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Straightforward Stereoscopic Techniques for Archaeometric Interpretation of Archeological Artifacts

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Abstract: Stereoscopic visualization plays a significant role in the detailed and accurate interpretation of various geometric features on the surface of archaeological artifacts, which can be challenging to perceive using conventional two-dimensional visualizations. Moreover, virtual 3D models can be shared with other archaeologists for interpretation and the exchange of opinions. The hardware requirements for rendering stereoscopic 3D models are often readily available on desktop computers, or require only a minimal investment for implementation. This article focuses on creating stereoscopic visualizations of a stylized dove-shaped cult vessel for a virtual museum project. The term "visualization" is defined, emphasizing its significance and everyday applications. The camerawork techniques and processes involved in stereoscopic image production, including anaglyph imaging and polarization, are described. Blender (community-driven project under the GNU General Public License (GPL), Blender Foundation is a member of Open Invention Network, Khronos, Linux Foundation and the Academy Software Foundation) and StereoPhoto Maker (Muttyan, Japan) are reviewed as they relate to the production process of stereoscopic visualizations using open-source software. A series of static stereoscopic visualizations, along with two dynamic stereoscopic examples, are created, one using the anaglyph process, and the other using polarization. Lastly, the article discusses the contribution of stereoscopic visualizations to the interpretation of archaeological artifacts and suggests the optimal parameters for creating stereoscopic visualizations.

Keywords: archaeological interpretation; Blender; photogrammetry; stereoscopy; visualization; Vučedol Dove

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1. Introduction

Information visualization, as a multidisciplinary field, is an active area of research and practice in both mainstream computer science and simulation applications [1]. Advancements in computer hardware and software have made visualization technology accessible to everyone. Visualizations are recognized as an innovative form of communication, leveraging the power of images to convey information, ideas, and emotions. In the past, 2D renderings were commonly used for this purpose, and only experts with specialized equipment could create 3D renderings [2]. However, we are now in a new era where 3D representations, visualizations, and animations are increasingly popular and, in some cases, even replace the traditional communication paradigm based on words, symbols, and 2D representations [3].

Culture represents the dignity of a nation. Therefore, cultural heritage holds immense importance and value that must be preserved and passed on to future generations [4]. While historical and archaeological artifacts provide valuable insights into the past, the field of archaeology is inherently destructive. The analysis of a site often involves the dismantling structures and the displacement and removal of artifacts [5]. These artifacts offer a glimpse into the lives and cultures of people from the past, serving as physical evidence that helps us understand the history of a place and its inhabitants [6]. However, many artifacts remain buried in the ground or stored in museums and other institutions [7–9]. Archaeologists employ various methods to unearth these artifacts and study them in greater detail [10]. Stereo visualization, which enables a 3D representation of artifacts, is one such method.

This article discusses the use of stereo visualization in archaeology and explores its benefits for archaeological research. Until now, the Vučedol Dove artifact has not been visualized using this methodology. Stereo visualization is a technique employed to create a three-dimensional representation of an object or scene [11–13]. It is based on the principle of stereopsis, which refers to the human brain's ability to interpret information received from both eyes, enabling the perception of depth in an object or scene. In stereo visualization, two images of the same object or scene, taken from slightly different angles, are merged to produce a 3D representation. Surprisingly, this method has not been utilized in archaeology [14]. Stereo visualization offers several advantages for archaeological research. Firstly, it enables a more accurate representation of artifacts. When artifacts are excavated from the ground, they often suffer damage or incompleteness, making it challenging to understand their original form. Through stereo visualization, archaeologists can recreate a more precise representation of the artifacts, facilitating further study. Another benefit of stereo visualization is its ability to support a more detailed analysis of artifacts. By combining two images captured from different angles, archaeologists can gain a better understanding of the artifacts' size, shape, and surface features. This proves useful for studying the intricate details of specific artifacts and for making comparisons between different objects. Finally, stereo visualization can also be employed to examine the contextual aspects of artifacts. By creating a 3D representation of an artifact, archaeologists gain a better understanding of the environment in which it was discovered [15,16]. This valuable information provides insights into the site and the people who once inhabited it.

Unlike traditional stereometric techniques used in disciplines such as architecture, engineering, or medicine, the production and utilization of stereo images differ significantly. In well-established photogrammetric techniques, stereoscopy is employed to measure the actual 3D artifact and generate its 3D model. Therefore, it is necessary to capture images that are suitable for human measurement using stereoscopic vision or for machine measurement using image correlation algorithms, such as least squares matching. The imaging geometry of the captured photographs is determined by the geometric accuracy of a point on the artifact, as established through the resection of photogrammetric rays. Consequently, the convergence angles between imaging axes are much larger than those required for achieving the most visually striking stereo view.

The approach presented here will be entirely different. It will not involve the production of a 3D model. Instead, it assumes that a 3D model already exists, and the focus will be on creating stereo images in a virtual environment using software Blender, employing two virtual cameras. The imaging geometry will no longer be adjusted to achieve the highest accuracy of measured points on the artifact, but rather to enhance the stereoscopic impression during the exploration of the 3D model. Therefore, the convergence angles of the virtual cameras will be examined, and optimal values will be suggested.

The primary focus of this article is to examine the process of stereo rendering for 3D models of archaeological artifacts using the free and open-source software Blender. The methodology of stereo rendering in Blender will be explored, and the parameters for determining the optimal viewing geometry for human stereoscopic observation will be provided. The introduction of stereo rendering for 3D models has revolutionized how archaeologists' study and document ancient objects. This technology enables researchers to quickly generate high-quality three-dimensional representations of artifacts that faithfully capture their intricate details [9]. Stereo rendering provides a more immersive experience when viewing an artifact, as it creates a sense of depth perception similar to that obtained by standing in front of the object itself.

2. The 3D Observation System

In recent decades, digital methods have had a gradual and significant impact on various aspects of the production of archaeological knowledge, including data collection, analysis, and interpretation, as well as public engagement and scholarly communication [17]. This digital transformation has brought forth new opportunities and challenges for the discipline, necessitating the acquisition of new skills and the adaptation to rapidly advancing technologies. To remain relevant in the current technological landscape, archaeologists must embrace digital methods and integrate them into their research practices.

With the increasing accessibility of 3D and interactive technologies, a wide range of digital tools are now available for effectively communicating the past in museums and online platforms. These tools encompass virtual and augmented reality applications, interactive displays, and mobile applications. It is crucial to critically evaluate their efficacy and consider their ethical implications to ensure appropriate and meaningful utilization.

Presently, virtual reality devices (VR) have garnered significant attention due to their ability to provide users with a 3D spatial experience that extends beyond visual elements, incorporating tactile sensations and immersing users within the virtual environment. This technology enables a form of "time travel" through archaeology, transporting viewers to ancient settings and allowing them to experience the perspective of ancient inhabitants first-hand.

2.1. VR Glasses

There are several VR headsets available on the market, including tethered and standalone options. Some popular wearable VR devices include the Oculus Quest 2 (virtual reality (VR) headset developed by Reality Labs, Redmond, WA, USA), Oculus Quest (virtual reality (VR) headset developed by Reality Labs, Redmond, WA, USA), Valve Index (Valve Corporation, Bellevue, WA, USA), HTC Vive (HTC Corporation, New Taipei City, Taiwan), and HTC Vive Pro (HTC Corporation, New Taipei City, Taiwan) (Table 1).

Table 1. Some of the features of the selected VR glasses [18].

Product Name	Resolution (Pixels per Eye)	Refresh Rate (Hz)	Weight (g)	Price (USD)
Oculus Quest 2	1832 × 1920	72–90	503	299 (64 GB ver)
Valve Index	1440 × 1600	80–144	809–810	999
HTC Vive Pro 2	1400 × 1600	90–120	850	800

The Oculus Quest 2 is a standalone VR headset that offers significant hardware upgrades compared to its predecessor, the Oculus Quest. It features a resolution of 1832 × 1920 pixels per eye, an improvement over the Quest's 1440 × 1600 pixels per eye. The Quest 2 is equipped with a more powerful Qualcomm Snapdragon XR2 chipset, surpassing the Quest's Snapdragon 835. Additionally, it boasts a lighter and sleeker design, enhancing comfort during usage. The Oculus Quest 2 supports hand tracking and provides room-scale virtual reality capabilities.

The HTC Vive and Vive Pro are premium tethered VR headsets known for delivering high-quality VR experiences. The Vive Pro stands out due to its dual-OLED displays, offering a resolution of 1400 × 1600 pixels per eye. Furthermore, it features an upgraded audio system that provides 3D spatial audio. The Vive Pro's sensors support room-scale virtual reality, enabling a more immersive experience. Both the Vive and Vive Pro are designed to be used with desktop computers equipped with powerful graphics cards.

The Valve Index is a high-end tethered VR headset that offers a seamless VR experience. It features a resolution of 1440 × 1600 pixels per eye, but its standout feature is the exceptional refresh rate of 120 Hz, ensuring smooth motion in a VR environment. The Index also incorporates Valve's unique "Knuckles" controllers, providing intuitive finger sensing and grip detection. Moreover, the headset is designed to be used with SteamVR tracking stations, offering a large play area or room-scale VR.

According to Wirecutter [17], the Oculus Quest 2 and Valve Index are among the most popular VR headsets in 2023. The Oculus Quest 2 is priced at approximately USD 299 for the 64 GB version and USD 399 for the 256 GB version. On the other hand, the Valve Index is a high-end tethered VR headset, with a price tag of around USD 999. It is worth noting that while the Oculus Quest 2 is one of the lightest VR headsets on the market, weighing 503 g, wearing it for extended periods can be challenging and tiring. As described by Wirecutter, "It's like hanging a half-litre bottle of water from your face" [17].

Although VR glasses can provide a virtual 3D space experience, achieving a stereoscopic interpretation of archaeological artifacts can be accomplished with simpler and more affordable devices that differ in the manner in which they separate the left and right images.

2.2. Mirror Stereoscope

In mirror stereoscopes, the left and right images occupy different positions in space, typically the left and right portions of the same display. A mirror stereoscope is used to view these images stereoscopically. It consists of a stereo head with chrome-surfaced mirrors and an adjustable screen view. This device directs each image to the corresponding eye, enabling stereoscopic vision and depth perception. The Mirror Stereoscope (USD 445.89 at [19]) can transform any computer into a stereoscopic viewing system, providing good color accuracy, image separation, and flicker-free viewing.

2.3. Anaglyph Glasses

In anaglyph stereoscopy, the left and right images occupy distinct positions in the visible spectrum. To achieve optimal image separation, the images are typically on opposite sides of the visible spectrum, with the left image being red and the right image cyan. Anaglyph glasses are used to view the appropriate image with each eye, creating the impression of depth. Anaglyph stereoscopy equipment is the cheapest option available, but it suffers from poor color accuracy and ghosting, making it unsuitable for detailed stereoscopic interpretation.

2.4. Passive Polarization Glasses

Passive polarization 3D systems use polarized glasses to create the illusion of 3D depth [20]. Two images are projected onto the same screen or display using various polarizing filters, enabling the presentation of stereoscopic images or videos. The viewer wears polarized glasses that correspond to the polarizing filters used for projection. This ensures that each eye receives only the image with the matching polarization, creating the 3D effect. Polarized 3D systems offer several advantages over other stereoscopy technologies, such as anaglyph 3D systems. They can produce full-color images without causing binocular rivalry, a phenomenon where the brain struggles to merge two images due to differences in color or contrast.

2.5. Active Shutter Glasses

Active shutter stereoscopy involves displaying stereoscopic 3D images by alternately blocking the view of the left and right eye. An active shutter 3D system shows the image intended for the left eye, while blocking the right eye's view, and vice versa, using specialized glasses that rapidly switch between opaque and transparent states. This technology relies on either infrared or radio frequency signals to synchronize with the display device, ensuring that the shutters open and close at the correct time.

Active shutter glasses are used in various applications, from cinema projection systems to home theater setups and game consoles. They deliver a high-quality 3D experience with full-color images and a wide range of viewing angles. Compared to passive glasses, active shutter glasses provide a sharper, higher resolution image by presenting a full 1080 p image to each eye. However, this method requires specialized equipment, including a screen with a high vertical refresh rate (120 Hz or better), a compatible video adapter, a synchronizer, and active shutter glasses. Consequently, it can be more expensive and cumbersome than other types of 3D systems, such as anaglyph or polarization-based methods. The comfort of active glasses is lower than that of passive or anaglyph glasses due to their weight, but it is still better than that of VR glasses. The low 60 Hz frequency of the LCD shutters can strain the eyes and cause user fatigue [18].

2.6. Guidelines for Selecting the Optimal Stereoscopic Equipment

Apart from hologram stereoscopy, which has not been considered in this article due to its high equipment costs, there are some general characteristics of the presented technologies that are important when selecting the optimal stereoscopic equipment for archaeometric interpretation, based on our needs and options.

VR glasses offer the best spatial resolution per eye and can produce the highest quality stereoscopic impression. However, they are also the most expensive compared to other types of glasses. Additionally, VR glasses tend to be heavy and can become uncomfortable when used for the detailed stereoscopic study of archaeological artifacts due to their active electronics.

The mirror stereoscope, placed in front of the computer monitor, achieves a spatial resolution of stereoscopic images equal to that of the computer screen. Therefore, it provides a good stereoscopic impression, with accurate color representation and minimal flickering. No special computer hardware, such as a video adapter or monitor, is required for mirror stereoscopy. This optical instrument is simple enough to construct yourself, and it is even easier to adapt old mirror stereoscopes for viewing stereoscopic images on a computer screen. Since no headwear is necessary, this technology allows for the convenient and prolonged study of artifacts.

The simplest and most affordable way to experience stereoscopy is with anaglyph glasses. No additional specialized hardware, such as a video card or monitor, is required. Anaglyph glasses utilize color filters (red and cyan) in front of each eye, but they significantly compromise color accuracy, often rendering them useless for expert archaeological interpretation. Moreover, the image separation in anaglyph glasses is poor, resulting in ghosting and limiting the ability to see and understand the fine details in stereoscopic images. As a result, anaglyph glasses are primarily used in the entertainment world for 3D movies and video games. However, other stereoscopic techniques, such as polarized or active shutter glasses, are preferred for scientific and professional applications.

A passive polarized 3D monitor, combined with passive polarization glasses, form a stereoscopic viewing system that provides a flicker-free display and accurate colors. However, the spatial resolution of the stereoscopic image is reduced to half of the original image, which negatively impacts the quality of archaeological interpretation. Nevertheless, this system is affordable, and passive glasses are inexpensive, lightweight, and comfortable to wear. Multiple individuals can view the stereo image simultaneously, allowing for direct involvement in the interpretation process.

Active shutter glasses deliver stereo images with accurate color and full spatial resolution, achievable by a monitor, making them well-suited for archaeological interpretation. Specialized hardware for stereoscopy, typically available as a stereoscopy kit comprising a special video adapter, a synchronizer, and active shutter glasses, is required. While this system is no longer manufactured, it is still available on the market at an affordable price.

The primary goal of this paper is to motivate archaeologists to engage in the stereoscopic interpretation of archaeological artifacts, gain initial experience, and, if satisfied with the results, consider using more sophisticated equipment as needed. To achieve this, we have proposed methods for generating stereoscopic images and videos that utilize inexpensive equipment but offer high potential for stereoscopic interpretation. Anaglyph glasses are the cheapest option, but they are not the most suitable type of equipment for stereoscopic interpretation. On the other hand, passive polarized glasses, which are comparable in price to anaglyph glasses, provide much more accurate colors and less ghosting, resulting in a significantly improved stereoscopic viewing and interpretation experience. The proposed method employs free software (Blender 3.5) for stereoscopic image and movie production and standard software included in (Windows Media Player, Microsoft, Redmond, WA, USA) for stereoscopic viewing and interpretation. The entire concept was implemented and validated by producing stereo images and videos of one of the most renowned Croatian artifacts, the ancient ritual figure called the Vučedol Dove.

3. Materials and Methods

The complete research methodology was developed, tested, and used on the Vučedol Dove, the well-known Croatian archaeological artifact.

3.1. Vučedol Dove

The Vučedol Dove, a vessel from the Vučedol culture, was discovered on Gradac, the acropolis of the Vučedol site near Vukovar, Croatia. It is considered one of the most significant archaeological findings in Croatia and is currently housed in the Archaeological Museum in Zagreb, identified by inventory number 8201. The Vučedol Dove is renowned for its exceptional beauty, craftsmanship, and symbolic significance, which transcended archaeology to become a national symbol of peace and freedom during the Croatian Homeland War (1991–1995). In a literature, very often one can come across a nice drawing of the Vučedol Dove created by Sead Čerkez [21].

The pit where the vessel was unearthed measured 2.30 × 2.0 m, with a maximum depth of 4.60 m. It contained ash and 44 fragments of white encrusted ceramics from the early classic Vučedol culture. Among the ceramic pieces, there was a bird-shaped vessel. The pot stands 19.7 cm tall and is supported by three cylindrical legs, each measuring between 2.5 and 3 cm in height. At the top of the pot is the opening, functioning as a bottle spout. The pot's surface is finely polished, with a slightly lighter shade due to a shorter baking time, and it features white inlay decorations on the back and chest. Ornaments also adorn the tail, eyes, and beak of the bird. Three double-axe-shaped clepsydra symbols are inlaid on the neck. Recent sand volume measurements yielded a result of 480 mL. Excavator Richard Rudolph Schmidt was captivated by its beauty and craftsmanship. He was the first to refer to it as a dove and concluded that it was not an object for everyday use, but rather a cult item used to store a ceremonial beverage. He arrived at this conclusion based on the presence of double-axe symbols on the bottle's neck, which were common cult symbols in Old Europe. Schmidt suggested that this "dove" originated from the Mediterranean region, specifically Egeida (Greece), and that it shows cultural influences in Vučedol.

Many of Schmidt's conclusions, such as the vessel's cult purpose as a storage item for a ceremonial drink, remain valid to this day. However, the identification of the object as a dove is debatable. The thesis proposing it as a partridge appears quite compelling, linking the bottle directly to metallurgy, one of the significant accomplishments of the Vučedol culture. In Greek mythology, two lame gods associated with metals and metallurgy, Hephaestus, the blacksmith god, and Talos, the brass giant who guarded Crete, are connected to the partridge bird [21].

For the purpose of this research project, the 3D model of the Vučedol Dove was obtained by scanning it with a MINOLTA VIVID 9i (Minolta Co., Ltd., Osaka, Japan) triangulation scanner. The scanning process was conducted as part of the project titled "3D Scanning of Selected Objects of Category A from the Archaeological Museum in Zagreb and Stone Monuments Exhibited in the Museum's Lapidarium" [22]. The dove (Figure 1) was scanned in 87 individual scans, which were divided into 9 sequences to ensure that individual details were not obscured. Photogrammetric recording was also carried out to capture photos for the purpose of texturing. A total of 153 photos were acquired using a calibrated NIKON D90 (Nikon Coroporation, Tokyo, Japan) digital camera. These photos were then projected onto the 3D model, and radiometric texture equalization was performed. The resulting model consisted of 1,092,040 triangles, and the modeling process achieved a high level of accuracy, within a few hundredths of a millimeter.

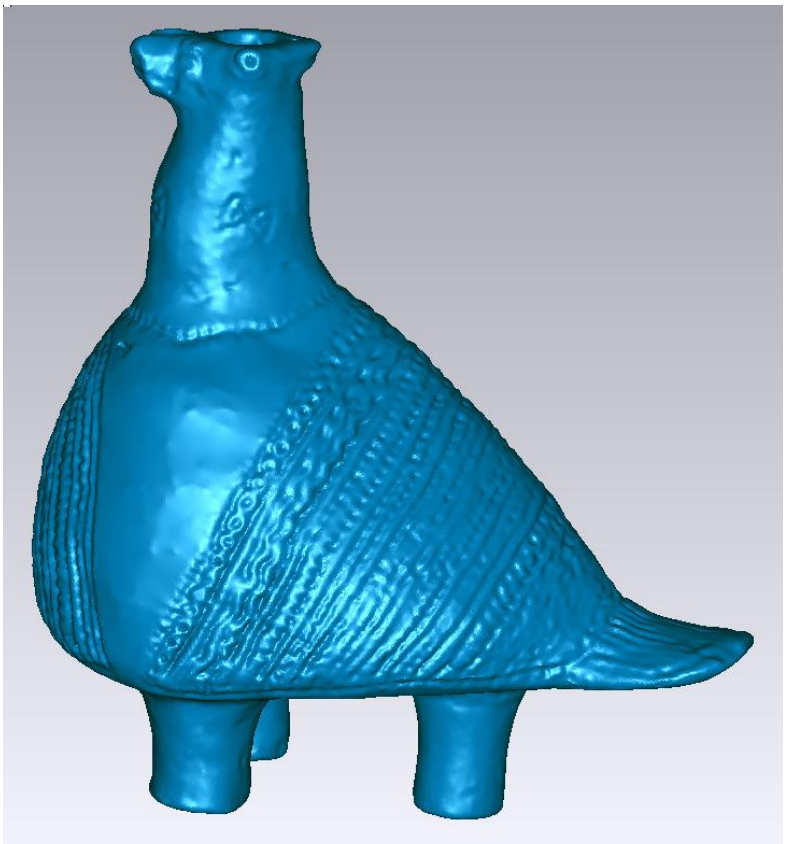

Figure 1. The 3D model of the Vučedol Dove, rendered in Blender.

3.2. Stereoscopic Visualisation in Blender

The use of computer-based visualization to present hypothetical reconstructions of the past dates back to the late 1980s [23,24]. Scientific stereoscopic visualization is a powerful tool for researchers and scientists, enabling them to visualize complex data and models in a way that adds depth and dimensionality to their work. Blender, a popular open-source 3D modeling and animation software, provides robust tools for creating stereoscopic visualizations applicable in various scientific domains. Blender's stereoscopic 3D features enable users to create a "stereoscopic viewport" that offers a 3D perspective of their models or data [25]. This effect is achieved by rendering the data or model from two slightly different perspectives, simulating the way our eyes perceive depth in the real world.

Rendering refers to the process of generating images, animations, or videos from a 3D model or scene. It involves transforming a complex 3D model, along with its lighting, materials, textures, and other attributes, into a 2D image suitable for display on a screen or in print. Rendering is a fundamental aspect of computer graphics and finds applications in various industries, including film, video games, architecture, and product design. The rendering process begins with the creation of a 3D model or scene, which includes information about the objects' positions, orientations, and properties such as lighting and textures. The model is then submitted to rendering software, which utilizes algorithms to calculate how light interacts with the objects in the scene [26].

To create a stereoscopic visualization in Blender, it was necessary to import the data or 3D model into the software. This could be accomplished using various file formats, such as OBJ, STL, or VRML. After loading the model in Blender, the configuration of the stereoscopic 3D view could be adjusted accordingly (Figure 2).

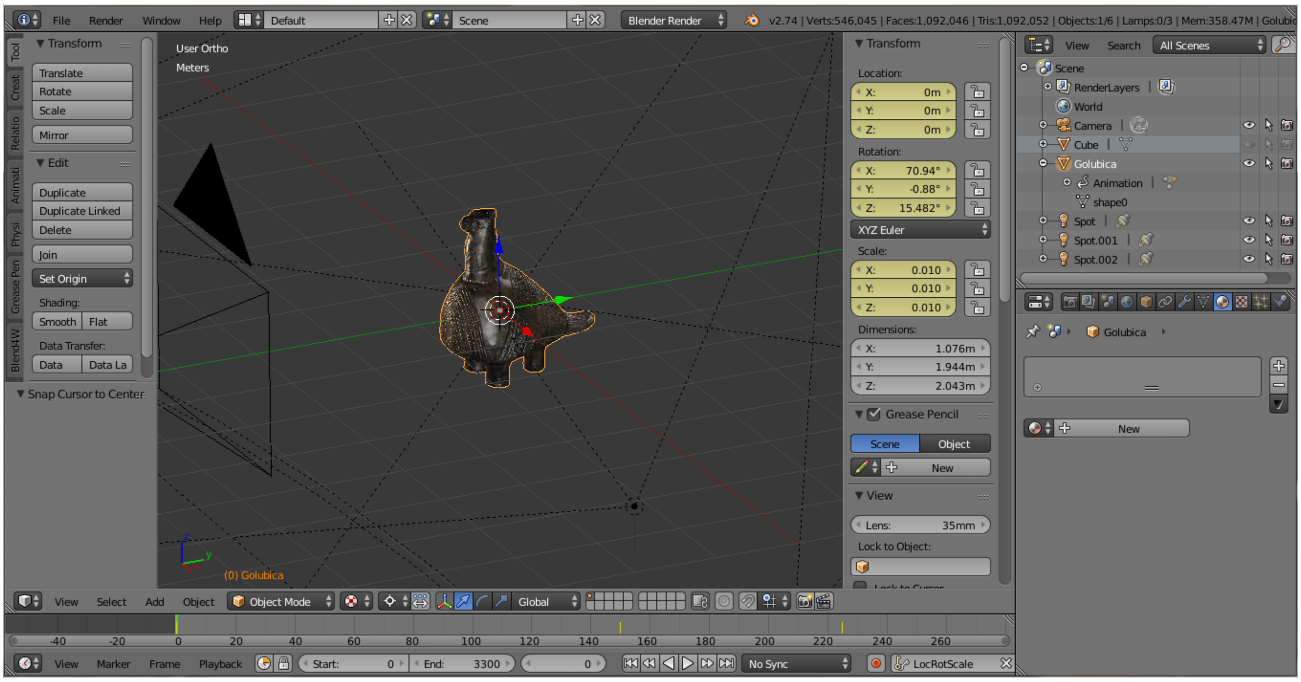

Figure 2. A 3D model of the Vučedol Dove imported into Blender—User interface.

This was achieved by enabling the "Stereo 3D" option in Blender's camera settings. This option generates two virtual cameras, positioned slightly apart, simulating the distance between human eyes (stereoscopic base). Subsequently, the position and orientation of the cameras were adjusted to achieve the desired stereoscopic effect.

Determining the Optimal Length of the Stereoscopic Base

The first step in rendering was to determine the position and orientation of the virtual cameras used to capture the stereo image. These cameras were moved around the scene, zoomed in or out, and then their settings were adjusted to control the exposure, focus, and other parameters of the image. For a pleasant stereoscopic viewing experience, it was important to ensure that both virtual cameras had the same zoom factor, focus, and exposure settings. The optical centers of the virtual cameras should differ in space by the length of the stereoscopic base, and the optical axes of both cameras should converge, as suggested in Table 1.

Once the cameras have been set up, the rendering software calculates how light interacts with the objects in the scene, taking into account factors such as the material properties of the objects, the direction and intensity of the light sources, and the position of the camera. The size of the stereoscopic base depends on the distance of the area or object being imaged. In close-range photogrammetry, there is a rule that considers both the farthest and closest sections of the terrain. When dealing with the farthest part, it is important to avoid a base that is too small, as it significantly decreases the accuracy due to the unfavorable cross-section of the photogrammetric rays. On the other hand, when dealing with the closest area, a base that is too large should be avoided to prevent perspective differences between the left and right imaged areas, which negatively impact the stereoscopic effect. Therefore, the size of the base is determined within a range of 1:4 of the distance to the closest point and 1:10 (for larger scales) or 1:20 (for smaller scales) of the distance to the farthest point in the imaged area.

Photography experts often adhere to the "1:30 rule", which states that the ratio of the base length to the distance of the object should be 1:30. This rule has sparked numerous debates in the field of stereo photography. Many suggestions can be found regarding when to increase or decrease this ratio. However, the consensus remains the same—it is necessary to test different base lengths when capturing the same scene, compare the results, and determine which yields the best outcome [11,12,27,28].

One of the primary objectives of this research is to determine the virtual camera parameters that result in a pleasant and immersive stereoscopic visualization. Since the distance between the camera and the object's center of mass is constant at 5 m, it is possible to calculate the base length and convergence angle for a given object distance using the theoretical ratios of base length and object distance (Table 2).

Table 2. Length of stereoscopic base and convergence angle for different camera-to-object distances and stereoscopic base ratios.

Stereoscopic Base Ratio r	Stereoscopic Base x [m]	$x/2$ [m]	c [m]	sin (φ)	Convergence Angle φ [°]
1:4	1.250	0.625	5.039	0.124	7.125
1:5	1.000	0.500	5.025	0.100	5.711
1:6	0.833	0.417	5.017	0.083	4.764
1:7	0.714	0.357	5.013	0.071	4.086
1:10	0.500	0.250	5.006	0.050	2.862
1:15	0.333	0.167	5.003	0.033	1.909
1:17	0.294	0.147	5.002	0.029	1.685
1:20	0.250	0.125	5.002	0.025	1.432
1:25	0.200	0.100	5.001	0.020	1.146
1:30	0.167	0.083	5.001	0.017	0.955

The length of stereoscopic base x and the convergence angle φ were calculated according the formulas:

The length of the stereoscopic base is

$$x = cr,$$

and the sinus of the convergence angle is

$$\sin \varphi = \frac{x}{2c}$$

where c is the distance to the reference plane of the 3D model, and r is the stereoscopic base ratio, as shown in Figure 3.

The convergence angle was calculated to ensure that the point of forward intersection falls precisely at the center of the object's mass within the plane, where the left and right images perfectly coincide (Figure 3).

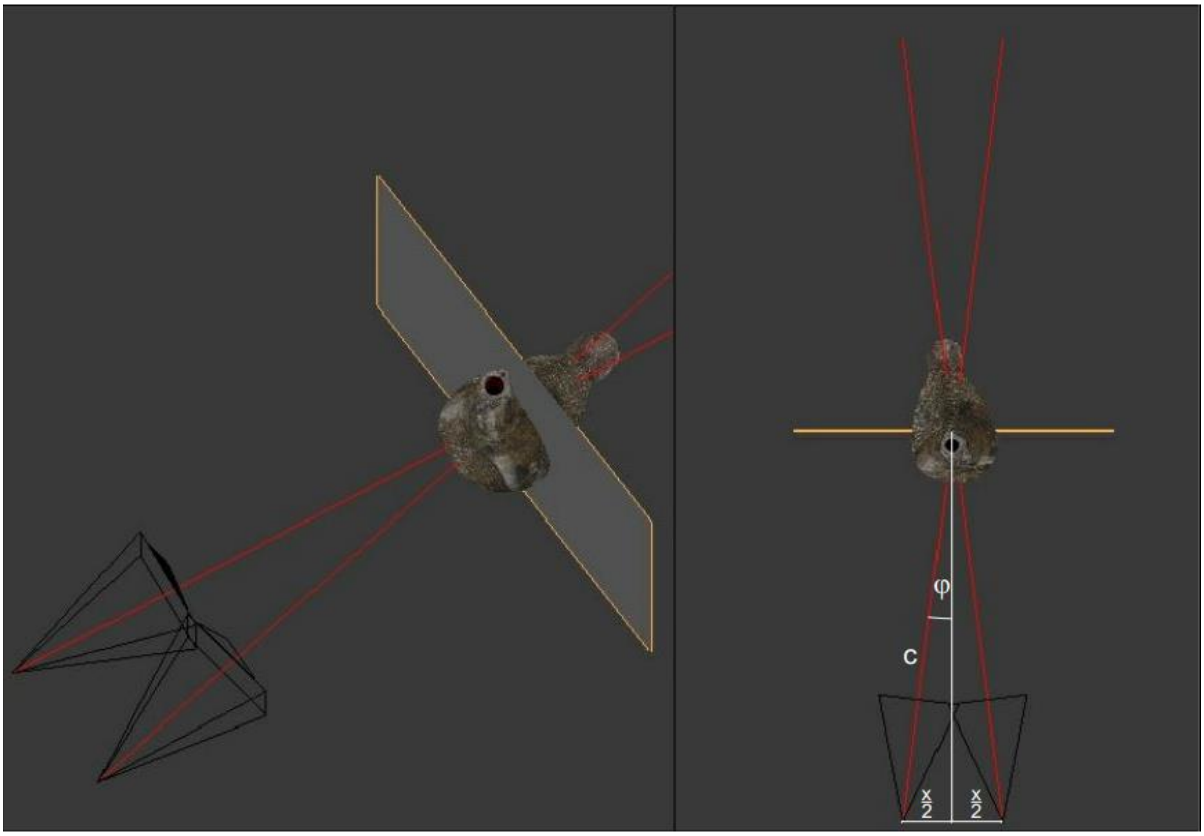

Figure 3. Setting the convergence angle between two virtual cameras in Blender.

4. Results

The animation consists of 4600 frames. Static visualizations were created for specific frames (0, 400, 1350, 2100, 2800, 2900, and 3200) using the base sizes listed in the table. Perspective cameras and OpenGL rendering were utilized to generate these static visualizations. To create stereoscopic static visualizations, it was necessary to render the left and right cameras separately. The software StereoPhoto Maker was then employed to produce an anaglyph and polarized stereo image. Figure 4 displays anaglyph static stereo visualizations created with StereoPhoto Maker. As an example, frames 0, 2100, and 3200 were selected from the animation, and they were recorded using cameras with the longest and shortest base lengths to observe the impact of base length on parallax shifts.

Upon careful examination of individual static stereoscopic anaglyph and polarized visualizations at their full size, it becomes evident that longer base lengths result in significant parallax shifts between the left and right images. This phenomenon significantly complicates stereoscopic observation, rendering it rather unpleasant.

However, base lengths derived from the ratios 1:15, 1:17, and 1:20 fulfill the observer's requirements. The visualizations created with these base lengths are enjoyable to watch, and the stereoscopic effect remains intact (refer to Figure 5). To determine the optimal camera selection, samples of the same frames were captured using both an orthographic camera and a perspective camera. A comparison was then made between these samples (as depicted in Figure 6).

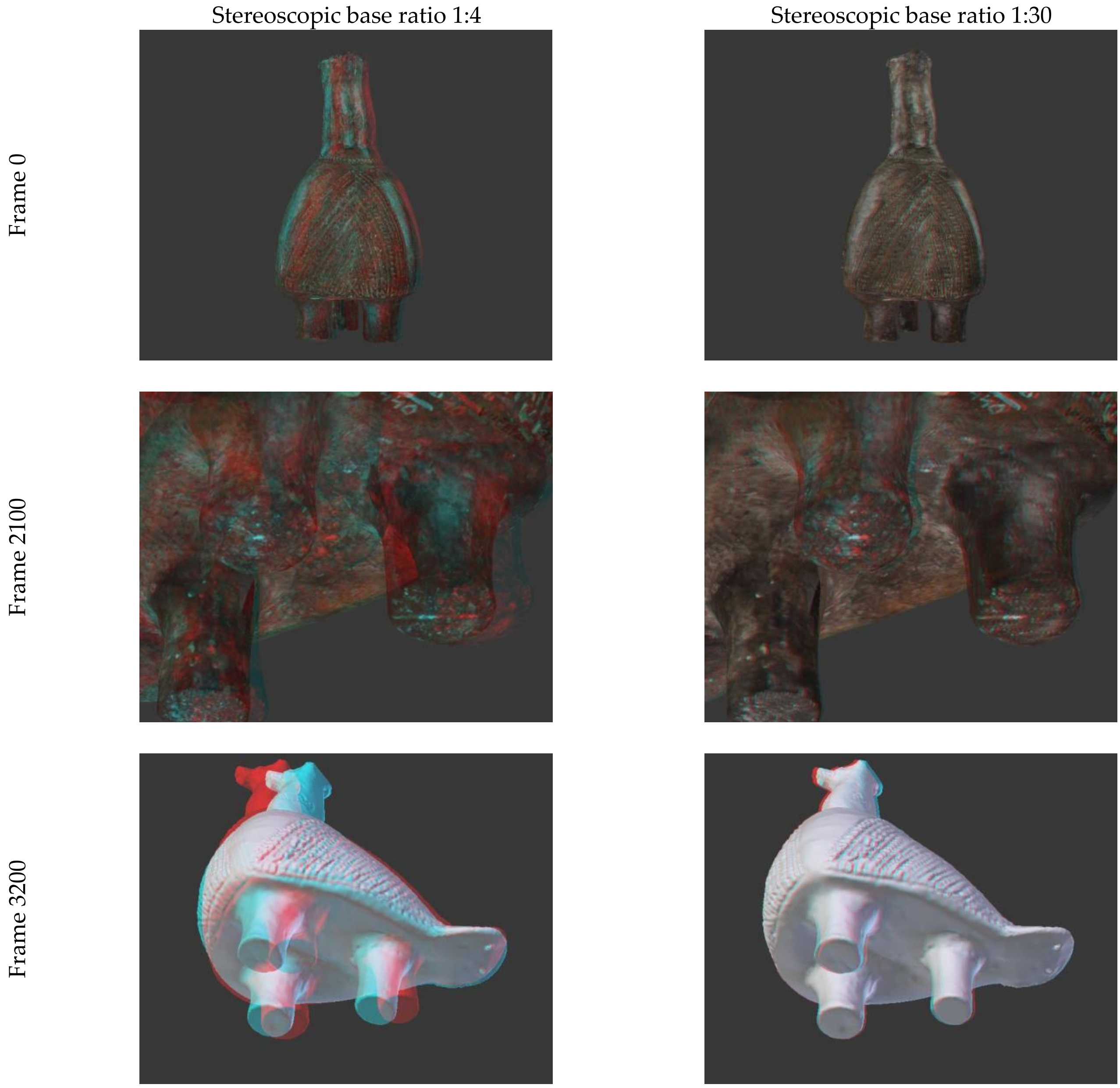

Figure 4. The impact of different stereoscopic base ratios on the stereo parallax.

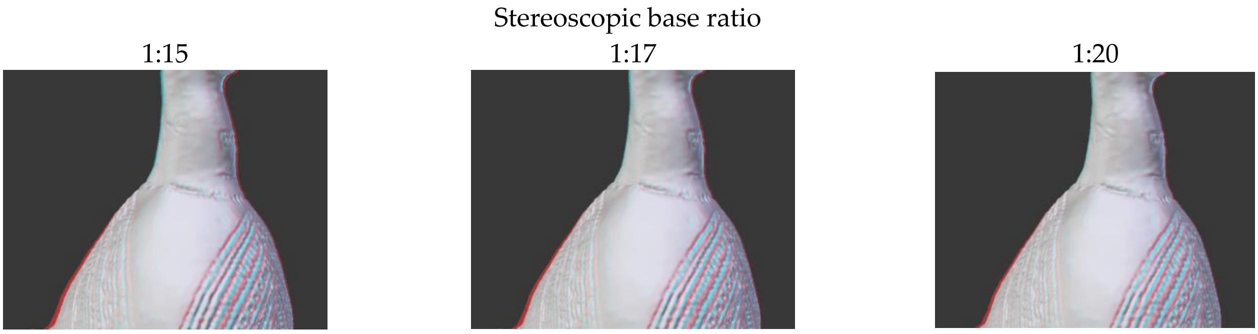

Figure 5. Three images with slightly different stereoscopic base ratios used to select the best representation.

After visually comparing the views captured using different cameras, it was determined that, in this case, employing a perspective camera enhances the perception of three-dimensionality. Furthermore, it was concluded that the perspectives recorded with a perspective camera featuring a base length of 0.294 m and a convergence angle of 1.685° (corresponding to a ratio of 1:17) best fulfill our requirements, resulting in a pleasant stereoscopic visualization experience.

To showcase the dynamic visualizations of the Vučedol Dove, the aforementioned parameters were utilized. These visualizations can be viewed using anaglyph glasses (stereo anaglyph HD.avi) or stereo equipment with polarized glasses (stereo polarized HD.avi) by accessing the following link: https://zenodo.org/record/7679249#.Y_val-zMLFo (accessed on 26 May 2023).

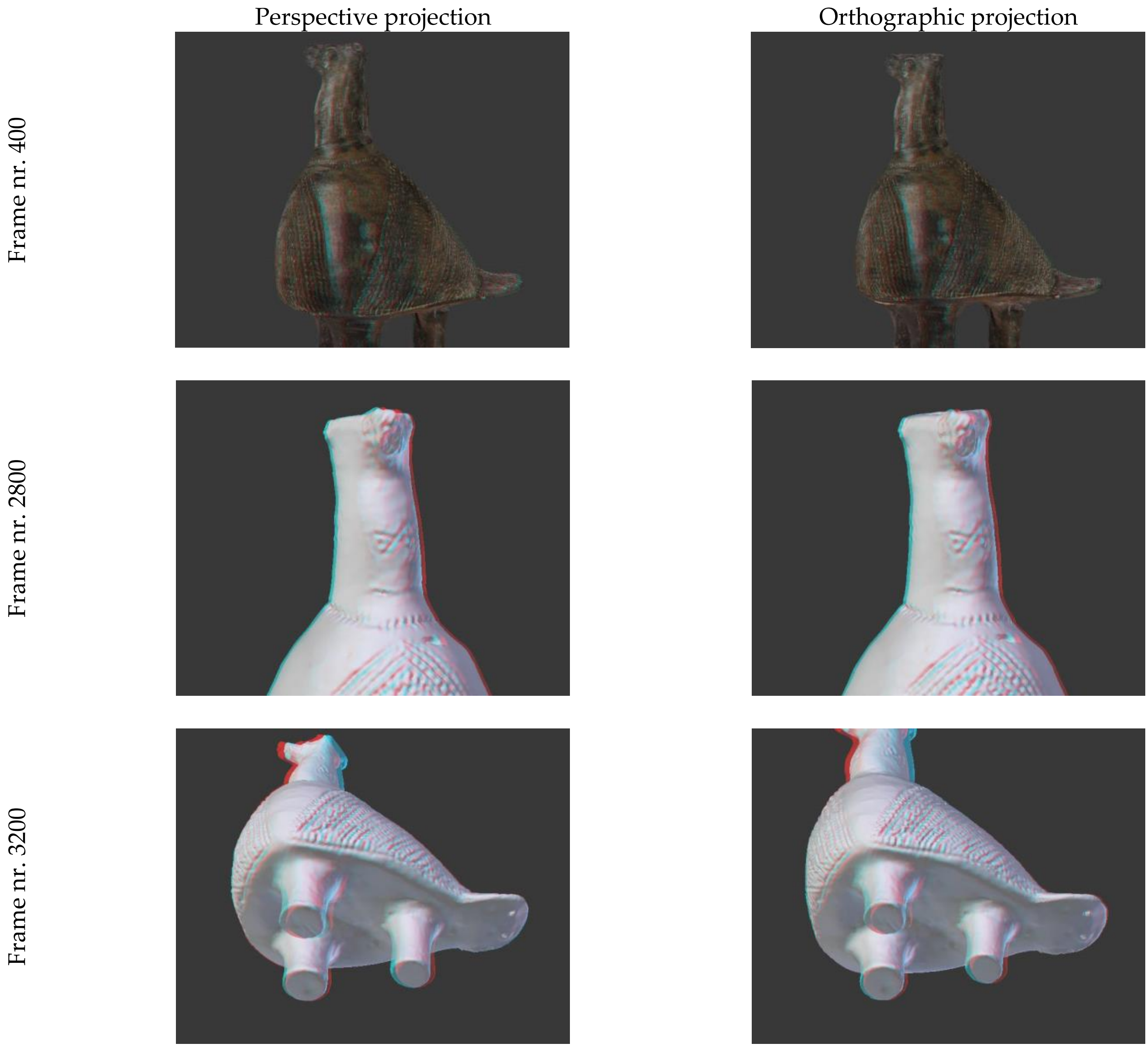

Figure 6. Comparison of the perspective and orthographic projection in different frames of the 3D video of the Vučedol Dove. Stereoscopic base ratio in all images is 1:17.

5. Discussion and Conclusions

The future of visualization and graphics is incredibly promising. Only a few decades ago, the field of data visualization did not exist, and computer graphics was considered a subset of the more formal disciplines within computer science. However, as technology advanced and computer graphics capabilities improved, engineers, scientists, and researchers increasingly turned to graphics to better understand and communicate data.

Today, computer graphics play a vital role in extracting, analyzing, comprehending, and presenting information from digital data [26].

In the past, the visual documentation of archaeological artifacts primarily relied on technical drawings of cross-sections, decorations, vessel edges, and other details. Such drawings necessitated meticulous measurements of the artifacts, requiring the use of rulers, compasses, meters, and similar tools, which proved particularly challenging when dealing with well-preserved objects. Furthermore, the drawn measurements had to be meticulously transferred onto paper and then shaded, making the entire process time-consuming and requiring a high level of expertise in technical drawing, documentation, and visualization.

The significant contribution of this article lies in presenting a methodology for creating stereoscopic visualizations (both static and dynamic) of 3D models of archaeological artifacts using free software, such as Blender. This methodology offers archaeologists a new explorative tool for their research. With the aid of 3D scanners and digital cameras, the process of measuring artifacts is facilitated and expedited. Once a 3D model is created, realistic visualizations can be generated, providing archaeology experts with enhanced insights into various aspects of the artifacts. These visualizations are particularly useful for creating captivating representations that appeal to the public and popularize these artifacts.

This research aims to increase the virtual accessibility of artifact collections through stereoscopic visualizations, benefiting both archaeological specialists and the wider public. To make the visualizations more user-friendly, dynamic stereoscopic visualizations were created using the anaglyph and polarization processes. The polarization process yields superior color representations and a more pleasant viewing experience compared to the anaglyph process. However, it requires a slightly higher investment, as polarized 3D glasses tend to cost around 50% more than anaglyph glasses. Additionally, polarized displays necessitate specialized display mediums, such as silver projection screens or lenticular screens, to enable the desired display mode.

These products serve as an additional source for reliable descriptions and documentation of archaeological findings. The advancements in technology empower archaeological users to respond to this challenge by creating virtual museums that are accessible to everyone [29–36], and dynamic stereoscopic visualizations represent a step toward achieving that goal. In the future, the authors intend to research and develop methodologies for producing interactive stereoscopic visualizations of 3D models. This will enable archaeologists to interactively rotate, move, and scale 3D models, while the optimal stereoscopy parameters are calculated in real-time. Interaction within web and GIS applications will also be possible for further analysis. By incorporating augmented reality, these techniques will attract museum visitors and contribute to the popularization of cultural heritage in modern times. Virtual museums, through the creation of 3D images of ancient artifacts, offer a new level of detail, interactivity, and accessibility to visitors.

- One of the most significant impacts of the stereoscopic visualization of archaeological artifacts is increased accessibility. By creating 3D images of artifacts, virtual museums can provide access to ancient objects that may be physically inaccessible to many people. This is particularly important for people with disabilities, who may not be able to visit physical museums. By making artifacts accessible in a virtual environment, museums can help to ensure that everyone has the opportunity to learn about ancient history and culture.
- Another significant impact of stereoscopic visualizations is that they will help to preserve ancient artifacts. By creating digital 3D models of artifacts, museums can reduce the need for the physical handling and transport of the objects. This can help to reduce the risk of damage and deterioration of the artifacts, which is particularly important for fragile and rare objects.
- Stereoscopic visualizations will also provide a level of interactivity that is not possible with traditional museum displays. Visitors will manipulate the 3D models of artifacts, zooming in and out, rotating them, and exploring different angles. This interactivity can help to engage visitors and provide a more immersive experience.

- Stereoscopic visualizations can also have significant educational value. By providing 3D images of ancient artifacts, museums can offer a level of detail and context that is not possible with traditional displays. Visitors can explore the artifacts in detail, learning about their history, cultural significance, and context. This can help to provide a deeper understanding of ancient cultures and history.
- Stereoscopic visualizations can also help with conservation efforts. By creating digital 3D models, museums can study and analyze the artifacts without the need for physical handling. This can help to identify areas of deterioration or damage, and inform conservation efforts.

In conclusion, the stereoscopic visualization of archaeological artifacts offers numerous advantages in terms of accessibility, preservation, interactivity, education, and conservation. These visualizations contribute to a better understanding and appreciation of ancient cultures and history. As technology advances, virtual museums are expected to expand and improve, offering even more benefits to visitors and enabling the preservation of our rich cultural heritage.

By publishing on online portals, it is possible to enhance the visibility and accessibility of 3D versions of archaeological and museum artifacts. These objects can be included as interactive elements. An example of such a solution is the "3D Digital Silk Road" portal [37]. This website provides a collection of 3D models representing historical landmarks and artifacts from the Silk Road. Individuals from around the globe can explore and learn about these significant historical and cultural treasures without the need to physically travel to their respective locations, as these objects are accessible online.

Instead of relying solely on virtual models created through 3D visualizations, archaeologists are increasingly turning to 3D printing to produce physical replicas of historical artifacts. These tangible replicas serve as valuable teaching aids, enabling students to interact with and examine accurate representations of significant artifacts, providing a deeper understanding of their historical context and usage. The use of 3D printing allows for the creation of precise copies of fragile artifacts and the fabrication of replacement parts for damaged items. This helps to mitigate the risk of handling damage, safeguards artifacts from further harm, and facilitates the restoration of damaged artifacts when conventional restoration methods prove insufficient [36].

The primary objective of this article is to capture the attention of archaeologists and highlight the potential of stereoscopy for the objective interpretation of archaeological artifacts. It also serves to demonstrate that even with a limited budget and a straightforward methodology, it is feasible to create stereo pairs that can be comfortably viewed in 3D. While the hardware required for stereoscopic viewing of 3D models has become less common, it can still be obtained on the market at a very reasonable price.

A recommendation for future research is to explore the use of holography as an alternative to stereo images. Holography has the potential to provide an even more immersive and accurate representation of an artifact's geometric characteristics, eliminating the need for viewers to wear 3D glasses. This advancement would enable the entire scientific community to engage in the study of unique artifacts, while ensuring their complete protection and preservation for future generations. Moreover, teachers and students would have the opportunity to study artifacts in unprecedented detail. The ability to create holographic representations would mark a revolutionary leap in artifact research, allowing for exploration and study without the need for physical contact.

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