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# The Use of 3D Scanning and 3D Color Printing Technologies for the Study and Documentation of Late Bronze Age Pottery from East-Central Greece

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**Abstract:** This study presents a comprehensive study focused on four distinct ceramic artifacts, revered burial offerings retrieved from a chamber-tomb site dating back to the late bronze age (LH IIIA1 period) in the region of "Vagia, " Kalapodi, East Locris, Greece. Emphasizing the integration of cutting-edge digital technologies in archaeological research, specifically 3D scanning and 3D color printing methodologies, this study aims to depict the materials and intricate design aspects of these artifacts. The artifacts, comprising of vessels and ritual objects, were meticulously scanned using advanced 3D scanning techniques to generate high-resolution digital models. The utilization of this technology allowed for the detailed documentation and preservation of these culturally significant items. Additionally, the potential application of 3D color printing enables the creation of physical replicas, providing tangible manifestations for further study and public engagement while aiding the preservation of the original artifacts. The analysis conducted on these acquired models revealed intricate details previously unseen, shedding light on the craftsmanship, symbolic motifs, and probable functions of these artifacts within the socio-cultural context of the late bronze age society in this region. Furthermore, comparative studies with similar artifacts from contemporaneous sites offered valuable insights into regional variations in ceramic production techniques and artistic styles. This interdisciplinary approach, combining archaeological excavation with digital scanning and 3D printing technologies, not only contributes to the comprehensive documentation and preservation of these invaluable artifacts but also offers new insights for enhanced interpretation and understanding of the late bronze age material culture in Eastern central Greece.

**Keywords:** 3D Scanning, 3D Printing, Cultural Heritage, Digitization, Preservation

## Introduction

The digitization of cultural assets holds significant significance in the conservation and dissemination of the multifaceted human history. The application of digital technology for the purpose of preserving and providing access to cultural items, records, artworks, and monuments ensures their long-term life and facilitates their accessibility for future generations. The process of digitalization serves as a means of safeguarding these precious artifacts from potential physical deterioration, loss, or destruction resulting from natural disasters, conflicts, or neglect (Rosner *et al*., 2014; Pavlidis *et al*., 2007; Khan *et al*., 2018; Bachi *et al*., 2014; Kantaros *et al*., 2023a). Furthermore, digital

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preservation enables widespread dissemination, overcoming geographical constraints and affording persons from various regions the chance to interact with and appreciate cultural content that would otherwise be inaccessible to them (Li *et al*., 2010; Byrne, 1991; Bogdanova *et al*., 2013).

The process of digitization enhances and expands the effort of doing research, education, and study. Digital libraries provide academics with an easy method of accessing a substantial volume of information, so enabling extensive investigations and analysis. The implementation of virtual tours, interactive displays, and online resources has shown to be advantageous for students and learners, by offering an educative experience and enabling the investigation of cultural heritage (Damala *et al*., 2016). The purpose of digitizing cultural assets is to provide equitable access to knowledge and comprehension of our shared historical heritage, hence preventing their restricted accessibility to a limited number of people. The use of this inclusive strategy facilitates the cultivation of cultural appreciation, identity formation, and connection within heterogeneous groups.

The application of 3D scanning technology facilitates the creation of digital representations of physical objects or environments. The process of 3D scanning involves the use of specialized scanners, which employ various techniques such as laser,structured light, or photogrammetry. These scanners are capable of correctly capturing the shape, texture and geometric subtleties of real items present in the physical world. The process described above enables the creation of complex digital models that can be applied for various purposes (Kantaros *et al*., 2023b; Bogdanova *et al*., 2013; Sitnik and Karaszewski, 2010; Baltsavias, 1999).

The utilization of 3D scanning offers a noteworthy advantage in its ability to accurately capture detailed and complicated characteristics that may provide challenges when attempting to recreate them using traditional measurement approaches. The aforementioned characteristics make it highly advantageous in fields like industrial and architectural design and forensics, where data precision plays an immense role. The use of 3D scanning technology enables the creation of digital files and virtual libraries, thereby making a valuable contribution to the preservation of cultural heritage by means of digitizing items and archeological sites. The utilization of this technology enables scholars, historians, and curators to efficiently document, examine and distribute noteworthy items and sites, there by enhancing their availability to a wider range of individuals. Furthermore, this methodology functions to protect these vital resources from future damage or extinction.

The application of 3D scanning technology facilitates the creation of digital representations of physical objects or environments. The process of 3D scanning involves the use of specialized scanners, which employ various techniques such as laser, structured light, or photogrammetry. These scanners have the ability to accurately capture the form, texture, and intricate geometric details of actual objects seen in the physical world. The process described above enables the creation of complex digital models that can be applied for various purposes in this field (Kantaros *et al*., 2023c; 2024a; Todorov *et al*., 2013; Sitnik and Karaszewski, 2010; Baltsavias, 1999).

The emergence of 3D printing has resulted in a substantial shift within the industrial sector, resulting in a transformative impact on the broader realm of production methodologies (Antreas and Piromalis, 2021; Kantaros *et al*., 2023d). The importance of this technology resides in its ability to convert theoretical ideas and blueprints into concrete manifestations with a high degree of precision and effectiveness (Kantaros *et al*., 2023e). The importance of this technology resides in its ability to convert theoretical ideas and blueprints into concrete manifestations with a high degree of precision and effectiveness. By employing additive manufacturing methodologies, 3D printers have the capacity to construct items in a progressive, step-by-step fashion. The utilization of this procedure allows for the creation of elaborate and sophisticated structures that would present considerable challenges or even be unachievable through traditional manufacturing techniques. The technology's adaptability offers a wide range of prospects in various sectors (Kantaros *et al*., 2023a; 2023f; 2024c Dodziuk, 2016; Shahrubudin *et al*., 2019; Lee *et al*., 2017).

One of the key advantages attributed to 3D printing is its intrinsic capacity to promote customization and personalization. This technological advancement facilitates the customization of designs by individuals and corporations, allowing them to cater to unique demands or preferences. The application of 3D printing technology enables the fabrication of personalized items, including customized medical implants, distinctive fashion accessories and distinct architectural prototypes, at a very cost-effective rate. The shown level of flexibility not only enables the production of innovative ideas but also enhances client satisfaction through the provision of solutions that perfectly cater to their individual requirements. Also, the use of this technology plays a major role in promoting a circular economy by vastly reducing material waste and carbon emissions. The primary means by which this is accomplished is through the intrinsic attribute of 3D printing that necessitates fewer resources when compared to traditional production methods (Ngo *et al*., 2018; Despeisse *et al*., 2017; Zhu *et al*., 2021).

In this context,the focal point of this investigation resides within the examination of four discrete ceramic relics-revered funerary offerings unearthed from a sepulchral context dating back to the late bronze age (LH IIIA1 period) within the archaeological precincts of "Vagia, " sited in Kalapodi, East Locris, Greece. These artifacts,gleaned from the sepulchral confines of a chamber tomb, encapsulate profound cultural resonances and material intricacies that divulge pivotal facets of an ancient societal milieu.

The course of this study focuses on assimilating state-of-the-art digital technologies into the realm of archaeological inquiry. Paramount among these methodologies are the concerted applications of 3D scanning and 3D color printing techniques. The cardinal objective underpinning this amalgamation of technological prowess and archaeological inquiry is the illumination of the composite structure, intricate delineations, and latent subtleties inherent within these archaeological remnants.

Thus, the precision-driven application of these cutting-edge advancements endeavors to transcend the conventional boundaries of archaeological analysis. Its purpose is to decode the properties of these artifacts, unraveling not only their physical and structural compositions but also exposing the nuanced nuances embedded within their design motifs and contextual significances. By meticulously employing these technological innovations, this study endeavors to unearth layers of information that traditional archaeological methods might overlook or fail to comprehensively elucidate.

The selected ensemble of artifacts, comprising a diverse array of vessels and ritualistic objects, underwent meticulous scrutiny employing advanced 3D scanning methodologies, there by engendering the creation of intricately detailed, high-resolution digital replicas. This technological leap allows the preservation and documentation of these culturally significant relics, allowing for an unprecedented level of scrutiny and analysis that was previously unattainable through conventional means. The subsequent contemplation of employing 3D color printing techniques stands as a potential way for future exploration, promising the creation of physical reproductions that faithfully mirror the original artifacts.

While the current phase of this study primarily harnessed the capabilities of 3D scanning to generate digital models, the envisaged integration of 3D color printing represents a promising trajectory for subsequent research endeavors (Chen *et al*., 2016; Yuan *et al*., 2018). The prospective application of 3D color printing holds the potential to materialize tangible replicas, offering a hands-on approach for continued scholarly investigation (Kantaros and Ganetsos, 2024). Moreover, these printed replicas have the capacity to serve as educational tools for public engagement, bridging the temporal chasm between contemporary society and the enigmatic vestiges of antiquity while safeguarding the intrinsic essence of the original artifacts.

Also, the analysis conducted upon the acquired digital models unearthed previously concealed intricacies, unveiling nuanced details concerning craftsmanship, embedded symbolic motifs and plausible functional attributions within the socio-cultural tapestry of the late bronze age society under scrutiny within this specific geographical domain. Furthermore, the envisaged future integration of 3D color printing holds promise not only in materializing physical replicas but also in potentially providing enhanced insights into the vibrant chromatic elements and their interpretative significance within these relics.

## Materials and Methods

Nowadays, progress is achieved in three-dimensional scanning technology, resulting in a wide range of scanner options currently available in the market. Structured light scanners and laser scanners are among the most prevalent types of scanners. Each category of scanners possesses distinct merits and demerits and choosing the proper scanner depends on the relevant use case and the nature of the object or environment under examination. The incorporation of portable, handheld, 3D scanners in recent times has expanded the range of capabilities for effectively employing these devices in field applications (Gautier *et al*., 2020).

One of the advantages of portable 3D scanners is their portability, as they can be utilized in diverse locations and environments. In addition, these devices possess portability features, facilitating convenient transfer and on-site utilization. Furthermore, it is worth noting that these scanners frequently yield outcomes of great precision, rendering them well-suited for use in sectors such as engineering, building, and product design. In addition, these devices demonstrate high efficiency by rapidly acquiring comprehensive 3D data, hence enhancing overall productivity. Portable 3D scanners are frequently characterized by their cost-effectiveness, as they offer a favorable return on investment when compared to conventional 3D scanning techniques. In

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addition, non-contact scanning technologies are employed, so mitigating the potential harm that may be inflicted upon the object being scanned. In addition, it should be noted that a multitude of portable 3D scanners exhibit compatibility with diverse software applications, hence facilitating the processing of data and its seamless integration into alternative systems (Grosman *et al*., 2008; Göldner *et al*., 2022).

In our case, a portable, handheld 3D scanner produced by shining 3D$^{TM}$ was utilized. Its variant is the "Einscan Pro 2x" and features the ability to operate both as a handheld 3D scanner as well as a stationery one, with the item to be scanned and placed in a platform that can rotate according to the user's parameter setting. Figure 1, depicts the experimental setting of the aforementioned equipment. On the top of the 3D scanner, a dedicated portable camera can be witnessed that is connected to the scanner in order for the scanner to be able to acquire color spectrum along with geometry mesh.

The dedicated software for the obtained mesh refinement operations and the final extraction of the 3D printable CAD file was the software "EXScanPro-3.7.4.0" developed by shining 3D$^{TM}$. Figure 2 depicts a screenshot of the aforementioned process upon the completion of the 3D scanning process.

**Fig. 1:** 3D scanning apparatus set-up

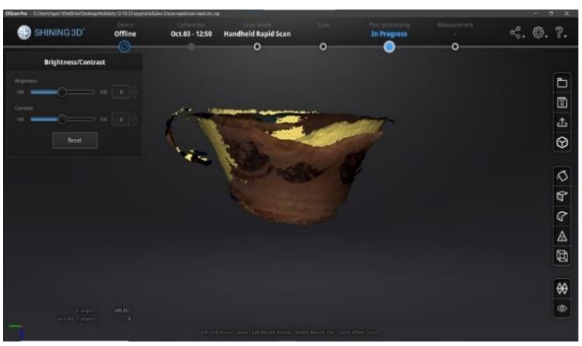


**Fig. 2:** Screenshot of the 3D scanning post-processing procedure

## Results

Regarding the artifacts, the four vessels examined are only a part of the wider archaeological context of the findings uncovered inside the monumental chamber-tomb T.I. that had a rectangular shape and a pitched roof. The alabasters (K 4364, K 4365) (FS 84) are decorated with a rock pattern (FM 32), the small goblet (K 4410) FS 254 is decorated with a foliated band (FM 64), and the early sample of the carinated conical cup (K 4909) FS 230 also decorated with rock pattern (FM 32). All vessels are made of high-quality clay, probably manufactured in a local Mycenaean ceramic workshop and the color of the decoration varies from dark brown to light orange. Figures 3-6 depict each one of the aforementioned alabasters.

**Fig. 3:** Alabaster K4364


**Fig. 4:** Alabaster K4365

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**Fig. 5:** Alabaster K4410

**Fig. 6:** Alabaster K4909

**Fig. 7:** Alabaster K4410 during 3D scanning procedure

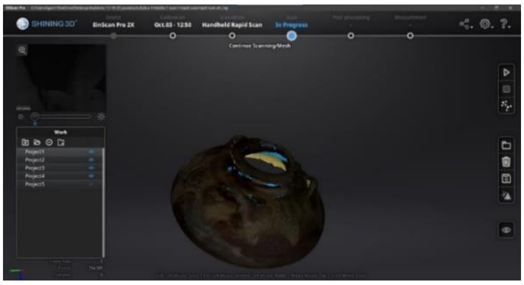

**Fig. 8:** Screenshot of the K4365 artifact's 3D scanning post-processing procedure

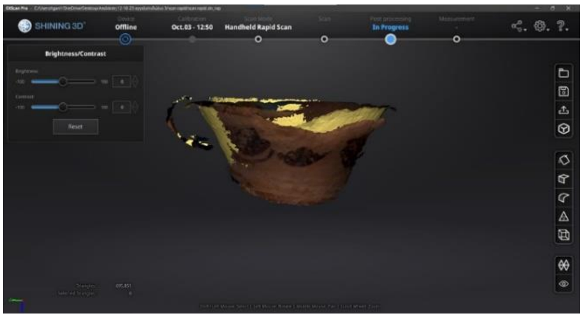

**Fig. 9:** Screenshot of the K4909 artifact's 3D scanning post-processing procedure

The artifacts were then forwarded for 3D scanning. Each one of them was put on the dedicated rotating platform of the 3D scanner. Each artifact was rotated 360°C while the 3D scanner was obtaining data at specified angles. The data obtained produced a digital mesh that also had information about the color of the item. These data needed further post-processing that will lead to the obtained mesh refinement. The post-processing of the collected data is often the most difficult stage of this process. It includes a number of steps to convert specific scan files to 3D models that can be printed. First, the scan data must be carefully cleaned to remove unwanted noise or artifacts. This process requires careful attention from the user because he has to remove small parts with great precision in order to achieve the specific geometrical features of the scanned form. Figure 7 shows artifact K4410 during the 3D scanning process while Figs. 8-9 depict screenshots of the aforementioned 3D scanning post-processing procedure.

After organizing and aligning individual scan data, a registration process merges the scans into a usable mesh file. Next, refinement steps are applied. Initially, a 'small object filter' removes tiny mesh elements caused by unwanted data noise. To fix this, the designer fills these gaps using nearby data, ensuring overall accuracy.

Continuing, the focus shifts to smoothing surfaces with scanning imperfections without compromising important item details. Once these refinements are done, the 3D mesh file accurately represents the item that is ready for 3D printing. Optionally, texture and color can be added, enhancing the digital twin's realism, even though texture isn't used in printing. After this step, it can be saved in file types like OBJ, STL, or 3 mf, each with its features: OBJ and 3 mf retain color, while STL is widely used in 3D printing but lacks color information.

## Discussion

Performing 3D scanning operations within a cultural heritage preservation environment poses several potential hurdles. First and foremost, the delicate nature of antiquities and artworks gives rise to concerns over potential damage during the scanning process. The equipment and necessary movement might inadvertently cause vibrations or collisions, posing risks to the objects' integrity. Furthermore, safeguarding valuable, and irreplaceable items becomes a security concern, as scanning could involve temporarily removing them from controlled environments. Ensuring these artifacts' safety remains a top priority. Another challenge pertains to acquiring accurate and comprehensive images. Museums frequently contain objects characterized by intricate textures, fine details, and reflective surfaces, which pose challenges in accurately capturing their true essence with high fidelity. Lighting variations and reflections further add complexity, leading to incomplete or distorted scans. Additionally, time constraints play a role. The restricted availability of artifacts due to exhibition schedules and tourist traffic poses a challenge in allocating sufficient time for comprehensive scanning. To overcome these challenges, it is necessary to engage in meticulous planning, possess expertise in scanning methods, and foster close collaboration between museum staff and scanning specialists. This ensures the preservation and accurate documentation of the museum's invaluable collection.

Furthermore, performing 3D scanning, especially in intricate settings like museums, often necessitates the use of powerful computers. These systems must boast robust processing capabilities, advanced graphics prowess, and substantial storage to manage the considerable data volumes from scanning devices. Effective data processing and 3D model reconstruction rely on high-performance CPUs equipped with multiple cores and high clock speeds. In addition, powerful Graphics Processing Units (GPUs) are crucial for real-time rendering to achieve accurate visualization and analysis of scanned objects. An adequate quantity of RAM is essential to efficiently handle extensive datasets. Additionally, the storage infrastructure should provide fast access to accommodate the large file sizes generated during scanning. Utilizing advanced supercomputers guarantees efficient and precise data processing, enabling the creation of intricate and realistic 3D models of museum artifacts.

Despite the remarkable progress in 3D scanning, inherent challenges and limitations persist in its application. Common issues arise in achieving optimal accuracy and resolution levels, especially when dealing with intricate forms or tiny details. Scanners often struggle to capture such fine elements or complex textures, leading to reduced precision in the resulting models. Scanning reflective surfaces poses particular difficulties for 3D scanners, especially with highly reflective or transparent materials. Light reflections or refractions from these materials can disrupt data capture, resulting in incomplete or distorted scans. In our case, the non-reflective nature of the statues eased the 3D scanning process.

Moreover, 3D scanning demands expertise and patience due to its time-consuming and complex nature. Proper scanner configuration, arrangement and calibration are critical, and scanning large or complex objects can be time-intensive. Additional steps such as post-processing and data alignment may be required to combine several scans or correct errors, increasing the complexity of the work. Moreover, scanners frequently have restricted range and field of view, which limits their effectiveness in scanning larger objects or collecting wide areas in a single scan.

In addition, the price of sophisticated 3D scanning equipment tends to be exorbitant, which restricts access for people or small enterprises. Obtaining top-notch scanners, along with the required software and hardware, might present substantial cost obstacles for anyone interested in adopting 3D scanning technology.

Also, color 3D printing has greatly evolved, transforming from a novelty to an integral part of additive manufacturing (Chen *et al*., 2016; Godec *et al*., 2022). Initially, 3D printing primarily focused on monochromatic or single-color outputs, limiting the visual fidelity of printed objects (Lee *et al*., 2017). However, advancements in technology have revolutionized this field, enabling the integration of vibrant, multi-color capabilities within the 3D printing realm (Kantaros *et al*., 2024b). The progression toward color 3D printing has been marked by breakthroughs in inkjet and material deposition techniques, allowing for precise color mixing and layering during the printing process. The subsequent use of color 3D printing equipment, since colored digital files were obtained via 3D scanning, is part of our future work.

The application of 3D scanning technology in the digitization of cultural heritage objects has resulted in a substantial revolution in the preservation and accessibility of precious artifacts, artworks, and historical sites. Through the acquisition of intricate three-dimensional depictions of these artifacts, scholars and enthusiasts alike are able to investigate, analyze, and value cultural heritage in manners that were before inconceivable. Nevertheless, despite the widespread use of grayscale 3D printing for replicating digital models, the incorporation of color 3D printing technology holds the potential to enhance this procedure to unprecedented levels of accuracy and immersion (Kantaros and Ganetsos, 2023).

Using color 3D printing has great potential in the field of cultural heritage preservation due to a multitude of compelling factors (Chen *et al*., 2016; Godec *et al*., 2022; Kantaros *et al*., 2024c). First and foremost, it improves the genuineness and lifelikeness of replicated things by accurately reproducing not just their forms but also their initial hues and textures. The importance of this degree of precision cannot be overstated when it comes to preserving the precise features and minute distinctions that characterize cultural relics, ranging from the vivid colors of antique ceramics to the delicate variations of historical fabrics.

In addition, the utilization of color 3D printing has intriguing prospects for immersive educational encounters and virtual displays. Museums and educational institutions may enhance audience engagement by faithfully replicating the visual characteristics of cultural heritage artifacts, resulting in more dynamic and engaging experiences. Visitors have the opportunity to engage with virtual reconstructions of ancient towns, scrutinize lifelike reproductions of renowned sculptures, and even physically interact with virtual items that possess unparalleled realism. This immersive experience facilitates the development of more profound relationships and enhanced comprehension of our collective cultural heritage.

Furthermore, the use of color 3D printing in the digitalization process has the potential to enhance researchers and foster collaboration across different academic fields. Access to extremely accurate and visually authentic digital copies of cultural items may be advantageous for scholars in several subjects, including archaeology, art history, and material science. Digital resources have the potential to function as significant research tools for the examination of materials, procedures, and cultural settings, hence facilitating the generation of novel insights and breakthroughs.

Color 3D printing can increase accessibility to cultural material by enabling the creation of high-quality replicas for wider distribution, as well as for academic and educational purposes. Reproductions of rare or delicate items can be made more accessible to institutions, students, and enthusiasts globally. This reduces the need to physically handle the genuine objects and minimizes the risk of damage or loss.

In general, the integration of color 3D printing into the process of digitizing cultural heritage objects signifies a notable progression that carries extensive consequences. By integrating state-of-the-art technology with a profound recognition of the abundance and variety of the collective human legacy, forthcoming generations will still derive advantages from the wisdom and splendor of history.

## Conclusion

The fusion of state-of-the-art digital methodologies, particularly the intricate applications of 3D scanning and the envisaged integration of 3D color printing, has markedly progressed the analysis and documentation of the Late Bronze Age artifacts unearthed at the Vagia site in Kalapodi, East Locris, Greece. The meticulous use of scanning techniques facilitated the creation of high-resolution digital replicas, unveiling previously imperceptible intricacies and illuminating facets of craftsmanship, symbolic motifs and plausible functional attributions within the socio-cultural tapestry of the late bronze age society.

This confluence of technological advancements with archaeological inquiry has transcended traditional limitations, enabling exhaustive documentation and preservation of these invaluable relics. In addition, the use of 3D color printing has the ability to create accurate physical replicas that closely resemble the originals. These printed replicas will serve not only as potential pedagogical aids for public engagement but also as bridges connecting contemporary society with the enigmatic remnants of antiquity, while safeguarding the intrinsic essence of the original artifacts.

The comprehensive analysis conducted on the acquired digital models, coupled with the potential integration of 3D color printing, holds considerable promise in providing deeper insights into the vibrant chromatic elements and their interpretative significance within these relics. In essence, this interdisciplinary approach, amalgamating past archaeological excavation with advanced digital scanning and printing technologies, not only contributes significantly to the holistic understanding and conservation of these artifacts but also unveils novel pathways for nuanced interpretation and heightened appreciation of the material culture of the late bronze age in Eastern central Greece.

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## Author’s Contributions

**Antreas Kantaros and Evangelos Soulis:** Contributed to the manuscript through drafted the initial text and revised it critically for important intellectual content.

**Maria I. Papageorgiou and Theodore Ganetsos:** Were instrumental in the conceptualization of the study and also played a significant role in the edited process to enhance the manuscript's quality.

**Konstantinos Brachos and Stella Mouzakiotou:** Were responsible for the composition of the original drafted, contributed to the creation of the written content.

## Ethics

This article is original and includes material that has not been previously published. The corresponding author affirms that all co-authors have reviewed and endorsed the article and that no ethical concerns are present.

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