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Unveiling the Past in Three Dimensions: A Methodology for Creating Versatile Digital Twins from Paleontological Findings in a Museum

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Abstract: In recent years, researchers in the field of cultural heritage have intensified their efforts to develop new ways to enhance the promotion and accessibility of cultural content in order to attract more audiences using virtual representations of physical objects (digital twins). Therefore, they increasingly include new technologies and digital tools in their operation, since their application both to the general public and among the cultural organisations themselves, is considered particularly effective. Simultaneously, the increasing quality of the produced digitizations has opened up new opportunities for further exploitation of digitization outcomes in a broader context than was initially anticipated. Responding to the growing demand of museum visitors for a personalized digital tour experience, especially in the midst of the recent Covid-2019 pandemic, the v-PalM project aims to develop a digital platform for offering virtual guidance and education services at the Museum of Paleontology and Geology that is hosted at the National Kapodistrian University of Athens. The development of the platform will be based on collecting data through several methods including crowdsourcing, innovative information and communication technologies, taking advantage of content digitization using 3D scanning devices. In this paper, we demonstrate a methodology for the digitization of paleontological findings that can be used for creating digital twins suitable for various scenarios including research, education, and entertainment.

Keywords: digital twins; cultural heritage; museum; 3d modeling; digitization; platform; cultural content; museum visitors; paleontological findings; paleontology; photogrammetry; methodology

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1. Introduction

The digitization of museum artifacts has revolutionized the field of Cultural Heritage (CH) [1,2], providing new avenues for enhancing the promotion and accessibility of cultural content. The digitization of movable cultural assets stored in museums and galleries follows a cycle of preparation, conversion, and access, with a focus on the technological aspect and the standards used [3]. By creating virtual representations of physical objects, commonly referred to as digital twins, researchers and cultural organizations aim to attract larger audiences and leverage innovative technologies and digital tools [4]. The idea of digital twins emerged in the engineering domain to mean a digital or virtual representation of a physical artifact [5].

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With advancements in technologies like laser 3D scanning, photogrammetry, and 3D design software, it is possible to capture detailed three-dimensional information of museum artifacts. These technologies enable the creation of accurate and immersive digital replicas that offer numerous opportunities for research, education, and entertainment [6-8]. In addition 3D, tangible representations of museum artifacts can offer more engaging experiences for museum visitors [9]. However, digitization is not without challenges, including the lack of a national strategy and guidelines in some areas [10].

In response to the growing demand for personalized digital experiences, particularly in the context of the recent Covid-2019 pandemic, the v-PalM project aims to develop a digital platform for virtual guidance and education services at the Museum of Paleontology and Geology, hosted at the National Kapodistrian University of Athens. This platform will harness innovative information and communication technologies (ICT), including the development of mobile applications that leverage the digitization of content using 3D scanning devices.

This paper presents a comprehensive methodology for the digitization of paleontological findings, specifically focused on creating digital twins suitable for various scenarios. The methodology serves as a practical guide for researchers and cultural organizations interested in utilizing digitization techniques to expand the reach and impact of cultural heritage objects. The digitized replicas generated through this methodology not only facilitate research by providing detailed and accurate representations of physical artifacts but also offer enhanced educational experiences. Through interactive and immersive learning opportunities, these digital twins enable learners to engage with cultural artifacts in novel ways. Additionally, the availability of such digital replicas opens up new possibilities for entertainment, allowing individuals to virtually explore and interact with paleontological findings.

In conclusion, the digitization of paleontological findings through technologies like laser 3D scanning and photogrammetry, supported by tools such as 3D design software, presents exciting opportunities for the promotion and accessibility of cultural heritage. The v-PalM project serves as an exemplary initiative in this domain, demonstrating a methodology that can be adapted for various contexts and facilitating the creation of digital twins for research, education, and entertainment purposes. By embracing digitization techniques, researchers and cultural organizations can contribute to the preservation and dissemination of cultural heritage in an increasingly digital world.

The rest of the paper is structured as follows: Section 2 reviews related work in the field of the digital twins and the digitization of paleontological findings. Section 3 presents the v-Palm project, the materials and methods used and Section 4 presents the proposed methodology. Finally, discussion, conclusions and future research points are drawn in Section 5.

2. Related work

In recent years, the digitization of cultural heritage artifacts and sites has gained significant attention due to its potential in preserving and disseminating knowledge about our past. Two prominent techniques utilized for this purpose are photogrammetry and laser scanning. Photogrammetry involves capturing and analyzing multiple photographs of an object or site to create a 3D model, while laser scanning employs laser beams to measure the shape and dimensions of objects with high precision. These methods have revolutionized the way we document and explore cultural heritage, enabling virtual access, research, education, and entertainment experiences.

Numerous projects and applications have emerged, showcasing the effectiveness of photogrammetry and laser scanning in the realm of cultural heritage digitization [11-15]. These endeavors have demonstrated the wide range of possibilities and advancements in this field. An exemplary project, such as the Aerariumchain Project [16], pursues the development of an intelligent system enabling users to compare 3D images captured during different periods and discern changes in artworks. This innovative system incorporates 3D scanning, blockchain, and artificial intelligence technologies. Notably, it features a highly precise monitoring system that facilitates timely interventions in artwork restoration processes.

Additionally, a case study conducted at the Palace of Knossos [17] exemplifies a methodology for digitizing archaeological sites. This study sheds light on the encountered challenges and underscores the significance of long-term data preservation through the utilization of an open data repository. The proposed digitization methodology aimed to achieve realistic reconstructions while minimizing data size and post-processing requirements. To accomplish this, the researchers integrated knowledge from previous projects and employed systematic approaches for representing CH. A primary focus of the study was on the registration of point clouds, mesh generation, and texture optimization, ensuring a harmonious balance between quality and realism in the final output. Moreover, the researchers recognized the importance of preserving data snapshots to facilitate future reuse, accommodate advancements in reconstruction algorithms, study deterioration, and support scientific investigations. To ensure the longevity of the data, the researchers adopted the Zenodo open data repository, which served as a reliable platform for storing both raw and processed data. Adhering to a restricted access policy, this approach facilitated the long-term preservation of the digitized archaeological data, safeguarding it for future generations.

In Switzerland, a notable excavation study delves into the comparison and evaluation of various 3D scanning systems and photogrammetry approaches. The researchers meticulously examine the advantages, limitations, and practical considerations associated with each method, encompassing laser scanning, structured light scanning, and photogrammetric image-based modeling [18]. Emphasizing their potential in capturing accurate and detailed 3D data of archaeological sites, the researchers shed light on the capabilities of these techniques. The article provides a comprehensive overview of the workflow employed and presents the outcomes of the data acquisition process, which encompass the generation of 3D models, point clouds, and orthophotos. Throughout the discussion, the researchers candidly address the challenges encountered during both the excavation and data processing stages. Furthermore, they explore the potential applications of the acquired data, highlighting its significance for documentation, analysis, visualization, and the preservation of the Neolithic dolmen.

Finally, regarding another project, collecting cultural data through crowdsourcing is a widespread technique and there are countless projects based on it [28]. There are even projects that specialize in public data collection methodology, specifically for paleontology [29].

These examples highlight the growing interest and advancements in digitizing cultural heritage using photogrammetry and laser scanning techniques. By employing these technologies and creating accurate and simple methodology workflows, researchers, educators, and the general public gain unprecedented access to our shared past, fostering a deeper understanding and appreciation for our CH.

3. The v-Palm project, materials and methods

3.1. Introduction

The v-PalM project (Advanced Tour and Education Services in the virtual Paleontology and Geology Museum) endeavors to develop a platform for personalized digital tours at the Museum of Paleontology and Geology, utilizing cutting-edge technology (conversational agents, machine learning, personalized recommenders, implementation of gamification techniques and content digitization). In response to the growing demand for immersive and interactive experiences, the project aims to leverage 3D scanning devices for content digitization. By capturing detailed three-dimensional representations of fossil findings, the platform aims to provide visitors with a remarkable level of realism and engagement. Through the integration of 3D technology, users are provided with the opportunity to explore and examine paleontological specimens from various angles, gaining a deeper understanding of their form and function. This innovative approach enhances the accessibility and educational value of the museum's collections, enabling virtual visitors to appreciate the intricacies of fossil animals and plants from all over Greece and abroad. The utilization of 3D technology within the v-PalM platform works towards enhancing the museum experience, bridging the gap between physical and virtual visits, and offering an immersive introduction to the fields of paleontology and geology.

The Museum of Paleontology and Geology of the Kapodistrian University of Athens traces its origins back to the founding of the Physiographic Museum in 1835. Its collections consist of several thousand fossils from all over Greece, specimens from abroad and historical representations of paleoenvironments, covering over 300 million years of geological history. Furthermore, it conducts scientific research and paleontological excavations in numerous localities throughout Greece.

3.2. Materials and methods

In every endeavor of digitization, it is crucial to approach the heritage object or site with meticulous consideration. Our project was no exception, as we encountered varying sizes of paleontological findings that required careful assessment. In order to address this, multiple visits to the Museum of Paleontology and Geology were carefully organized, where the v-palm researchers provided valuable assistance in studying and determining the most suitable digitization strategy. Notably, certain challenges were encountered, such as :

- Inadequate lighting in some instances, while in others, intense daylight illumination posed its own set of obstacles.
- The presence of glass cases posed challenges to the 3D scanning process for numerous paleontological findings, adding complexity to the digitization efforts. These glass cases were impossible to remove, as either they were extremely heavy and fragile which made their removal expensive and difficult, or there was a great risk to the safety of the exhibits.
- Some exhibits hung from the ceiling at a great height, which made access to them extremely difficult. Photographing or scanning the surfaces between the exhibit and the ceiling required special techniques.
- Some exhibits use metal supports (posts, brackets, etc.) to be able to stand at a certain angle. These props required special processing to be removed later from the 3D model.
- Some exhibits were too close to fixed obstacles such as a wall, and there was not the slightest space for the equipment (camera or scanner) to be able to capture images.
- For each exhibit, there are "dead zones", places where it is impossible to photograph or scan. These points are usually cavities to which access is impossible, especially for equipment. These dead spots create holes in the final 3D model and require special processing.

In addition to conducting a technical study, it was imperative to consider the requirements of digitization quality. Certain instances necessitated achieving the highest possible level of digitization quality, particularly when dealing with historically significant locations within the site. To address this, special emphasis was placed on incorporating additional scanning locations and capturing more densely populated photographic documentation. These measures were taken to ensure a comprehensive and detailed digital representation that accurately captured the significance of the specific location within the site.

3.2.1. Materials

The selection of the paleontological findings was guided by various factors, including the physical tour provided to museum visitors, where specific paleontological findings are highlighted based on object significance and available tour time. The following criteria were taken into account for determining the selection of specific paleontological findings per thematic area:

- Rarity of the paleontological findings: Findings that are rare or unique hold priority for inclusion as 3D models.

- Representativeness of the paleontological findings for the subject area: Findings that exemplify and represent the specific subject area are given consideration.
- Importance of the excavation: Findings associated with significant excavations hold importance for both the museum and the country, influencing their inclusion.
- Interest and appeal to the general public: Findings that generate curiosity and captivate the interest of the general public are considered for 3D modeling.
- Sample authenticity: Authenticity of the findings is a determining factor for its inclusion as a 3D model.

It is important to note that the selection of the paleontological findings may be subject to modification over time by the museum's scientific staff. This allows for the renewal of the digital exhibition, incorporation of new scientific data, and the maintenance of visitor interest. The table below presents the number of selected paleontological findings per thematic area.

Table 1. Paleontological findings per thematic area at the v-Palm project.

Code	Thematic area	Number of findings
1	Geology, Paleontology and the Beginning of Life	3
2	Paleozoic Era	5
3	Mesozoic Era	7
4	Cenozoic Era and hominids	7
5	Pikermi and Miocene faunas	16
6	Terrestrial fauna of the Pliocene and Pleistocene	12
7	Endemic island faunas	13
8	Marine faunas	4

In order to achieve accurate and detailed digitization of the selected paleontological findings, we employed two laser scanning technologies: the FARO M70 laser scanner and the *Scan-in-a-box* laser scanner. These scanners were chosen for their capabilities in capturing high-resolution 3D data with precision.

The FARO M70 laser scanner [19] works mounted on a tripod and is capable of detailed scanning of large surfaces and objects, at distances from 20 cm, up to approximately 20 meters. It can do extremely dense scans giving great detail in the texture of surfaces, yet producing multi-GB volume files. It offers advanced functionality and flexibility, allowing for efficient data acquisition. Its portability and ease of use made it suitable for capturing paleontological findings of various sizes within the Museum of Paleontology and Geology. In our case, the FARO M70 was the ideal choice for the large paleontological findings. It was also used to scan the museum area, in case this was needed in a future application. The scanner utilizes laser technology to measure distances and create point clouds, ensuring the capture of intricate details.

The *Scan-in-a-box* laser scanner [20], known for its user-friendly interface, proved to be an ideal choice for digitizing smaller paleontological findings. It also works on a tripod and requires particularly careful handling. The objects to be scanned need to be prepared. We move the objects in front of the scanner at a certain distance and make sure that the background behind the object is uniform (a single color). We follow a process of calibrating the device and then make sure that the object is scanned from all its sides. To complete the scan, we will need to rotate the object and reposition it several times. Its compact design and versatility allowed for convenient scanning in confined spaces, ensuring accurate representations of complex objects. It can render surface colors

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and textures correctly, but its use is limited to small portable objects. Of course, the presence of an expert was needed for the way we touch and handle the exhibits as they are particularly sensitive.

In addition to laser scanning, photogrammetry played a significant role in our digitization process. We utilized both professional cameras and smartphones to capture a series of high-resolution photographs from multiple angles. Professional cameras, equipped with high-quality lenses and advanced settings, provided precise image acquisition. These cameras were particularly useful for capturing larger paleontological findings or objects with intricate details, where fine-grained textures were crucial for an accurate digital representation. Smartphones, equipped with increasingly sophisticated cameras, served as a valuable alternative for capturing smaller paleontological findings or objects in less controlled environments. With their ease of use and portability, smartphones enabled us to quickly capture a wide range of objects, ensuring efficiency in the digitization process.

3.2.2. Digitization method and tools

As stated in Chapter 4.1, for the scanning of the large paleontological findings, the FARO Focus M70 laser scanner solution was employed. To ensure complete coverage, the scanner was strategically positioned at multiple points according to the designated placement plan. Approximately fifteen FARO scans were performed for each paleontological finding during the digitization process. Each scan required approximately 6 to 10 minutes to capture color point clouds and panoramic images. In order to align the different scans from different points, 6 reference white sphere pedestals with magnet plates were used. The acquired data underwent processing using FARO Scene software [21], and registration was performed for each site. Subsequently, meshes were generated and exported. The scanning process incorporated a high overlap to facilitate automatic data registration [22,23]. The resulting 3D models were characterized by a well-defined structure and low-resolution textures, as depicted in Figure 1 below.

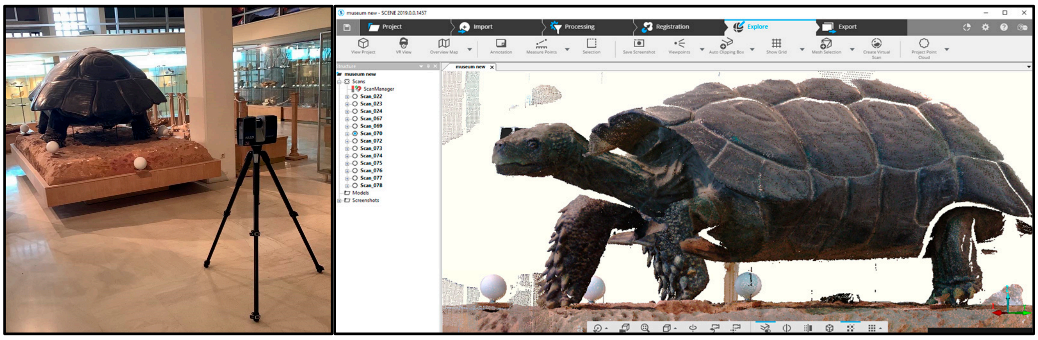

Figure 1. Scanning a giant turtle with FARO M70 and depicting the model with FARO Scene.

Regarding the smaller paleontological findings, the software utilized for scanning with *Scan-in-a-Box* is IDEA. This comprehensive software facilitates all stages of the digitization process for physical objects, including capturing range images and subsequently generating and editing their corresponding 3D models. IDEA software is using the active Stereo Vision Structured light technology as an optical 3D scanning technique employed to capture the geometric details of a physical object. The object is illuminated by two cameras, arranged in a stereo configuration, to capture images of the scanned part, and specialized software processes these images to generate two coded representations. Through the process of triangulation, a range image is derived, providing information about the object's depth and shape [24]. To obtain a comprehensive 3D model, it is necessary to capture the entire surface of the object using multiple frames. These frames are then aligned and transformed into a triangular mesh, resulting in a complete digital model of the object (Figures 2 and 3).

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Figure 2. Scanning a coral with *Scan-in-a-box* laser scanner.

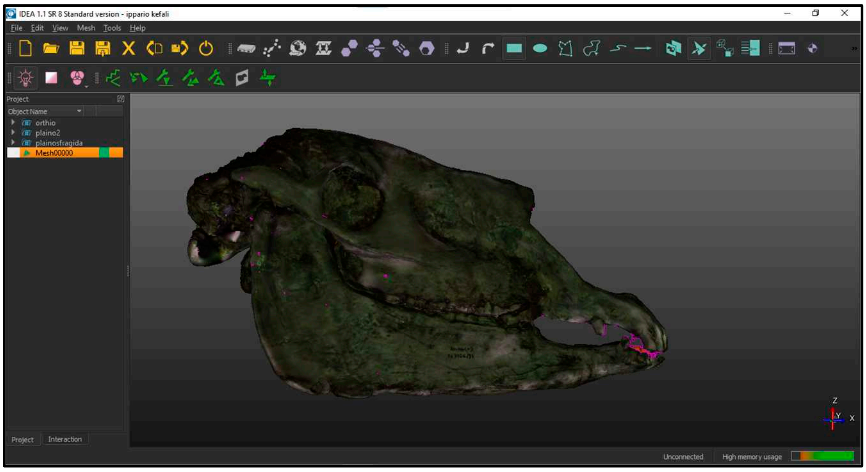

Figure 3. 3D processing of a horse skull with IDEA software.

Finally, to capture finer details of the paleontological finding, a photogrammetry approach was employed using a mobile phone (iPhone). Specifically, the *Polycam* software was utilized to create a highly realistic 3D model [25]. This was achieved by capturing a series of overlapping 2D photographs of the paleontological findings from various viewpoints. The software leveraged these photographs to measure and extract the necessary information, resulting in a photorealistic representation of the paleontological finding in the 3D model [26], as shown in Figure 4.

 doi:10.20944/preprints202307.1366.v1

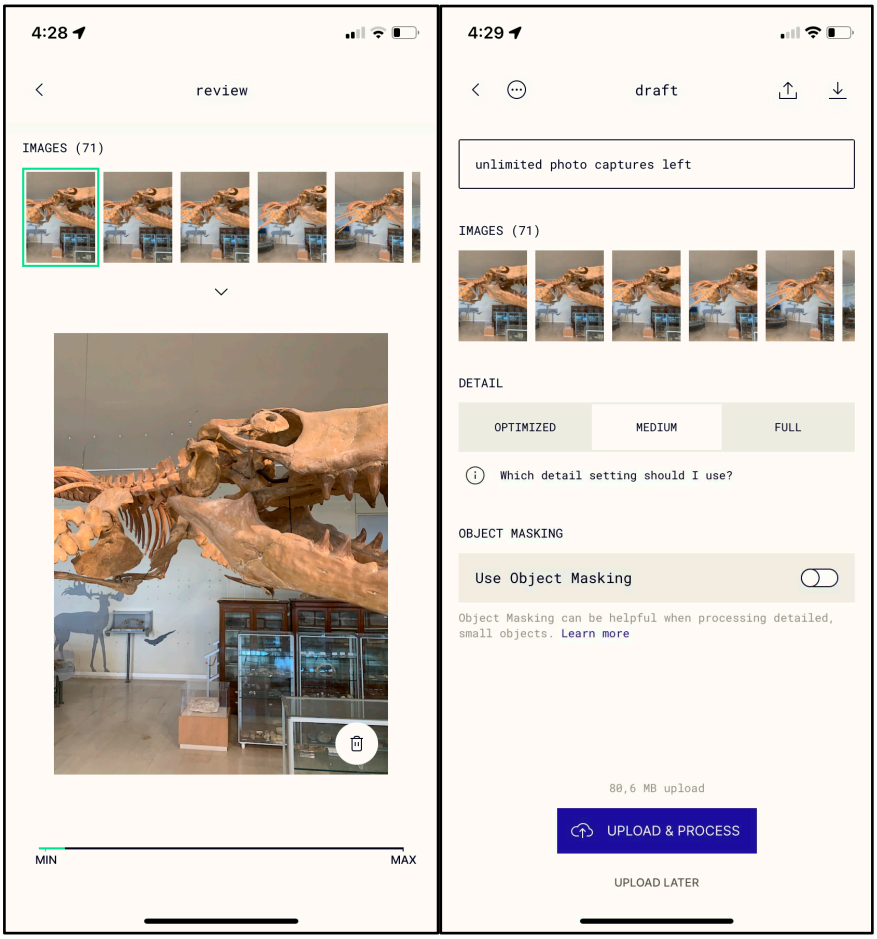

Figure 4. Using iPhone and Polycam software to scan a giant Mosasaurus (lizard).

4. The v-Palm methodology

To cater to mobile-centric applications of the v-Palm project, it is essential to combine all the laser scans and photogrammetry mesh creations into a unified, low-polygonal mesh. This unified mesh serves as a suitable format for such mobile applications. Additionally, the unification process enables the generation of high-resolution textures. These textures are carefully distributed to ensure an approximately isotropic texture distribution, which plays a crucial role in preserving the historical accuracy and ensuring the dissemination of accurate information.

Although the software used in each case is fully compatible with the respective devices employed to capture the digital information from the museum room, within the framework of the e-Palm project, a methodology was developed to assist in achieving the best possible results and faithfully creating three-dimensional digital replicas of the project's objects.

First of all, raw data from the 3D scanners are processed within their respective softwares, such as IDEA and FARO Scene. In our case, IDEA is used for small objects without many details, while FARO Scene is utilized for larger objects with complex details that require high quality scanning. In both cases, the Photoshop software has been used to correct any mistakes in the object’s texture.

Agisoft Metashape is a photogrammetry software that enables the creation of high-quality 3D models from a collection of 2D images or aerial photographs [27]. By creating multiple chunks based on the group of photos taken from different devices or angles, we managed to create detailed pointcloud and 3d models files that digitally recreates the cultural artifacts. Crucial points in the above procedure were the photogrammetric parameters and the required quality calibrated in the software’s algorithms, in order to reconstruct the captured scene into accurate and detailed 3D models. More specifically, the methodology developed for the project that integrates methods for

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data alignment from different devices and types, includes the following steps, as shown in Figure 5 below.

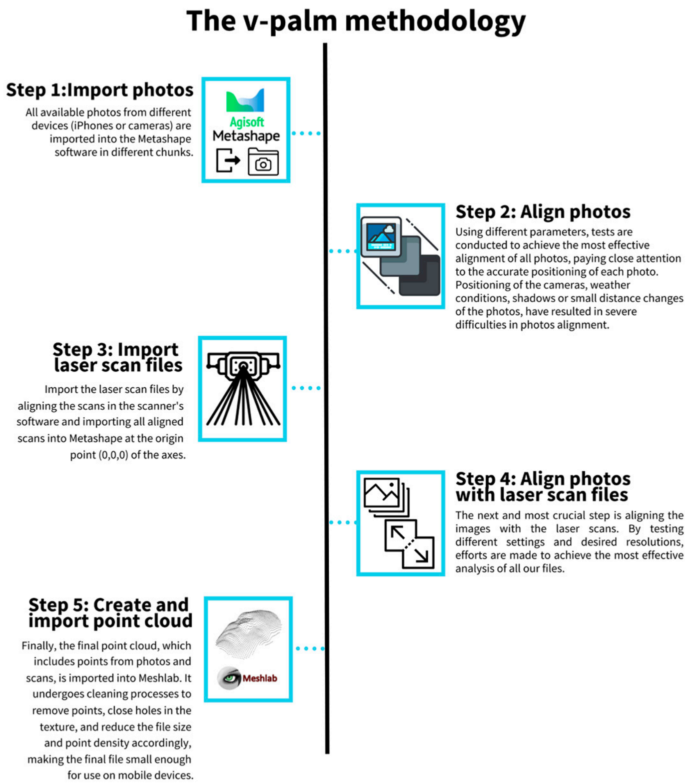

Figure 5. The v-palm methodology.

As an additional method, we utilized advanced algorithms from the *Meshlab* software, to correct any mistakes or reconstruct any "holes" in the 3D model, or minimize the file's size. *Meshlab* was also utilized to help us use a comprehensive set of tools for cleaning, repairing, and refining meshes obtained from 3D scanning or modeling processes. Also with *MeshLab*, we performed tasks such as mesh simplification, texture mapping, smoothing, and measurement analysis.

4.1. Innovation in v-Palm methodology

Scanning and photographing objects is of course something that has been done for many years, especially in the study and preservation of cultural heritage. The innovations of the v-Palm project lie in the following:

- Multiple media can be combined: Camera photos, cell phone photos, drone photos, laser scans from multiple scanners of various technologies, 360 images, ready-made point clouds from previous work.
- Media coming from different moments: Photos and scans do not have to be taken on the same day, at the same time. Having all the data from a specific point in time makes the modeling process easier, but in the v-Palm methodology it is something that can be overcome. We collect our data, process it, and if something has gone wrong in the modeling (for example, we're missing a part of a cavity in an exhibit), we can generate new data at another point in time.
- Crowdsourcing: As a result of the above, the images we will use, as well as the scans, may come from multiple users and from data that is already shared on the network.

- Historical material: Even historical material can be used. In all probability this material will be black and white photographs, but if it covers parts of the exhibits which we cannot otherwise have, then it is sufficient.

The rendering of exhibits, objects and spaces in three-dimensional form has occupied many researchers in multiple projects. It is a demanding project and requires powerful computers to process the data. The data derived from this work are files of tens of GB in size for each exhibit and their management requires powerful processors, large RAM memory and fast storage units. It is expected, of course, that advances in computer hardware, software used, and 3D scanning technologies will make 3D imaging easier and faster.

5. Discussion and Conclusions

The digitization of museum artifacts has revolutionized the field of CH, offering new opportunities to promote and access cultural content. The creation of digital twins, virtual representations of physical objects, has emerged as a means to attract larger audiences and leverage innovative technologies and digital tools. Advanced technologies like laser 3D scanning, photogrammetry, and 3D design software enable the capture of detailed three-dimensional information of museum artifacts, leading to accurate and immersive digital replicas. These digital twins have extensive applications in research, education, and entertainment, offering engaging experiences for museum visitors. However, the digitization process is not without its challenges. In some areas, the lack of a national strategy and guidelines hinders progress. It is crucial to address these gaps and establish clear standards and frameworks for digitization efforts in the CH domain.

In this paper, we present our endeavor to digitize the Museum of Paleontology and Geology at the Kapodistrian University of Athens, undertaken as part of the v-Palm project. Extensive visits to the museum were organized to study the paleontological findings that required digitization and establish a suitable methodology for the process. The digitization efforts resulted in a substantial volume of data, necessitating post-processing to generate the final 3D models.

The v-Palm project serves as an exemplary initiative in the field, showcasing a methodology that can be adapted to diverse contexts and facilitating the creation of digital twins for research, education, and entertainment purposes. By embracing digitization techniques, researchers and cultural organizations can contribute to the preservation and dissemination of cultural heritage in an increasingly digital world.

During the post-processing stage, several challenges were encountered, leading to valuable lessons learned from this work. Given the limitations of photogrammetry described earlier, the utilization of a laser scanner was preferred for larger paleontological findings. Careful analysis was conducted for each finding to determine optimal scanning locations that covered a maximum area with minimal scans. Illumination changes emerged as a major issue since the findings encompassed areas with varying light conditions, ranging from external light sources (high illumination) to locations with reflected light (medium illumination) and even areas with minimal light (low illumination). These lighting variations posed challenges in capturing accurate data, with some areas being over-illuminated while others were under-illuminated. To mitigate this, photographic documentation was employed during data capture to aid in the post-processing stage. The illumination-related issues were addressed during post-processing, following the methodology described earlier in this work. Additionally, the presence of glass cases posed challenges to the 3D scanning process for numerous paleontological findings, further complicating the digitization process.

For smaller paleontological findings, once again, the lighting settings with the Scan-in-a-box posed significant challenges that required careful consideration and adjustments during the scanning process. In example, by changing the positioning of the Scan-in-a-box laser scanner into a darker room and selecting appropriate angles and orientations, we minimize the reflections, shadows and other lighting issues in the final scans.

In summary, this paper highlights the importance of digitization in the museum context and presents the v-PalM project as a case study for the digitization of paleontological findings. The methodology outlined in this paper serves as a practical guide, providing insights and recommendations for researchers and cultural organizations embarking on similar digitization endeavors. The advancements in digitization technologies and the availability of digital twins present immense opportunities for the CH domain, fostering research, education, and public engagement. As technology continues to evolve, further exploration and research in this area will undoubtedly lead to new insights and innovations in the field of cultural heritage digitization.

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