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Digital Archaeology: A Review of the Application of Information Technology in Archaeological Data Management and Analysis

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Abstract. This paper provides a comprehensive review of the current application of information technology in archaeological data management and analysis, discusses the progress and practical application of digital archaeology, and looks ahead to its future development directions and challenges. With the rapid development of information technology, archaeology has gradually introduced digital tools such as database management systems, geographic information systems (GIS), remote sensing technology, virtual reality (VR), and augmented reality (AR). These technologies not only improve the efficiency of data management but also offer entirely new methods for analysis and presentation in archaeological research. This paper evaluates the application of different digital tools in archaeology, analyzes their technical advantages and limitations, and proposes strategies to address issues related to technical complexity, data standardization, and interdisciplinary collaboration. The study aims to provide valuable references for archaeologists, technology developers, and cultural heritage conservation professionals, promoting the further development and application of digital archaeology to achieve the efficient preservation and dissemination of cultural heritage.

Keywords: Digital Archaeology; Information Technology in Archaeology; Geographic Information System (GIS).

1. Introduction

Archaeology is the study of the ancient and recent human past through material remains. Traditional archaeological methods mainly rely on human resources to investigate sites, excavate ruins through the subjective experience of archaeologists, and judge the historical information of cultural relics [1]. With the development of information technology, on the basis of traditional excavation and analysis methods, archaeology has gradually introduced digital tools, such as database management system, geographic information system (GIS), remote sensing technology, virtual reality (VR) and augmented reality (AR). These techniques not only improve the efficiency of data management, but also provide archaeology with entirely new means of analysis and presentation.

Digital Archaeology is predicated upon an ever-changing set of apparatuses - technological, methodological, software, hardware, material, immaterial - which in their own ways and to varying degrees shape the nature of Digital Archaeology [2]. For example, large amounts of high-resolution data are produced by using 3D data capture and remote sensing, whether through the direct use of scanners to acquire point clouds or the computation of 3D points from digital photogrammetry at an item, site, landscape, or excavation surface scale [3]. When operated in a GIS or modeling program, coordinates can present geometrically accurate point clouds of road systems, stations, ditches, and individual artefacts in two- and three-dimensional space. The spatial relationship of the sites can be easily analyzed. The ability to digitally transmit 3D artifact scans and the ability to reproduce artifacts using 3D printing technology allows artifacts to be printed with a range of materials, enhancing the possibility of post-excavation analysis far from the museum where the originals are housed [4]. Virtual reality (VR) and augmented reality (AR) are often used to make virtual displays of monuments and ancient artifacts, which makes digital reconstruction of artifacts and sites possible [5]. The introduction of these technologies has not only made archaeologists' research more efficient and precise; it has also opened up entirely new areas of interdisciplinary collaboration and promoted the digital transformation of archaeological research.

The rise of digital archaeology has not only changed the way traditional archaeological research is conducted, making the preservation, management and analysis of data more efficient and precise. At the same time, it also promotes interdisciplinary cooperation and provides strong technical support for the preservation of sites, the dissemination of culture and public education. Archaeologists, computer scientists, geographers and other experts in different fields work together to develop and apply new technological tools to enable complex archaeological problems to be solved through multi-dimensional digital means. For example, the GIS system needs the cooperation of experts in many fields, because it is based on the geospatial database, supported by computer hardware and software, and uses the theories of system engineering and information science to collect, calculate, analyze, simulate and express the geospatial distribution data of the whole or part of the earth surface (including the atmosphere) [6], which the process is highly complex. In addition, through 3D scanning technology, archaeologists can create digital copies of artifacts, thereby reducing reliance on physical objects and protecting precious cultural heritage; Through VR technology, the public can visit ancient sites in an immersive manner, enhancing the social influence and educational value of archaeology.

With the rapid development of digital technology, digital transformation in the field of archaeology has become a trend. However, the functions, application scenarios and applicability of different digital tools in archaeology are still quite different, and systematic research is still needed. This paper aims to make a comprehensive review of the current application of information technology in archaeological data management and analysis, discuss the progress and practical application of digital archaeology technology, and look forward to its future development direction and challenges. Specifically, this paper will evaluate the application of different digital tools in archaeology, analyze their technical advantages and limitations, and propose coping strategies in terms of technical complexity, data standardization, and interdisciplinary cooperation. Through this study, it is expected to provide valuable references for archaeologists, technology developers and cultural heritage protection workers, promote the further development and application of digital archaeology, and finally realize the efficient protection and dissemination of cultural heritage.

2. Application of information technology in archaeological data management

2.1. Development and application of Archaeological Data Management System (ADMS)

Archaeological Data Management System (ADMS) is a specialized system designed for the collection, storage, management and retrieval of archaeological data. It can shepherd data from digital creation, through editing and analysis, to online archiving and publication of reusable datasets. Such an ecosystem would improve the scope and rigor of archaeological research and cultural heritage management by facilitating reinterpretation, promoting regional and comparative studies, and broadly contributing towards the repurposing of data [7]. As the scale of archaeological projects continues to grow, so do the requirements for data management. The emergence of ADMS has greatly improved the efficiency and accuracy of archaeological data management. Through digitization, archaeologists can manage various types of data, such as cultural relic information, geographical location, excavation records, and image data, in a unified system. At the same time, ADMS also supports multi-user collaboration, facilitating real-time data sharing and synchronous updates between teams.

ADMS was applied to many significant projects in the archaeological field in different parts of the world. For instance, the Heritage Information System (HER) in UK achieves the systematic collection and dissemination of the data on the archaeological sites across the country with ADMS; it offers abundant supply of archaeological information to the research centers and the populace. Likewise, the National Archaeological Database (NADB) in the United States also utilizes ADMS in a heavy manner; the database organizes a vast amount of archaeological data across the United States and encourages cross-regional research and data sharing.

Despite such functions assigned to the ADMS in management of archaeological data, their utility is not without some drawbacks as will be discussed below. First, spread of the archaeological data is vast and it is heterogeneous in nature; there are huge variations in data used formats and ways of data pre-processing across the different projects and different institutional settings. Secondly, the compatibility of the system also makes it difficult to share as well as interchange data between one ADMS and another. To overcome these challenges, experts are advancing other options of the system structures that can support multiple types of data. In addition, international cooperation in standardization is also going on steadily, in view of establishing unified standard of archaeological data to further the objectives of data exchange and compatibility.

2.2. Applications of Geographic Information Systems (GIS) in archaeological data management

GIS is an integrated spatial information analysis and management system, which is widely used in the distribution analysis of archaeological sites, spatial pattern recognition and environmental change research. Starting from the spatial location of archaeological relics or phenomena, GIS establishes multiple spatial information and attribute information coexisting databases and graphic image libraries, so as to facilitate hierarchical or comprehensive display, query, and simulation of various data information, and intuitively and concisely restore the social conditions at that time [6].

The adoption of GIS for managing archaeological data has yielded a number of good results. For instance, in the discussion of the location of pyramid groups in Egypt, by using GIS to investigate their environment and geology, assessment of ancient Egyptian civilizational spatial structure has been viewed from a new angle. As in the Maya culture of Central America where GIS has been employed in cities' spatial planning and water resource elucidation to view the rise and decline of the Maya civilization.

GIS has unique advantages in processing spatial data, but its high-precision data acquisition and processing need advanced hardware equipment and professional technical support. In addition, to be able to use them, one must have education in these technologies. Knowledge in a variety of fields, including geography, mathematics, and computer engineering for its more technical aspects, is necessary for an accurate implementation of GIS. It also requires an adequate spatial thinking framework for its analytical and interpretative areas. All these elements make using GIS in archaeology challenging [8].

2.3. Application of database technology in archaeological data storage and retrieval

Relational databases and NoSQL databases are widely used in archaeological data storage and retrieval. Among them, the relational database is a database system that supports the relational model. It is the most important and widely used database system among all kinds of databases at present, mainly used for the management of structured data. NoSQL data stores, on the other hand, do not require a fixed table structure and usually do not have join operations. There is no relationship between the data, so it is very easy to extend [9]. Therefore, NoSQL databases are better suited for handling unstructured data, such as images and text records.

Database technology in archaeology has been successfully applied in many projects. For example, the "Archaeological Database of the Roman Empire" integrates a large number of site information, cultural relic records and historical documents, and realizes rapid retrieval and multidimensional visualization of data through relational database technology. In addition, in archaeological image analysis, NoSQL database is also widely used in the storage and management of large-scale image data, supporting the rapid retrieval and processing of images.

Despite the fact that database technology brings robust support to manage archaeological data, the application also has some issues. First of all, as the amount of data increasing, the storage space and the speed of database searching and obtaining information become critical problems. Secondly, the matter of security of data is also another factor which is a real issue when it comes to management of archaeological databases not to mention where cultural heritage sensitive data is involved. The future trends of development will tend to turn to the construction of more substantial and safeguard database system capable of addressing the storage challenges of ultra-large volume of data with equal consideration to privacy and security.

3. Application of information technology in archaeological data analysis

3.1. Application of remote sensing technology and LiDAR in archaeological analysis

A broad definition and fundamental application of archaeological remote sensing, including the use of aerial photographs, satellite imagery, geophysical prospecting and topographic data to investigate past landscapes [10]. It is widely used in archaeological site discovery and environmental analysis, especially in hard-to-reach or extensive areas such as tropical rainforests, deserts and mountains. This technique can obtain a wealth of images and data without directly touching the surface, providing archaeologists with new research perspectives.

Airborne light detection and ranging (LiDAR) is a technology that offers the ability to create highly detailed digital terrain models (DTMs) that expose low relief topographic features. The model's availability presents an opportunity to improve archaeological field research by generating visual representations that may be utilized to spot signs of prehistoric human activity. This capability is particularly useful in hard to access areas and in areas of dense vegetation, where manual surveys are difficult to plan and to execute [11]. For example, in the study of the Maya civilization in Central America, LiDAR technology successfully revealed many previously undiscovered sites. Researchers have used airborne lidar to discover Mayan ruins and the site of Angkor hidden beneath dense forests, revealing the complete structure of these sites and helping archaeologists redraw the map of ancient civilizations in these areas.

The main benefit of remote sensing technology and LiDAR technology is more extensive and rapid detection which meets the demand of large amount of information in a short time and can discover some hard-to-find sites by traditional methods. But these technologies also have some difficulties. First of all, collection and data processing need expensive equipment and qualified technical assistance. Secondly, as for remote sensing and LiDAR data, they are big and complicated, that is, the problem of how to analyze and interpret them effectively occurs.

3.2. Application of machine learning and artificial intelligence to archaeological data analysis

AI technologies, especially machine learning and deep learning, have significant potential in archaeological data analysis. Archaeologists can now more fully use AI to extract information from vast amounts of archaeological data to determine the most ideal dig site in a complex cultural landscape [12]. For example, through image recognition algorithms, aerial or satellite images of sites can be automatically analyzed to identify potential archaeological sites.

There are a few examples of the application of the AI technology in different archaeological investigations. For instance, in the identification of ancient Roman city ruins in Italy, the research team fed a large number of historical images to the deep learning models where they managed to achieve automatic site identification and classification. This aspect demonstrates that not only identification efficiency of the sites is increased through the use of this technology but some earlier unknown sites or geomorphic features are also identified. In the same way, in the field of Egyptology, AI algorithms are applied to the analysis of the numerous hieroglyphs of ancient Egypt - texts and symbols that have not been deciphered so far.

With the accumulation of big data and the improvement of algorithms, the application of AI technology in archaeological data analysis will be more extensive, and its automation and high precision are valued by people. However, the AI approach cannot be considered a panacea for archaeological research. Firstly, the diversity and complexity of archaeological data require algorithms to be highly flexible and adaptable. However, in some cases, the number of large representative samples is limited, and therefore, this limits the training performance of AI models [12]. Especially for the analysis of ceramic types, there are still huge uncertainties in AI.

3.3. 3D modeling and virtual reality (VR) in archaeological analysis

3D modeling technology is often used for the digital reconstruction of archaeological sites and artifacts, which can provide visual and interactive research tools. For example, by using 3D scanning technology, it is possible to accurately reconstruct ancient buildings or statues. In this case, archeologist can obtain detailed geometric information for research. This technology can be used not only for academic research, but also for display and education, allowing the public to learn about and explore history through digital means. For instance, as audio-visual technology is combined with 3D technology, it can display social and cultural elements. It is possible to register national dances (their successive sequences), perform traditional craft, pass the storytelling, ancient events or the knowledge about building in the ancient times [5].

Virtual reality (VR) technology takes the results of the 3D modeling process even further and let the users to “enter” archaeological sites as if they were physically there with the use of VR devices for interaction. In particular in the education stage of the archeological process, VR technologies can be harnessed to remedy the disconnect between spatial context and archeological materials, often found in traditional museum exhibits [13]. This technology not only improves the methods of archaeological investigation, but also greatly amplifies how cultural history can be presented and shared.

This is so even though 3D modeling, and VR technology offers several plausible and unambiguous benefits in the examination of archaeology. Nonetheless, there is some challenge that is encountered in the application of these technologies. There is a necessity to use high-tech equipment and skills for performing high-quality 3D models and VR development; it can be a problem for some archaeological projects with a limited budget. In addition, the application of new technology is also extremely fast-paced, new issues of data storage and utilization have also emerged, and the issue of how to efficiently store these digital resources and how to efficiently use them in the long term will be a problem.

4. Challenges and Future Directions in Digital Archaeology

4.1. Technical Complexity and the Need for Interdisciplinary Collaboration

Digital archaeology has brought into the process many states of the art techniques as 3D modeling, Geographic Information Systems (GIS) and several levels of statistical analysis. Nevertheless, such advancements are characterized by high technical requirements, and, at some point, the archaeologist has to learn new things or involve specialists from other professions, for example, an IT specialist.[14]. Technology in archaeological projects is integrated sometimes, and there can be times when the technologies employed are not fully synchronized due to attempts of different working teams of a project to implement adaptive methods on their own will.[15].

The solution to this challenge lies in interdisciplinary collaboration. Fields such as computer science, geographic information science (GIS), and statistics are key to advancing the application of technology in archaeology. By establishing partnerships and creating interdisciplinary teams, archaeologists can access the necessary expertise while continuing to develop their own digital competencies [14]. It is also possible to arrange a series of technical training for archaeologists to deal with the steep learning curve typical for digital tools.

Moreover, the development of more user-friendly and intuitive tools for archaeology would significantly lower technical barriers, enabling a wider range of archaeologists to engage with digital methods without requiring deep technical expertise [14]. This would facilitate a more seamless integration of digital archaeology into everyday practice.

4.2. Data Standardization and Sharing Issues

The diversity and complexity of archaeological data make data standardization and sharing a major challenge. For basic data analysis, the main problem here is poor interoperability of file types from different versions of the same software. When an update is released, a small configuration is changed, or a program behaves differently because of a different operating system, and the output results may cause the entire workflow to fail. For example, computationally intensive analysis often uses mathematical functions based on single-precision floating-point operations, the implementation of which varies by software and operating system [16]. In addition, different projects and research teams often use different data formats and processing methods, which prevents widespread sharing of data and comprehensive analysis.

Thus, to solve this problem, the key to the strategy is the development and introduction of internationally standardized archaeological data. In the first way, it can control and normalize the ways that individual projects and teams track, archive, and analyze archaeological data so that data becomes more interchangeable and exchangeable. For example, archaeologists have the internationally recognized metadata standards such as Dublin Core or CIDOC CRM which can be used to input the basic data information of the data; in this way, the data transmission and the data acceptance of different systems can be facilitated.

In case of data sharing open data, sharing platform is another effective method to solve this issue. These platforms should not only be a vehicle of storing information; they also should possess powerful tools of searching, filtering, and analysis in order to enhance data utilization for new research. Such tools and facilities, for example, the ADS or Open Context offer archaeologists access to huge quantities of data, which are freely available. These platforms typically secure access to data through open licensing agreements that allow data to be freely shared in compliance with copyright and intellectual property rights.

4.3. Balancing Technology and Ethics:

In archaeology, there are some arising ethical concerns, and they are related with use of digital technologies particularly with data privacy and culturally sensitive information. Archaeologists who use new technologies to record, analyze and display cultural heritage must be alert to the possible negative effects of these technologies. Especially when it is a matter of ethnic or religious or other, culturally sensitive minorities, the inadvertent public sharing or misuse of the data may bring ethnic clashes and is likely to erode communities' appreciation of cultural legacy and respect for it. This presents a key challenge: how to promote technological progress while maintaining the authenticity and integrity of cultural heritage.

Thus, a strategy of setting up ethical standards as well as following them remains an essential one. Specifically, archaeologists and research institutions need a clear code of ethics to guide the use of digital technologies. For example, when sharing and using data from archaeological sites, it is necessary to obtain the consent of local villagers and local governments, so that they feel respected and satisfied.

In addition, raising awareness of ethical issues among the public and researchers is also an effective strategy. For instance, discussion and training on data privacy and sensitivity, ways of using information technology while at the same time considering cultural preservation can be enhanced in academic training and policy education. These shall assist in bringing the professionalism of the archeological work and also inculcate the public into embracing the social responsibility towards cultural heritage.

5. Conclusion

The integration of information technology has significantly advanced the field of archaeology, particularly in data management and analysis. This review demonstrates that digital archaeology is in a period of rapid development, with various digital tools and technologies being increasingly adopted. The results highlight the potential for these technologies to revolutionize archaeological practices, offering enhanced precision, efficiency, and new insights into past human activities. Furthermore, digital tools have the capacity to overcome traditional limitations in data handling and interpretation, paving the way for more comprehensive and collaborative research approaches.

The significance of this study lies in its ability to outline the current state and future potential of digital archaeology. By highlighting both the achievements and challenges, such as technical complexity, data standardization, and ethical considerations, this research provides a roadmap for enhancing the integration of digital tools in archaeological practices.

Future directions for digital archaeology include the development of innovative applications and integrated solutions, which will further improve research efficiency and data analysis capabilities. Additionally, digital technologies can play a crucial role in education and public engagement, allowing archaeology not only to advance research but also to enhance public involvement and awareness of cultural heritage. By embracing these advancements, the field of archaeology can continue to grow and evolve, offering deeper insights into human history while preserving the integrity of cultural resources.

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