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Review

A Systematic Review on Virtual Reality Technology for Ancient Ceramic Restoration

Yue Ming [1,2], Rosalam Che Me [1,3,*], Jue Kun Chen [2] and Rahmita Wirza O. K. Rahmat [4]

[1] Department of Industrial Design, Faculty of Design and Architecture, Universiti Putra Malaysia, Serdang 43400, Malaysia; ming.yue@student.upm.edu.my
[2] Digital Art Industry Institute, Hubei University of Technology, Wuhan 430068, China; ken0121@126.com
[3] Malaysian Research Institute on Ageing (MyAgeing), Universiti Putra Malaysia, Serdang 43400, Malaysia
[4] Department of Multimedia, Faculty of Computer Science and Information Technology, Universiti Putra Malaysia, Serdang 43400, Malaysia; rahmita@upm.edu.my
* Correspondence: rosalam@upm.edu.my

Abstract: The protection of intangible cultural heritage has received much attention, among which the "ancient ceramic restoration technique" was included in The National List of Intangible Cultural Heritage of China (the fourth batch) in 2014. In preserving and restoring ancient ceramics, virtual reality (VR) technology has been widely applied, as it provides a new way to showcase the appearance and structure of ancient ceramics in a VR environment. This paper provides a systematic review of the application of VR reality technology in the conservation and restoration of ancient ceramics. The methodology comprises four steps: research problem formulation, literature search, study selection and data extraction. A total of 30 articles out of 1479 peer-reviewed database articles from six databases (Web of Science, SpringerLink, IEEE Xplore, Scopus, CNKI, Google Scholar) were extracted and screened, which covers the application of VR technology or VR-based devices in ceramic conservation. It has been found that the existing VR application on ceramic restoration is hardly systematic or user-oriented. Thus, we develop a VR-based Platform on ceramic restoration utilized with Unity and 3DS Max, ensuring authenticity, minimal intervention, and promising reversible repair within the VR environment. The findings show that VR technology applied to ancient ceramic restoration has contributed to the learning efficiency and learning willingness of users.

Keywords: virtual reality technology; intangible cultural heritage; ancient ceramics; virtual restoration

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1. Introduction

Ancient ceramic relics play a crucial role in research on culture due to their unique historical and artistic value. Ancient ceramics, generally called ceramics, can be classified according to different historical dynasties and kilns worldwide. Historically, China has been the main producer and exporter of ceramics, with abundant ceramic resources and many professional researchers. According to the first national census on cultural relics from the State Bureau of Cultural Relics in China, ancient ceramics ranked fifth in the quantity of moveable cultural relics [1]. It also has the maximum number of art collections category in the Palace Museum. Nevertheless, many ancient ceramic relics need to be repaired urgently. For example, according to the lasted public data, in 2005, there were 35 million ceramics required to be restored in Palace Museum, but the professional restorers were less than 90, and only ten experts engaged in ceramic restoration [2].

Even though the number of ceramic restorers has increased in the past decades with the reform of national policies and the introduction of talent training programs [2,3], the restoration works are still too enormous to undertake. Under such circumstances, the restoration technique of ancient ceramics, listed as the Chinese national intangible cultural heritage in 2014, was developed to meet the demand for reusing broken ceramics after repair and serve the purposes of collection and appreciation [4]. In other words, the restoration of ancient ceramics is no longer only based on practicality but is motivated by cultural exhibition and esthetic taste [5]. However, traditional ceramic restoration technique proves insufficient in many regards, such as high costs of time, shortage of experts, deficiency of preservation awareness etc. [6,7]. In a nutshell, the current situation of cultural relic restoration is quite severe [8]. Therefore, studying how to restore traditional ceramics effectively has become urgent.

The conception of virtual restoration [9], virtual archaeology [10], and virtual heritage [11] appeared among interdisciplinary research since 3D technologies were applied to cultural heritage approximately in 1995. Unlike the manual techniques evolved from ancient sawing nails, gold manufacturing and modern chemical reagents [12], VR technology utilizes scientific theories and computer technology to achieve a high restoration degree of cultural relics [13]. As a digital display method, VR technology generates multi-sensory three-dimensional information, such as vision, hearing, and touch, to give users an immersive experience and interact with the environment [14].

VR was proven effective for in-situ, noninvasive and nondestructive restoration and preservation of various art objects, such as ancient architecture, ancient photographs, archaeological pottery, and rock art. During the past 20 years, many scholars and organizations have utilized VR technology to preserve tangible and intangible cultural heritage (ICH) [13,15–17]. For example, compared to general information models (e.g., 3D Geographic Information System, Building Information Modeling, and Heritage Building Information Modeling [18–20]) for the restoration and reconstruction of large spatial scale architectural relics, 3D laser scanning technology and 3D point clouds are mainly applied to the 3D reconstruction of cultural relics in micro to mesoscale models.

Under the realm of VR, virtual restoration technologies include deep learning, 3D printing, and 3D laser scanning, which are widely applied to cultural heritages such as stone sculptures, pottery sculptures, and massive architectures [6,21–24]. Since ancient ceramic restoration is a branch of cultural relics restoration, these VR technologies are also applied to ceramic restoration [25–27], which is still relatively rare compared to other archaeological categories. In most cases of VR ancient ceramic restoration, the technologies applied mainly include 3D scanning, 3D modeling and 3D printing [28]. These technologies contribute to the simulation and reconstruction of the original shape of ancient ceramics after comparing the methods for replication and restoration of ancient ceramics among manual and virtual paths. Weimin Bu believed that the 3D restoration method is efficient and convenient but highly demands facilities, computer technologies, and interdisciplinary talents [12].

Motivated by the need to develop in-depth knowledge of ceramic restoration techniques within a fully digital and interactive environment, this paper aims to review the recent literature on VR application to ancient ceramic restoration. Unlike traditional restoration methods that encounter massive challenges in restoring ceramics with complex surfaces, VR technology can repeatedly and effectively portray ceramic surface details and present detailed 3D models of complex ceramic models. The application of VR technology to the restoration process of ancient ceramics can be studied from several aspects, including visualization, usability, and interaction. Following this, this paper undergoes a systematic review to unpack the roles of VR technology in the restoration process of ancient ceramics.

2. Methodology

2.1. PRISMA Statement

With the main objective of how VR is used in ancient ceramic restoration, this systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [29]. Web of Science, SpringerLink, IEEE Xplores, Scopus, China National Knowledge Infrastructure (CNKI) and Google Scholar databases were searched by following four steps: (1) identification, (2) screening, (3) eligibility, and (4) data extraction. A summary of the documents obtained at each stage according to the PRISMA is given in Figure 1.

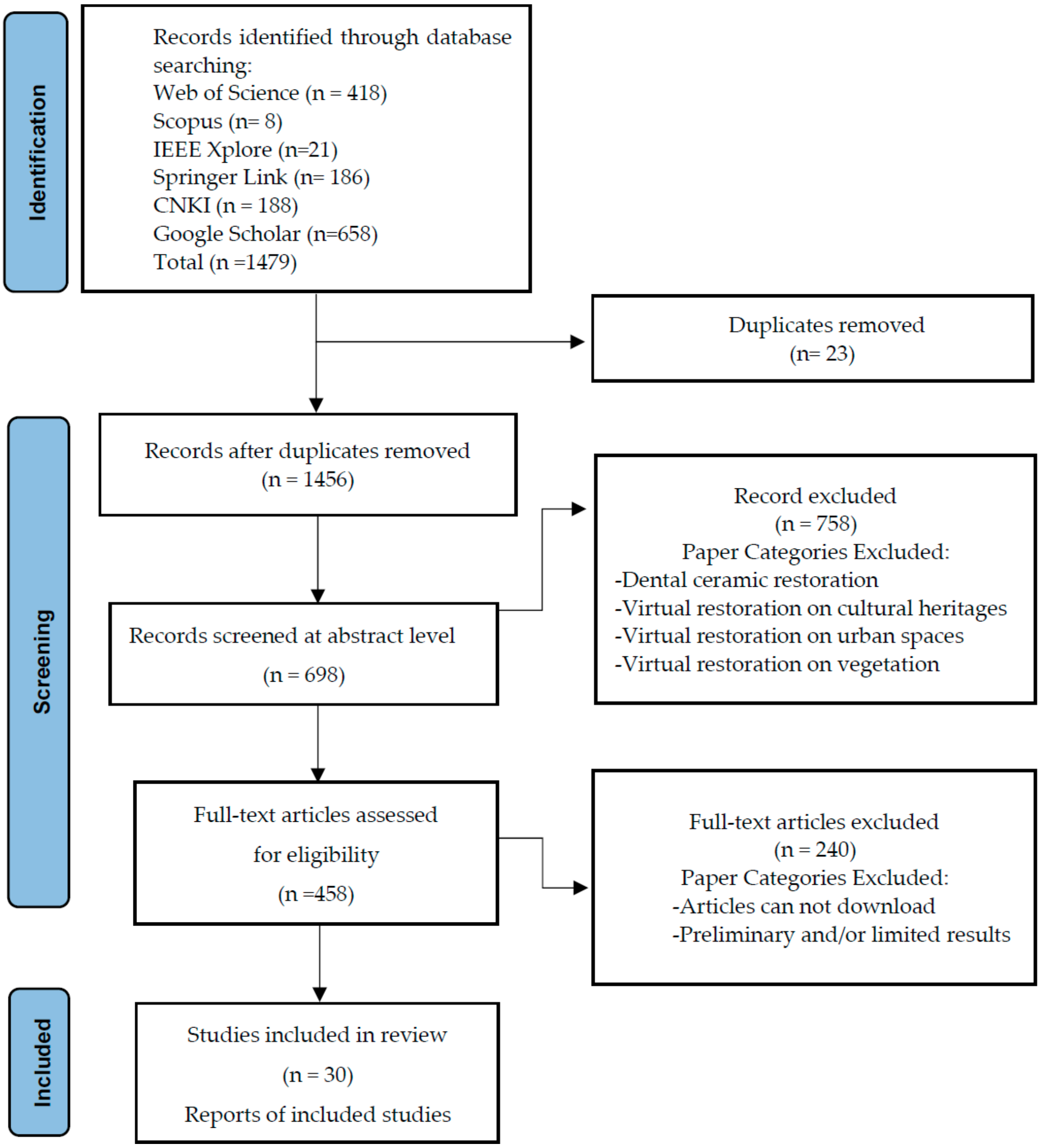

Figure 1. PRISMA flow diagram.

2.2. Identification: Search Strategy and Sources

This review focuses on three broad concepts: (1) virtual reality, (2) ancient ceramics, and (3) restoration, based on the objective of understanding the application of VR technologies on ancient ceramic restoration.

The following terms were selected: ("ceramic*" OR "pottery" OR "porcelain") and ("restoration" OR "repair" OR "fix") AND ("virtual reality" OR "VR" OR "3D scanning" OR "3D printing" OR "3D reconstruction"). The language for the search was restricted to English and Chinese, without a specific search time frame, as it helps to outline the development of VR technology applications on ceramic restoration. The search was sorted by relevance, opinion, title, abstract and keywords to purposely capture as many relevant papers as possible, generating 1479 results.

2.3. Screening and Eligibility

In this stage, the criteria for inclusion and exclusion were applied, as shown in Table 1. In total, we considered several aspects here, such as the language of the paper, topic, and content. Peer-reviewed articles meeting the following criteria were included: (1) The discussion is about applying 3D scanning, 3D printing, and 3D reconstruction to ancient ceramic restoration; (2) English and Chinese written articles; and (3) the discussion includes the use of VR in ancient ceramic restoration.

Table 1. Inclusion and exclusion criteria.

Criterion	Inclusion	Exclusion
1	3D scanning, 3D printing, and 3D reconstruction applied to ancient ceramic restoration	Duplicates from different databases
2	English and Chinese-written articles	Studies published in other languages
3	Articles on the use of VR in ancient ceramic restoration	Preliminary and/or limited results Studies published in other areas

We first reviewed whether the article provided the necessary evidence for the objective of this review. Duplicated articles from different databases were moved. Then, studies on VR technology applications for ancient ceramic restoration were matched. Other VR studies on dental, cultural heritage, urban space, vegetation and so on were excluded. Also, articles with preliminary findings and/or limited results were moved. Finally, we verified and validated all selected articles to confirm that their categories and contents were pertinent.

2.4. Data Extraction

We again reviewed the final list of selected articles according to the relevant requirements and confirmed the appropriateness of our choice. In Appendix A, the articles are arranged by the year of publication, with the information extracted from each article based on the objective of this review. How VR technologies are applied to the restoration of ancient ceramics is listed, including the term category, objective, and strategy.

3. Results

We categorized the articles into visualization, usability, and interaction for the review. The main research contribution of each article is used as an index for assigning them into one of these three categories to avoid overlapping between categories.

3.1. Paper Selection

A total of 30 articles were ultimately selected based on the three broad categories (see Figure 2). Among them, 53% correspond to visualization (visual restoration of ancient ceramics with computerized algorithm and machine manufacturing), and 30% focus on usability (expanding application after visual reconstruction, 3D printing for display and comprehensive database, etc.) Finally, 17% relate to interaction (allowing participants to cooperate with or engage in ancient ceramic restoration with VR technology).

Figure 3 shows the tendency of the research under each category from 2005 to 2023. It is worth noting that the data from 2023 only accounts for a small percentage, as the search was performed in July 2023. Corresponding with the largest proportion in Figure 2, articles on visualization were published consistently from 2016 to 2023. Articles on usability and interaction were only published in 2018, as it is a relatively new topics of virtual ceramic restoration. Notably, the topic number of usability and interaction was higher than that of visualization in 2021.

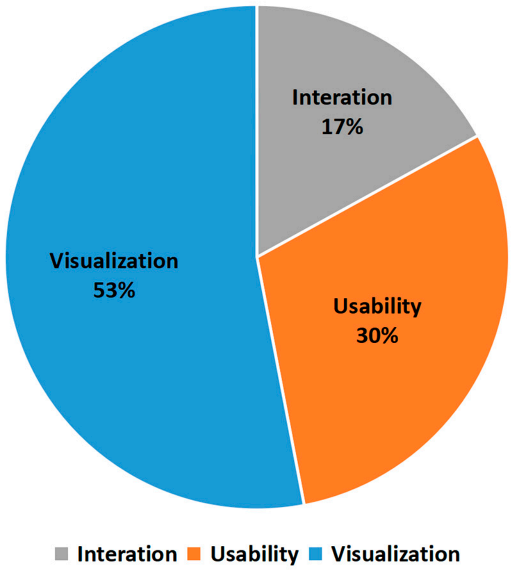

Figure 2. Division of articles in each category.

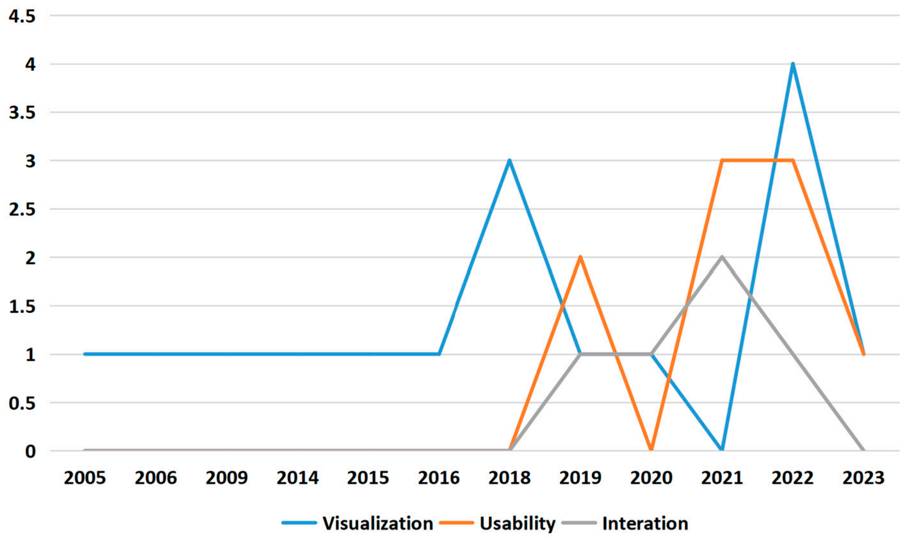

Figure 3. Tendency of the research topics of each category.

3.1.1. The Visualization of Ceramics after Restoration with VR Technology

As ceramic restoration and preservation is a branch of archaeology, the original and primary goal is to restore ceramics as authentic as possible. The visualization concepts focus on reasonable, rigorous reality reconstruction with VR technology instead of manual working. The virtual restoration technologies differ according to the damage degree of excavated ceramics while following archaeological and cultural restoration principles, including authenticity, minimal intervention, and usage of reversibility.

Accurate data on ancient ceramic characteristics should be captured with appropriate scanning equipment, such as computed tomography/µ computed tomography, structured light, laser scanners, motion sensors, and photogrammetry/SfM [14]. Barreau, J.-B. et al. believed that a low-cost facility could obtain a satisfying experimental result of repairing symmetrical objects. However, accuracy problems in digitization and printing still existed [30]. Sipiran et al. found that unscanned bases of relics lead to limited scanning results and acquisition process mistakes during the digitalization of archaeological relics. His research aims to integrate the missing surface of an object and retain the existing geometry and refined details [31].

However, some valuable ceramic relics collected by museums and private collectors are hardly removable due to security problems and cannot be scanned and restored with general methods. Wu, H. and Ma Y. reconstructed a 3D model based on 2D images of rotating ancient ceramics through a new reconstruction algorithm. This new algorithm solved the problems of previous image processing methods, for instance, 2D image distortion, complex image background, and large varieties in image quality [26]. This method could yield a high-accuracy 3D model for 3D printing without a high-cost 3D scanner; however, the objects under reconstruction are restricted to rotating shape ceramic.

Reconstruction algorithms on computer graphics are the primary tool for researchers. The data captured from the 3D scanner had to be adjusted with advanced computer science for virtual anastomosis and reconstruction [14]. Liu Y. et al. developed an efficient algorithm for surface reconstruction of archaeological pottery, but not on obtaining prior knowledge [32]. Jiang Y. proposed a 3D digital reconstruction method for ceramic paintings by obtaining ceramic relics' complete color point cloud data, which is suitable for VR applications [33]. After accomplishing the digital scanning and 3D reconstruction of 115 Shiwan ceramic relics in the Ceramic Museum, he argued that the ceramic information preserved through +5 exposure blend methods on average in 6 combined modes contributed to VR application.

Nikolas Lamb et al. proposed DeepJoin, an automated approach for repairing fractured shapes for asymmetrical and symmetrical objects, which is an automated and predicted approach for generating high-resolution restoration shapes with ground truth fractures and restoration [34]. DeepJoin generates plausible restoration shapes for ancient Greek pottery from the Cultural Heritage dataset and serves for more complex objects. This code is open access on the GitHub website and contributes to further work on automated restoration. Machine learning algorithms, such as the optimized parameters of the backpropagation (BP) neural network model, could improve ceramics' identification and classification accuracy in different dynasties [35].

Piecing together dismembered fragments of archaeological objects is challenging for virtual and manual restoration. Liu E. et al. proposed a method of global archaeological fragment pairings based on artificial fish school algorithm technology. He extracted the edge features of ceramics by removing the noise of the point cloud after 3D scanning, of which the algorithm provided intelligence pairing for broken fragments [36]. Ioannis Kalasarinis and Anestis Koutsoudis proposed a 3D pose normalization algorithm applied to vessel restoration that had great applicability in processing 3D data to generate synthetic missing shreds [37].

The high-accuracy 3D model with complete archeological information could be printed with a 3D printer to display in different spaces. Yang, Y. believed that symmetrical objects of a ceramic relic could be printed easily with the mirror principle of 3D software (3DsMax 2012), avoiding the previous manual plastic complex processes such as mould turning [38]. Iqbal Marie and Hisham Qasrawi proposed that the 3D shape of archaeological pottery could be fixed by the shadow moiré technique. Then, their accomplished virtual modeling with 3D-MAX modeling software [39,40] provides an innovative idea that a 3D printed inner support matched with the ceramic bowl's shape could be used to place ceramic fragments.

3.1.2. Usability of Ceramic Restoration with VR Technology

The literature above indicates that the visualization of ancient ceramics depends on computer technologies to decrease the cost. Research on virtual ceramic restoration has mainly focused on the 3D establishment of ceramic models but not 3D printing objects for display [41]. One of the main objectives of relic restoration is to understand profound historical facts through these wares and to explore the people's lives, behavior, and cultural traditions [42] from the archaeological perspective. The virtual archaeology of ceramic pigments and THE reconstruction of their decorations contributed to more knowledge of the specific culture, origin, and trading information [43].

Consequently, some scholars have focused on the usability of ceramic restoration with VR technology. For example, according to the different restoration accuracies and demands, Lv J. and Fu J. divided the 3D data of the virtual model into four grands as follows [41].

- Level-0, original statistics of 3D scanning for back-ups but not applied directly.
- Level-1, 3D model scanned in situ with high 3D accuracy for general display.
- Level-2, nondestructive and high-precision 3D models with optimized virtual reality data are mainly used for teaching and research.
- Level-3, thumbnail model of 3D data storage and managed by museum database.

The 3D model with high-precision 3D data of Level-3 [41] not only provides a better stereoscopic visual experience for visitors but is also available to 3D printing, which can promote the data preservation of cultural relics. Liu S. et al. restored a gold foil-decorated Black Ding bowl collected by the Chifeng Museum through a virtual conservation approach. By an innovative combination of digital acquisition, virtual anastomosis, virtual reconstruction, and 3D printing of a transparent reversible prosthesis [14], they achieved this artefact's physical and aesthetic restoration while conforming to the cultural restoration principles. During the restoration of the Double-Ear Clashing Color Vase with the Lotus pattern, Lv J. and Fu J. improved the 3D accuracy of the model and the registration quality of the texture color model with better reconstruction efficiency.

Lin S. restored the Warring States Period Deer Shape Golden Porcelain and Double-Ear Dragon Vase with VR technology. This virtual restoration process followed the reversible principle, the minimum intervention principle, and the retaining of primary data principle. The double-dragon ear model was printed with a 3D printer, and the broken ends of the vase were spliced together. This ceramic relic could be displayed after polishing, spray painting, coloring, and glazing [44]. Similarly, Amanda Berg identified a method to reduce the corrugation of FDM-printed ceramic surfaces. Her method enables the researchers to use ABS polymer to print because it is not only easily accessible at a low price but also helps to remove the corrugation within the shortest time and with the least solvent [45].

Regarding the application path of 3D printing, the 3D model of restorative ceramics could be expanded to cultural creative products in daily life and holographic museum displays [28]. Tatum Shannon and Nancy de Grummond restored the artefacts excavated at the site of Cetamura del Chianti in Italy to provide more insights into the actual size and volume of the excavated artefacts [46]. They also tried to promote these 3D printing models to other fields. However, the data on restored ceramics is minimal compared to the vast broken heritage sites.

Luca Di Angelo, etc., proposed a new approach combining 3D scanning, automatic recognition features, and identification of 3D characteristics with a database designed for the classification, documentation, reconstruction, storage, and management of ancient ceramic fragment information [47]. This approach has been applied to cultural relics from ninety-seven Roman archaeological potsherds and is available over the internet. Lin S. [44] and Chen J. et al. [35] also believed that the integrated application of big data and VR promotes the establishment of ceramic relics databases. Nacer Farajzadeh and Mahdi Hashemzadeh also built a deep neural network for broken pottery restoration, studying inpainting results with a database of 677 pottery images [48].

3.1.3. The Interaction Function of Ancient Ceramics Restoration with VR Technology

For the category of interaction, participants/users involved in ceramic restoration could communicate interactively but not at the receptive and passive ends with the help of VR technologies, including two kinds of situations: The first is the interaction between cooperated participants. The second is the interaction between the participant and the computer programming. The subsequent discussion on the participation of VR technology in the conservation and development of ceramic culture aims to explore feasible paths and methods for the conservation, inheritance, and development of ancient ceramic culture worldwide.

Zhong X. believed that virtual restoration technology should be widely applied to the education field and not only among research institutes; however, the main organizations for ancient ceramic restoration and preservation are the museums and institutes established at the national level [4]. Moreover, both virtual and physical conservation strategies should be promoted for cultural communication. In this regard, Sipiran et al. proposed that the algorithm for reducing reconstruction mistakes and retaining ceramic features is the foundation for further research on virtual displays and virtual education environments [31]. Aligning with this, Yu X. established a VR display system with interactive mode after accomplishing the virtual restoration of Shouzhou kiln ceramic relics, presenting a virtual ceramic exhibition with friendly interaction and roaming functions [49]. This research uses VR technology for ceramic firing process simulation, providing users with a real-time experience without entering the kiln.

Rao J. et al. established a framework for a virtual e-learning platform to solve the actual problems during ancient ceramic restoration [50]. It has been difficult to make a breakthrough in the conservation and preservation of ancient ceramics preservation due to historical and social reasons. The virtual simulation framework was designed based on a case study of cultural relics' virtual restoration platforms. The process setting of virtual restoration relies on experts from the restoration field and the research of 3D virtual engines [17]. This research hypothesized that integrating E-learning patterns and VR technology could broaden the limited methods of original ceramic restoration from the interaction perspective.

Ren Z. and Hong Y. proposed a self-developed porcelain cleaning system with Unity 3D [51]. This VR e-learning system allows participants to study the simulated porcelain restoration process and review related professional knowledge in four modules, including the theory knowledge module, practical test module, knowledge quiz module and evaluation feedback module. The statistics of the digital model database of marine porcelain for the theory knowledge module were collected from the Underwater Cultural Heritage Protection Center of the State Administration of Cultural Heritage. Participants can be well immersed in this VR system to achieve a sense of situational integration, which paves a foundation for the subsequent practical operation [51]. This kind of 3D data can be summarized in the grand Level-2 according to [41] and can be used for educational purposes.

Patrice L. et al. proposed a new research paradigm with a transdisciplinary approach to heritage studies. They produced a unique "knowledge space" on cultural heritage, networked with archaeologists, computer scientists, and digital media researchers. After accomplishing this 3D Colonial Philadelphia Project founded by the National Science Foundation, they presented a convergent cultural space within interdisciplinary cooperation and contributed to heritage research. In this Project, participants from computational researchers and digital media practitioners engaged in developing computer vision technologies, which contributes to the promotion of notions like "community" and "heritage" [42].

4. Discussion

The 30 selected articles provide insights into how VR technology is applied in ancient ceramic restoration.

The analyses above demonstrate that new advanced ceramic VR simulations are a promising way to reconstruct traditional ceramics better to experience obstacles. This type of application focuses on enhancing the performance of virtual ceramic applications by incorporating distinctive acoustic resonance as a more likely infinite geometric phenomenon texture mixed with the basic shape. The monotonous nature of traditional teaching often leads to rejection and boredom, whereas e-teaching with virtual reality offers a more engaging and captivating experience. The motivation for implementing VR technology is that it is a low-cost option for projects with high trial and error costs or few opportunities for trial and error. Furthermore, VR can provide users with an interactive, immersive, and innovative learning process. On a technical level, VR distinguishes itself from all other technologies by contributing more to a sense of near-real experience and receiving feedback accordingly. Unity 3D, one of the most commonly used real-time development platforms for developing VR ecosystems [52], is a graphics engine that can be used with a head-mounted display.

However, the main challenges include (i) The digitalization of cultural heritage has the problem of showing off too much technology and ignoring the content. The way to realize the digitalization of cultural heritage is to combine "culture" and "science and technology", but the mission of preserving the lifeblood of culture and spreading cultural genes was ignored [53]. (ii) The 3D data of the ancient VR ceramic model is mainly from private archives and cannot be obtained for public education. Using VR in e-learning will enable a deeper understanding of concepts [54]. (iii) The existing VR system of ancient ceramics lacks modules to show restoration techniques and processes, and the audience is relatively narrow, resulting in a limited promotion of the ancient ceramic culture. (iv). The interface aesthetics and interactivity design of existing VR cultural relic restoration platforms need further improvement for a better user experience. Based on all these, our team developed a VR-based e-learning platform on ceramic restoration with Unity virtual engine.

4.1. A New Virtual Reality E-Learning Platform on Ceramic Restoration

According to the review work above, there is rare attention to VR e-learning platforms on ceramic restoration that deems ceramic restoration a professional branch of archaeology and traditional craftsmanship. With the increasing attention of ICH safeguarding, integrating VR technology into ceramic restoration becomes meaningful. Compared to traditional education, the VR-based platform provides a more immersive experience since interaction with the 3D environment is more natural than browsing 2D web pages [55]. The VR-based platform is widely used in education, reducing the cost of learning and bringing new opportunities for individuals [54]. Furthermore, the VR e-learning platform is a comprehensive database including visualization, usability and interaction features of 3D data.

In terms of VR-based platforms for ceramic or pottery, scholars including Rao J., Ren Z. and Sarah Dashti [50,51,56] contribute to transmitting knowledge of ceramic production and cleaning—Sarah Dashti et al. proposed hand-made ceramic pottery using VR technology combined with traditional methods [56]. Sarah focuses on improving the performance of virtual pottery applications by adding unique acoustic resonance as a more likely infinite geometric phenomenon texture mixed with the basic shape. However, an essential topic in this stage concerns how to present the restoration process for ceramics with a VR-based platform to preserve this traditional craftsmanship listed in ICH.

To transmit the ceramic restoration knowledge more efficiently and extensively, a VR E-learning platform (Chinese Version 1.0) utilized with 3DS Max, Maya, Visual Studio and Unity 3D was established by our team after clarifying the design principles of education platforms and understanding specific users' needs. Operation systems include Windows, Unix, IOS and Android. MySQL database is also used in this case. This platform has been awarded a national software copyright patent.

It consists of two modules for (i) theory knowledge (relic restoration, restoration instruments, restoration materials) and (ii) restoration practice. The platform allows the users to simulate the entire restoration process of the object by clicking the buttons and following the prompts to select different tools and restoration areas. For example, ultrasonic cleaning and dismantling can be practised (Figure 4). Users can also practice gluing, matching, and shaping, as well as coloring and painting, and adjusting the luster. It is believed all these functions will contribute to the protection of ceramic restoration and the promotion of traditional cultural transmission. In this case, the research question is, does VR technology help to improve users' learning efficiency?

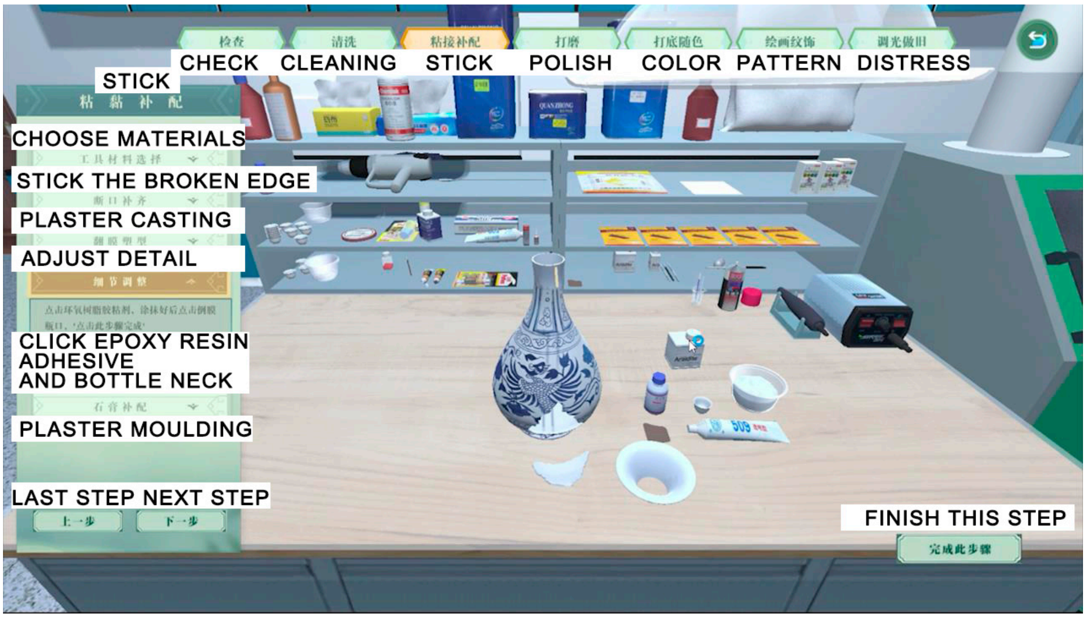

Figure 4. The Interface of VR ceramic restoration platform.

This study collected data from a questionnaire (https://www.wjx.cn/vm/PwcG7Ds.aspx (accessed on 19 June 2023)). The measurement items in the questionnaires include emotional commitment, interactivity, system quality, learning efficiency, and willingness. Based on the "negative-positive-anchor" theory [57], the factors influencing migration behavior from traditional online education platforms to VR-based platforms have been analyzed [58]. As users' risk-perception assessments may affect the pull of VR-based platforms [59], emotional commitment is variable. Chen J. then proposed that interactivity and system quality positively affect users' adoption. In the information-system success model, system quality is generally used to evaluate information systems regarding technical indicators, such as reliability and ease of use. Following that, Chen X. et al. surveyed the user experience evaluation data of the museum platform. The indicators include evaluation of visual, function, interactivity and information content, among which users most value interactivity and system quality [60]. Li J. and Yu N. surveyed learning efficiency as an indicator for validating the VR technology adoption for the Qingdao Agricultural University (QAU) museum education platform [61].

The 5-point Likert scale measured all potential variables, with 1 indicating strong disapproval and 5 indicating strong approval. The researchers collected formal data through an online questionnaire in July 2023. The participants refer to users who are interested in ceramic restoration. In this case, a preliminary survey was conducted with 35 undergraduates and postgraduates to ensure that the reliability and validity of the scale met the requirements. The questionnaires collected that did not meet the basic quality requirements for responses were screened and excluded. Ultimately, 34 valid questionnaires were obtained. Most of the respondents agree that this VR platform provides a good interactivity experience (86.66%), superb usability of system function (91.14%), and satisfies their emotional commitment (87.61%). The majority of respondents are convinced that VR has promoted their learning efficiency and learning willingness, and among them, 41.71% strongly agree with this view. The next section will discuss how interactivity, usability, and emotional commitment impact learning efficiency. And the scale will be adjusted according to the preliminary survey results to make it more suitable for the Chinese context.

4.2. Further Study on the Field of Ancient Ceramic Restoration with VR Technology

3D visualization and database establishment of the ceramic restoration with VR technology are needed. As discussed in Section 3, the general VR technologies applied to the visualization of ceramic restoration include 3D scanning, reconstruction algorithms for splicing fragments, and 3D printing. These technologies contributed to restoring ceramics following conservation–restoration principles, presenting a relatively complete ceramic relic to archaeologists. Computer scientists and digital media researchers have consistently researched and developed high-accuracy 3D models with intelligence algorithms in the past 20 years, which will continue and transform historical archaeology practice. The multidimensional information of ceramic relics by integrating a high precision visualization 3D model with point cloud data is an open and extensible model framework, forming a database for the reconstructed ancient ceramics. Scholars worldwide have established several ancient ceramic databases during archaeological excavations in recent decades. Nonetheless, rare databases are open to the public.

The 2003 UNESCO Convention promotes educational, awareness-raising and information programs aimed at the general public, particularly young people. Different technical challenges, such as the accuracy of 3D scanner manufacturing, the complex surface of the cultural relics, the pairing of fragments, the high reflective property of the surface glaze, the accuracy of 3D printing, the simulation details of ceramic's surface, and the consistency of glaze color after restoration, are solved by participants (3D scientist, archaeologist, artist etc.) of the heritage community. The increasingly exponential development of the software and hardware technologies involved in virtual reconstruction has benefited researchers of archaeological projects to optimize their framework and algorithm to achieve physical/aesthetic restoration. However, participants are still making efforts to collect the richness of 3D information on ceramic surfaces with high-accuracy data.

Expanding the application of virtual restoration of ancient ceramics among communities, museums, and education institutes is in need. Regarding computerized algorithms and machine manufacturing, VR technologies are the main tools for visualization and database frameworks for ceramic restoration from archaeology. In addition to these technical applications, VR could promote progress in the humanities and social sciences. According to Waterton, E. [62], these kinds of cultural heritage projects emphasize the relationship between "community" and "heritage", meaning that every participant, such as scientists, multimedia designers, and archaeologists, can make tremendous contributions to national and social identity building as heritage researchers. They are also the participants and creators of public archaeology.

More involved creative interactions between humans and machines have empowered science, art, and technology. Such new technologies have included advanced and sophisticated graphics engines, wearable devices, and innovative interface systems. VR technology enhances the ability of humans to interact and explore the physical and visual aspects. Considering VR devices makes it easier to train in various operations in research effectively and practically. It provides the researcher with an opportunity to cope with adverse and unknown situations and to learn how to react to adverse and unknown situations simultaneously. The series of findings have shown that integrating objects into the environment and the user's sense of spatial presence positively impact all aspects of the object, enhancing the user's experience of the object and improving the overall evaluation [63]. In addressing the abovementioned challenges, VR technologies are supposed to offer the following benefits for the restoration of ancient ceramics.

i. Learning opportunity. While traditional methods of restoring ancient ceramics are more costly in terms of trial and error and encounter bottlenecks that make it difficult to continue research, VR devices can offer lower-cost opportunities for experimentation.
ii. Learning efficiency. To reduce irreversible experiment errors, VR equipment should provide a safer scenario where the researcher can practice acquiring the necessary skills.
iii. Speed. Thanks to VR digital tools' innovative and attractive approach, researchers can access more information about their research and effectively accelerate the progress of related studies.

iv. Recordability. Because VR works with computer-generated environments, researchers can easily obtain any desired statistics, such as the time it takes for an operator to perform an activity, the most common accidents, or less complex procedures.

5. Conclusions

This paper has presented a systematic review summarizing the main findings on implementing VR technologies in ancient ceramics. The literature analysis presented the continuous development of VR technologies used in the visualization, usability, and interaction of ancient ceramic restorations. These technologies effectively reduce the cost of trial and error, following the principles of being reversible, using minimum intervention and retaining the primary data, and bringing various possibilities for displaying ancient ceramics. Fifty-three percent of the selected articles exhibit sound results in the visualization problems of ceramic restoration based on VR technologies, and the remaining articles provide comprehensive and interdisciplinary research on ceramic databases, E-learning, and community heritage that have been a strong uptrend.

A VR-based ceramic restoration platform is established to enhance learning efficiency and increase preservation consciousness within the VR environment—a comprehensive evaluation of emotional commitment, interactivity, system quality, learning efficiency and willingness. Compared to traditional education, the VR-based platform has new features of bilateral interactive display and collaboration of multiple senses in coordination with display methods. VR technology opens a new interdisciplinary portal, a concept that has long changed with the development of virtual reality modeling applications. On one side, new VR technology includes advanced and sophisticated graphics engines, wearable devices, and innovative interface systems that enhance the ability of humans to interact and explore. On the other side, how to promote the conservation of ancient ceramic restoration from visualization to storage, documentation, and metadata adoption strategic initiatives leveraging virtual reality technology should be considered in the future. This review and the conclusions obtained herein should be considered a first step in analysing ceramic restoration in the sector.

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Appendix A

Table A1. The research objective and strategy of selected papers.

Reference (n = 30)	Title	Database	Year	Category	Objective	Strategy
[43]	A novel implementation of the INFN-CHNet X-ray fluorescence scanner for the study of ancient photographs, archaeological pottery, and rock art	Springer Ling	2023	Visualization	This paper aimed to illustrate the specific application value of the XRF scanner from the INFN-CHNet laboratory with the restoration of archaeologically decorated pottery.	This paper applied the XRF scanner used in ancient photography to quickly and accurately identify the materials and techniques used to conceptualize the networks of the future.
[41]	Digital Restoration and 3D Printing of Porcelain—A Case Study of Double-Ear Clashing Color Vase with Lotus Design	Google Scholar	2023	Usability	This paper aimed to create a 3D color model with high-precision 3D and texture information. In the process of 3D reconstruction, the high precision characteristic of 3D laser data processing is fully utilized to make the 3D model more accurate in geometric detail.	This study applied to display more historical information on this double-ear clashing color vase by 3D modeling and 3D printing technology and to unveil the historical connotation behind this cultural relic.
[51]	A Virtual Restoration Experiment System for Porcelain Relics Cleaning	IEEE Xplore	2022	Interaction	It was expected to explore a virtual system with a sense of situational integration and immersion, which will lay a rich experience and foundation for the porcelain relics cleaning practical operation.	This paper applied 3D modeling and Unity 3D technology for experimental simulator data processing and construction to complete the construction of the porcelain cleaning and repair experiments, which helps participants well immersed in it.
[14]	Transparent reversible prosthesis, a new way to complete the conservation–restoration of a Black Ding bowl with the application of 3D technologies	Springer Ling	2022	Usability	This research aimed to complete the physical and aesthetic restoration of the Black Ding bowl with minimal intervention and reversibility.	This paper applied a combination of digital acquisition, virtual anastylosis, virtual reconstruction, and 3D printing of a transparent reversible prosthesis with slots to restore a gold foil-decorated Black Ding bowl collected by the Chifeng Museum.
[33]	Based on Virtual Reality Technology Research on Innovation and Design of Ceramic Painting Products	WOS	2022	Visualization	This research aimed to propose 3D reconstruction technology and virtual display method made a positive exploration for the protection, inheritance, and promotion of China's ceramic artworks	This paper applied new postprocessing methods, such as fusion and repair was investigated and proposed to obtain the complete optimized color point cloud information.

Table A1. *Cont.*

Reference (*n* = 30)	Title	Database	Year	Category	Objective	Strategy
[26]	Application of 3D Printing Reconstruction Algorithm in Ancient Ceramic Restoration	WOS	2022	Visualization	This research explores using 3D printing technology to identify ceramics for authenticity, value determination, cultural types, and dissemination channels.	This paper applied the modeling algorithm of 3D printed ceramics can be used to accurately obtain the 3D model of ancient ceramics, which has certain significance for exploring the new direction of 3D printed ceramics.
[34]	Deep Join: Learning a Joint Occupancy, Signed Distance, and Normal Field Function for Shape Repair	WOS	2022	Visualization	This research explores high-resolution restoration shapes by inferring a corresponding complete shape and a broken surface from an input fractured shape.	This paper applied repairs using our DeepJoin approach for synthetically fractured objects from ShapeNet. DeepJoin outperforms three baseline approaches in terms of chamfer distance and normal consistency.
[31]	Data-Driven Restoration of Digital Archaeological Pottery with Point Cloud Analysis	WOS	2022	Visualization	This research proposes a method to repair the digital objects' surface using a data-driven approach.	This paper applied an end-to-end neural network architecture that calculates the missing geometry and merges the known input and the predicted point cloud. The approach effectively repairs pottery objects with large imperfections during the scanning.
[44]	3D Printing Technology in Ceramic Cultural Relic Restoration and the Application of Replication	CNKI	2022	Usability	This paper aims to the application of 3D printing technology in the restoration and reproduction of ceramic artefacts through specific examples.	This paper applied the application of 3D printing technology in ceramic restoration is of great significance to the restoration and replication of ceramic cultural relics.
[35]	Progress in Auxiliary Ceramic Art Design Under Big Data	Google Scholar	2022	Usability	This paper aims to research and develop high-performance ancient ceramic restoration materials, the present situation of material preparation, additive manufacturing technology and machine learning algorithm are discussed.	This paper applied it is confirmed that the ML algorithm has significant application value in am precision manufacturing of high-performance ancient ceramic restoration parts, and provides a new design idea for the precision development direction of AM manufacturing technology.
[49]	Research on the Application of the Internet of Things and VR Technology in the Protection and Development of Shouzhou Kiln	WOS	2021	Interaction	It was expected to explore feasible paths and methods for the protection, inheritance, and development of ancient ceramic culture in China and even the world through the discussion of VR technology involved in the protection and development of the Shouzhou kiln.	VR reverse engineering technology was used to restore the fragments of Shouzhou kiln ceramic relics. VR technologies are applied to Shouzhou kiln ceramic product design and display system structure.

Table A1. *Cont.*

Reference (*n* = 30)	Title	Database	Year	Category	Objective	Strategy
[45]	Comparing The Efficacy of Four Methods of Preparing 3D-Printed Polymer Surfaces to Take Paint and Their Effect on An Acrylic Paint Layer	Google Scholar	2021	Usability	This paper aims to assess methods of processing the surfaces of Fused Deposition Modelled (3D printed) PLA and ABS polymers.	This paper used the solvent method to process the surfaces to reduce the appearance of the corrugation inherent to these objects to create a surface upon which a paint layer could be applied.
[48]	A Deep Neural Network-Based Framework for Restoring the Damaged Persian Pottery via Digital Inpainting	Google Scholar	2021	Usability	This paper proposed to develop an intelligent system to provide an image of the refurbished artifact before the restoration operation.	This paper applies a deep artificial neural network-based approach to paint images of pottery to restore their damaged parts and repair irregular structures that usually exist.
[50]	Ancient ceramic restoration platform based on virtual reality technology	Scopus	2021	Interaction	This paper proposed to establish the framework of a virtual platform to solve the actual problems during ancient ceramic restoration.	The virtual simulation layer structure flow was designed based on the case study on cultural relics virtual restoration platforms.
[47]	A 3D Informational Database for Automatic Archiving of Archaeological Pottery Finds	WOS	2021	Usability	This paper focuses on the integration of a shape feature recognizer, able to support the semantic decomposition of the ancient artifact into archaeological features, with a structured database able to query a large amount of information extracted.	This paper proposes using shape feature identifiers to measure the dimensional attributes of various features automatically. This can facilitate comparative analysis between archaeological artefacts and inferences and reduce the daily workload of archaeologists.
[4]	Vehicles and Paths for Present-day Education of Ancient Ceramics Renovation Techniques	CNKI	2020	Interaction	This paper focused on the significance of setting preservation organization to train professional talents on ancient ceramic restoration with VR technology.	This paper pointed out that virtual restoration technology should be widely applied to the education field, not only among research institutes.
[36]	Application of Three-Dimensional Laser Scanning in the Protection of Multi-Dynasty Ceramic Fragments	IEEE Xplore	2020	Visualization	This paper aimed to avoid the secondary damage of ceramic fragments when splice them with virtual reconstruction and restoration.	This paper proposes to extract the edge feature of ceramics by removing the noise of point cloud, a bilateral filtering point cloud denoising algorithm. The improved Artificial Fish Swarm Algorithm is used to get the matching strategy, and the point cloud is used to reconstruct the 3D model by the Dual Quaternion Transformation method.

Table A1. *Cont.*

Reference (*n* = 30)	Title	Database	Year	Category	Objective	Strategy
[42]	Computational Science, Convergence Culture, and the Creation of Archaeological Knowledge and Understanding	Scopus	2019	Interaction	This paper aimed to demonstrate the Reconfigured Notions of "Community" and "Heritage" based on a case study of the 3D Philadelphia Project funded by NSF.	This paper presented a new space of convergent heritage activity form with collective intelligence, including archaeologist, digital media researchers, computer scientists, and computer engineers.
[37]	Assisting Pottery Restoration Procedures with Digital Technologies	Google Scholar	2019	Visualization	This paper discusses a low-cost pottery-oriented restoration pipeline based on exploiting technologies such as 3D digitization, data analysis, processing, and printing.	This paper applied to slow-cost commercial and open-source software tools and the authors' previously published 3D pose normalization algorithm and described in detail the involved procedures such as the photogrammetric 3D digitization, the 3D data analysis and processing, the 3D printing procedures, and the synthetic shreds post-processing.
[28]	Application of 3D Printing Industrial Robot in Ceramic Relic Protection and Repair	Google Scholar	2019	Usability	This paper focuses on the process and method of applying 3D printing industrial robots to restore such cultural relics.	This paper used a brief introduction to the 3D printing process. It divided the application of the restoration of cultural relics into three aspects: three-dimensional scanning, reverse modeling, database establishment and cultural relics derivatives, which explains the practicality, efficiency, and convenience of it.
[25]	3D Laser Scanning and Digital Restoration of An Archaeological Find	Google Scholar	2018	Visualization	This paper aims to demonstrate the digital recreation and 3D printing of a missing fragment of ancient ceramic pottery using three-dimensional laser scanning following digitisation. It is a breakthrough in the field of digital archaeology.	The paper applies reverse engineering methods for recreating ceramic pottery, which is part of the field of digital archaeology and is expected to benefit a wide range of people, including 3D CAD users.
[12]	Comparative study on the methods of filling a vacancy in ceramic restoration	CNKI	2018	Visualization	This paper aims to sum up more than 20 years of ancient ceramic restoration experience for safe and effective repair. Replicating and replicating different types of ancient ceramics provides references.	This paper applies to the comprehensive comparison of various reproduction methods for repairing different types of damaged ancient ceramics. It provides a reference for the safe and effective restoration and reproduction of ancient ceramics.

Table A1. *Cont.*

Reference (*n* = 30)	Title	Database	Year	Category	Objective	Strategy
[40]	FTIR analysis and 3D restoration of Transylvanian popular pottery from the XVI–XVIII centuries	WOS	2018	Visualization	This paper aimed to restore in a virtual environment using 3D laser scanning and computer-aided design of pottery restoration software.	This paper applied digital restoration technology to the correct spatial positioning of ceramic container fragments. The three-dimensional modeling of the container shape is carried out by using the contours obtained after the fragment matching. Then the pottery is simulated and repaired in the virtual environment.
[46]	3D Printing of Etruscan and Early Roman Artifacts	Google Scholar	2016	Visualization	This research aims to make the study of ancient artifacts easier by experimenting with the 3D printing of archaeological artifacts, specifically the artifacts excavated at the site of Cetamura del Chianti in Italy.	This paper discussed that 3D printing in ancient artifacts helps researchers study their volume, shape, and potential use without damaging the artefact. 3D printing allows artifacts to be recreated in their entirety without the cracks and missing pieces many excavated artifacts have.
[38]	3D printing technology in the application of ceramic restoration and replication	CNKI	2015	Visualization	This paper aims to introduce 3D printing due to the features of contactless scanning. Therefore, in the process of replicating and restoring ceramics, it is a new means to protect the fragile material and precious value of ceramic cultural relics.	This paper applies the 3D printing technology that can not only be used for cultural relics restoration but also has the characteristics of non-destructive, rapid and accurate compared with traditional restoration methods and plays a role in cultural relics restoration.
[17]	Feasibility analysis of VR technology support for ancient ceramic relics	CNKI	2019	Usability	This paper proposed to apply VR to ceramic restoration according to the present situation of ancient ceramics in museums all over the country and got new ideas and ideas for the protection and display of ancient ceramic relics in museums.	This paper discussed three virtual ceramic restoration methods for archaeology, display, and commercial trading.
[64]	Research and Application of VR Technology on Ancient Ceramic Display	CNKI	2014	Visualization	This paper mainly discussed the application of VR technology in restoring and displaying ancient ceramics. Processing with intelligent artificial and human-computer interaction has achieved satisfactory results.	This paper illustrated the specific virtual restoration process through VR technologies.

Table A1. *Cont.*

Reference (*n* = 30)	Title	Database	Year	Category	Objective	Strategy
[30]	Ceramics Fragments Digitization by Photogrammetry, Reconstructions and Applications	Google Scholar	2009	Visualization	This paper aims to apply photogrammetry to two ceramic fragments to help reconstruct the original shape of the ceramic as close as possible.	This paper applied the 3D technology can easily generate a rendering of the photogrammetric data shape of two ceramic fragments to help reconstruct or be as close as possible to the original shape of the ceramic.
[32]	Constrained 3D shape reconstruction using a combination of surface fitting and registration	WOS	2006	Visualization	This paper aims to study the three-dimensional shape reconstruction from measurement data under constrained conditions, including the reconstruction of fragments of archaeological pottery.	This paper applied the Newtonian optimization algorithm is adopted. Due to the traditional method, this algorithm can combine the multiple scanning of the object and the model into an optimization process.
[39]	Virtual assembly of pottery fragments using moiré surface profile measurements	WOS	2005	Visualization	This research uses shadow moire’s experimental technique to obtain the 3D model of pots from 3D measurements of the surface profile using the photos captured.	This paper applied the virtual assembly technology adopted in this paper can find the missing fragments with the shortest time and the least damage of fragments, estimate the effective fragments combination, and accurately measure the matching of fragments.

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