statement

NA

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