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3D Technologies on the Underwater Archaeological Site of the Ancient Lighthouse of Alexandria (Egypt)

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Abstract

Located in Alexandria, Egypt, the ancient Pharos ruins lie scattered across approximately 1.6 hectares under the Mediterranean Sea. Since 1994, the Centre d'Études Alexandrines (CEAlex), a research unit operating under the aegis of the CNRS, has been leading extensive studies of this complex submerged site with an international team of underwater archaeologists. Due to the scale of the work, scientists initiated a photogrammetry program in 2009 for studying and potentially reassembling the archaeological fragments. This effort expanded in 2013 with the creation of a digital twin of the entire site. Digital technologies have profoundly transformed the scientists' work, both in the field and during post-excavation analysis, opening new avenues for site analysis and research perspectives.

CCS Concepts
· Computing methodologies → Machine learning; · Applied computing → Physical sciences and engineering; Archaeology;

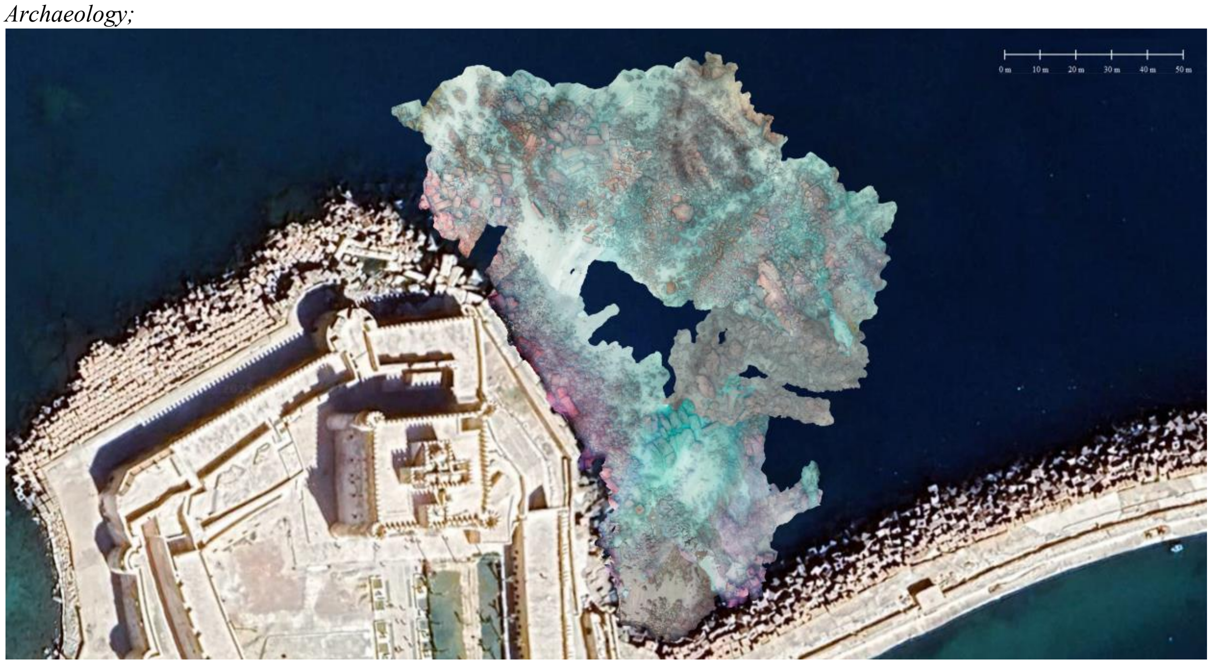

Figure 1: *Orthophoto map of the underwater archaeological site*

1. Introduction

The ancient Alexandria Lighthouse, also called the Pharos, was built at the beginning of the Hellenistic period (297-283 BC). Its ruins now lie at a depth of 5 to 10 metres at the foot of the Citadel of Qaitbay, the oldest section of which dates to the end of the 15th century (Fig. 2). The site, discovered by the Egyptian amateur diver Kamal Abul Saadat (1933-1984) in the early 1960s [M00][H00][A00][A01][KA02][DA02][E13], was not excavated until 1994. The Centre d'Études Alexandrines (CEAlex) and the Institut Français d'Archéologie Orientale (IFAO) in Cairo carried out the first salvage excavation while the Municipality of Alexandria was constructing a modern underwater breakwater over the ancient site. The aim of this first archaeological mission was to list the important pieces of statuary and architecture of the submerged antique site so that they could be refloated enabling the ongoing construction of the concrete breakwater designed to protect the eroding coastline. Jean-Yves Empereur, who was then the director of the CEAlex, headed the mission and decided to conduct a cartographic survey of the site, which revealed its importance. The findings led the Egyptian authorities to stop work on the modern seawall [E95a][E95b].

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Scheduled for 1995, the initial mission primarily aimed to map the site to understand its extent, while simultaneously conducting a detailed inventory of the ashlars and statuary fragments [E96a][E96b][E96c][E97][EG97a][EG97b]. Later, numerous metal seals made of iron, bronze, and lead, found on the bedrock and used to reinforce the lighthouse walls, were added to the inventory of immovable archaeological artifacts [Ha][Hb].

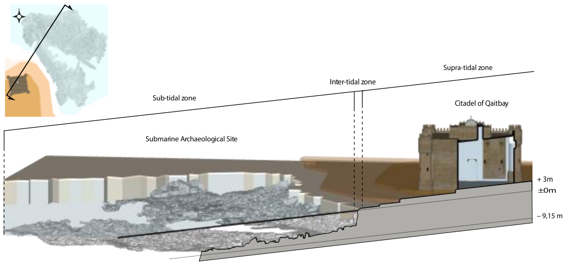

Figure 2: *Situation of the submarine archaeological site on the coast*

2. A brief overview of the topographical methods applied to the site

Given its surface area (1.6 hectares) and the richness of the underwater site, a rational system for managing the archaeological survey quickly became necessary; consequently, a Geographic Information System (GIS) was established using the collected data. Initially developed using Mapinfo, the GIS was later transferred to QGIS. [H20] Simultaneously, a database developed in FileMaker Pro was used to compile comprehensive data for each mapped block through an identity card system. This included intrinsic data (dimensions, weight, conservation, material, etc.) and extrinsic data (relative position, orientation, association, etc.), along with associated sketches, scale surveys, photographs, and videos. This sustainable database formed the matrix for our studies of the ashlars and statuary [H04a][H04b][H07][H16][HEAS16][Hc][Hd][He].

The methods used for mapping the site ranged from the simplest, using a decameter, to the most complex, with the Aquamètre D100. This is a local underwater positioning system, based on an acoustical interferometry scheme [S]. Measurements of points are taken within a radius of up to 250 m. The CEAlex total station then positions each mapped surface within the reference coordinate system used in Egypt, employing a method of measuring reference points by direct topography [M].

2.1. 3D geometrical model of broken artifacts

Until 2009, each fragment of architecture or statuary was drawn to scale using traditional methods, but reassembling these drawings was tedious, approximate, and prone to errors

Between 2009 and 2012, CEAlex started the SeARCH research project (Semi-automatic 3D Acquisition and Reassembly of Cultural Heritage) bringing together several fields of science: archaeology, computing and engineering [RMGHV11]. Aiming for the virtual reassembly of broken statues found on the submerged Pharos site, researchers chose photogrammetry for several reasons, including its applicability both underwater and on land, and its ease of implementation by archaeologists, making it a sustainable method. Since 2012, we have integrated the creation of digital twins of architectural and statuary fragments into our working procedures. This enables the study of multi-tonne pieces, particularly challenging in the shallow, low-visibility waters off the Alexandrian coast. Digital twins also facilitate the reassembly of large, three-dimensional puzzles composed of eroded fragments from various locations into a single coordinate frame. Several statues and parts of monuments have been virtually reconstructed, a capability that manual drawings did not offer (Fig. 3).

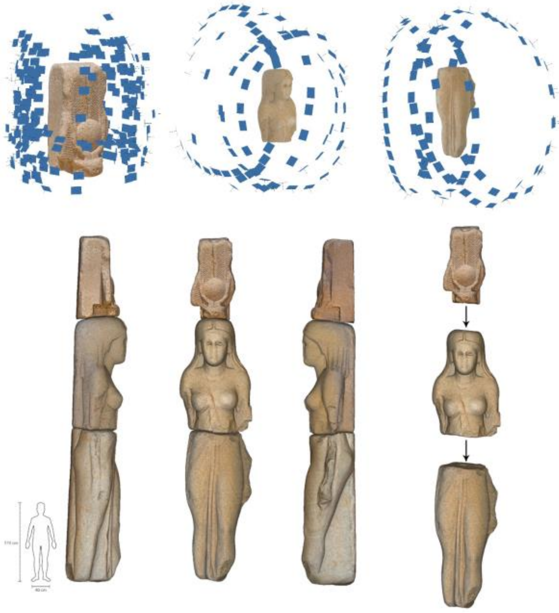

Figure 3: *Virtual reconstruction of a broken Isis Statue*

2.2. Digital technology set up on the site

In 2013, CEAlex launched a new project aimed at creating a digital twin of the entire archaeological site.This 3D approach is vital as the site's remains are reduced to a single level on the seabed. Swell and erosion have swept away and destroyed the archaeological soil, leaving no stratigraphically accumulated layers by period. On the seabed, alongside other remains, we find reused pieces dating back to the Pharaonic period [S22], the ashlars and metal seals from the lighthouse's masonry [Ha][Hb], the restored parts of the tower [Hc], and the ruins of the buildings that surrounded the lighthouse, including their statuary [QH], The presence of these surrounding structures initially led to their association with the lighthouse itself.

GIS served as a first step in managing and understanding the site. By 2014, the archaeological map included almost 3,000 blocks. Photogrammetry, now covering over 70% of the site, has added nearly 2,000 stone pieces to the GIS. Cumulatively, close to 5,000 architectural fragments and stone statuary from various periods have been recorded to date.

Initially, the site gives the impression of being a complete chaos. The partial digital twin has already enabled us to take a fresh look at the analysis of the vast archaeological site of diachronic architectural ruins, which testify to the lighthouse's long history. The 3D twin of the site helps us understand the number of distinct monuments here and how arrived on the seabed. Ultimately, it will aid in determining the coexistence and chronological use or abandonment of the monuments [Hc].

Swell and erosion have also caused accumulations of native substratum materials, which serve essential indicators for explaining the transformation of the topography of the formerly emerged islet. These findings will be presented shortly in a forthcoming book on the underwater archaeological site. The 3D model of the site is a precious resource for studying the question of subsidence and its consequences on the coastline changes. It has enabled us to identify various ancient marine levels that have marked the coast of the island since the construction of the lighthouse, and consequently to calculate the rate of subsidence over the last 23 centuries [Hf] (Fig. 4).

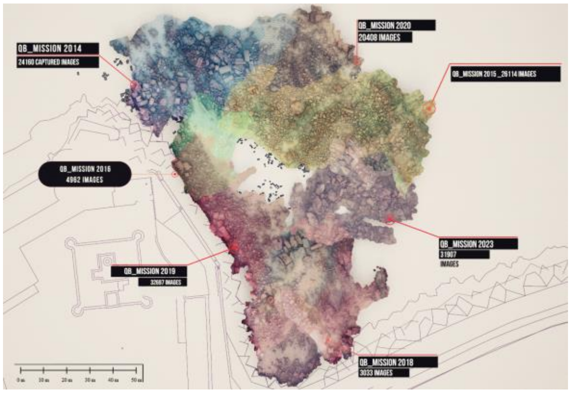

Figure 4: *The development of photogrammetry from 2014 to 2023.*

3. Revealing details: use of VRTI on underwater inscriptions

Reflectance Transformation Imaging (RTI) is an important archaeological recording technique that captures multiple photographs from a stationary viewpoint while varying the angle of light. The resulting images are displayed in an RTI viewer, allowing users to manipulate virtual lighting and observe dynamic changes in the scene.

Virtual Reflectance Transformation Imaging (VRTI) enhances the traditional RTI method by integrating photogrammetry and noncontact digitization. This approach utilizes animated virtual domes to create sequences of renderings of 3D models, offering improved interaction and visualization of surface details. VRTI enables automated reconstruction of detailed 3D models, revealing both visible and hidden features by manipulating lighting conditions.

In this study, VRTI was applied to two 3D models of red granite statue bases located underwater (for a more detailed account, see [AE]). One base featured an inscription that was partially legible underwater, while the presence of text on the second base was uncertain. Traditional RTI was not feasible underwater, there are no alternative solutions to the preservation of the recently discovered artifacts, as the Egyptian government has imposed a weight restriction on elements eligible for refloating, limiting them to 100 kg. In contrast, the 30 blocks with inscriptions found at the site each weigh between 1 and 7 tons. Consequently, none of these significant artifacts can be refloated due to this regulation, so photogrammetry was used to create high-resolution digital twins of the inscriptions. VRTI was then applied in the lab to enhance legibility and determine the inscribed details of both models. These cases were selected to evaluate the effectiveness of the VRTI method.

3.1. Block no. 2422 (Fig. 5)

Dimensions: H= 132,67 cm; L=68,9 cm top/71 cm bottom; inscribed surface: L=61 cm top/66 cm bottom - 1,3 tons

The red granite base was discovered underwater at a depth of 4.8 m by archaeologist Mourad el-Amouri, who noted an inscription on one side, though it was hard to read due to underwater conditions. Egyptian authorities allowed CEAlex to create a cast of the inscription using latex. While one or two lines are missing at the beginning, seven lines of text are preserved, with letter heights of 1.5 to 1.7 cm and line spacing of 1.0 to 1.4 cm. Erosion further complicates the readability of the inscription [EH21].

Figure 5: *Block 2422. Left: photograph in situ; center: photogrammetric 3D model; right: 3D model enhanced by VRTI, 101 spot lights surround the object.*

3.2. Block no. 2385 (Fig. 6)

Dimensions: H = 125 cm; L = 69 cm; 72 cm bottom; inscribed area: l = 68.7 cm.

The second inscribed red granite base was discovered in 2019 at a depth of 7 m in the Qaitbay underwater site. Initially, divers found no inscription after cleaning, but a 3D photogrammetric model revealed its presence. VRTI processing was applied to enhance the inscription's visibility, yet the text remained challenging to interpret. The base has six preserved lines of text, with letter heights of 1.5 to 1.7 cm and line spacing of 1.0 to 1.4 cm. Erosion, particularly at the ends, further complicated readability.

Proceedings published by Eurographics - The European Association for Computer Graphics.

Figure 6: *Block 2385. Left: photograph in situ; center: photogrammetric 3D model; right: 3D model enhanced by VRTI, 101 spot lights surround the object.*

The two inscriptions, with the same wording but a different layout, correspond to the latest state of these 2 bases, which were used right-side-up and then upside-down for the erection of statues in both directions. Dedicated to Constantine and Licinius (4th century CE), and found together, they could be located not far from where they were erected [EH21].

3.3. Workflow

After developing high-resolution photogrammetric models of the two bases, they were imported into 3ds Max 2024 and positioned at the origin (0x, 0y, 0z). Two scripts were utilized to incorporate a virtual dome light along with a camera. A black sphere was introduced to capture highlights, akin to traditional methods. This configuration aids in determining the best light distribution and enables the rescaling of the 3D model within the dome light. The scene is enveloped by 101 spotlights arranged in a hemispherical pattern, with each spotlight assigned specific X, Y, and Z coordinates for accurate placement. The first script is used to integrate the dome lights and the camera (Fig. 7) as follow:

```
function GDLight unaposicion =
   (l1=omnilight() l1.position=unaposicion)
caml=freecamera()
caml.position = [0,0,12]
GDLight[4.330127,7.5000000,5.000000]
GDLight [7.500000,4.3301270,5.000000]
GDLight [8.660254,0.000000,5.000000]
```

The second script includes information about when each spotlight is turning ON or OFF, and it saves the file in the chosen destination, as shown in the following example:

```
$omni001.enabled=on
r=render camera:$camera001 outputwidth:3200
   outputheight:2400
r.filename="C:\Users\....\Desktop\RTI_Render
   \img001.jpg"
save r
$omni001.enabled=off
$omni002.enabled=on
r=render camera:$camera001 outputwidth:3200
   outputheight:2400
r.filename="C:\Users\....\Desktop\RTI_Render
   \img002.jpg" saver
```

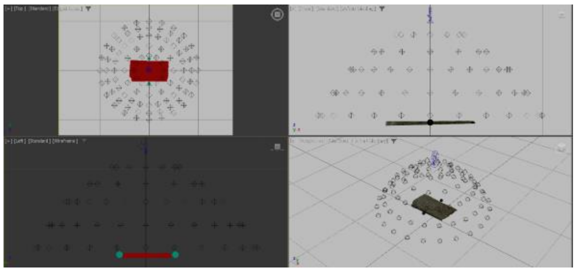

Figure 7: *Graph showing the distribution of the virtual dome lights and cameras.*

3.4 Conclusions

Digital technology used for documenting, conserving and sharing archaeological site, its area, components, and the ashlars, has opened up new avenues for research and for dissemination.

The digital twin allows us to explore and study this underwater archaeological site which cannot be visited easily because of its difficult access related to its position at sea, because of water quality degraded by pollution resulting in high turpidity, and because of the size of the site. The 3D documentation of the fragments facilitates dialogue with experts worldwide and enables a more sophisticated approach to analyzing the complex archaeological context, where the lighthouse's longevity is reflected in ruins from many periods.

By providing virtual access to the site, digital technology helps promote and widen its accessibility. To this end, a 3D animation of the site is projected in the museum at the Citadel of Qaitbay (Fig. 8). This provides visitors, particularly Egyptians who were largely unaware of the underwater site at the foot of the fortress, with an introduction to the submarine archaeological remains.

The launch of the "Reconstruction of the Pharos" project in 2022, supported by the Dassault Systèmes Foundation (France), opened up a new perspective. An HBIM (Heritage Building Information Modelling) is currently being developed to facilitate the cross-referencing of heterogeneous data from various scientific fields. This model integrates archaeological, architectural, and artistic findings from site studies, along with analyses of ancient iconography and texts describing the Pharos, drawing on disciplines such as architecture, archaeology, geology, chemistry, petrography, epigraphy, numismatics, and history. The HBIM, which will index the heterogeneous data corpus, will result in a digital model offering a new image of the Lighthouse of Alexandria based on the latest research advances.

Underwater VRTI combines photogrammetry with RTI to improve the visibility of hard-to-read inscriptions affected by underwater conditions. Unlike traditional RTI, which is limited by camera framing, VRTI offers unlimited control over object scale due to its photogrammetric basis. However, ensuring the photogrammetric model meets quality standards is essential.

Figure 8: *An image taken from the animation shown in the Citadel of Qaitbay in Alexandria.*

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