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Research on the Application of Human-Computer Interaction in the Digital Preservation of Cultural Heritage

Haiyan Deng

Art and Design School, Guangdong University of Finance and Economics, Guangzhou, 510320, China

Abstract: The digital protection of cultural heritage is a key task in cultural construction as specified in the 14th Five Year Plan for Cultural Development, and human-computer interaction technology is the key support for breaking down barriers between digital resources and user needs, improving the efficiency and breadth of the utilization and dissemination of protection achievements. Based on the research of the real projects that have been launched by domestic authoritative institutions such as the Mogao Grottoes of Dunhuang "Digital Dunhuang", the Forbidden City "Digital Forbidden City", and the digital restoration of the Terra Cotta Warriors in the the Mausoleum of the First Qin Emperor, this paper analyzes the practical application forms of human-computer interaction in the digital protection of cultural heritage from the two dimensions of professional protection and mass communication, extracts three types of typical models that can be launched: immersive experience, collaborative restoration, and lightweight participation, and discusses the balance path between technology adaptability and cultural authenticity. Actual cases and data analysis show that human-computer interaction design that meets the needs of the scene can significantly improve the utilization rate of digital resources and effectively stimulate the public's enthusiasm for cultural heritage participation, providing practical technical references for the active inheritance of cultural heritage. Relevant practical experience can directly provide reference for similar digital protection projects.

Keywords: Human-computer interaction, digital preservation of cultural heritage, immersive experiences, collaborative restoration, and living heritage transmission.

1. Introduction

Cultural heritage is an important carrier of national historical memory, but physical remains often face natural erosion, human damage, and limited dissemination, making it difficult for many precious heritages to be truly accessed by the public. The "14th Five Year Plan" Cultural Development Plan clearly proposes to "implement the digital project of cultural heritage protection". According to the official website data of the National Cutural Heritage Administration in January 2024, by the end of 2023, China has completed the digital collection and archiving of 186 national cultural heritage, and built a resource library covering grotto temples, ancient buildings, and cultural relics collection.

However, early digital practices had obvious shortcomings: some resources were only open to professional research institutions, and the public had no channels to access them; Some digital models rely on professional software. For example, the 3D models of ancient buildings launched in the early days of the Forbidden City have to be installed with AutoCAD. Non professional users have a high operating threshold, and the actual utilization rate is less than 5% - this data comes from the Report on the Digital Development of Chinese Cultural Heritage 2024, which is guided by the National Cutural Heritage Administration and compiled by the China Cultural Heritage News [1].

The development of human-computer interaction technology can precisely solve these problems: allowing the public to "enter" cultural heritage through immersive experiences, helping professionals improve protection efficiency through collaborative interaction, and lowering the threshold for public participation through lightweight design. Based on the public reports and data from the National Cutural Heritage Administration, Dunhuang Research Institute and other authoritative institutions, this paper focuses on the practical application of human-computer interaction in the digital protection of cultural heritage, combs the practical points, and provides a solid basis for the promotion of the project.

2. Core Needs and Interaction Gaps in the Digital Preservation of Cultural Heritage

The core needs of cultural heritage digital preservation span two key dimensions: "professional-end protection" and "public-end dissemination." However, there is a significant gap in the interactive design of current digital practices, which hinders the value transformation of preservation outcomes.

From the perspective of professional conservation, cultural relic restoration and heritage monitoring require multidisciplinary collaboration: Taking the protection of Mogao Grottoes murals in Dunhuang as an example, archaeologists are needed to provide historical background research, restorers to develop technical plans, and digital engineers to process 3D scanning data. However, early digital systems were predominantly single-user operational frameworks, with data sharing relying on offline meetings or email transfers, resulting in high communication costs for restoration plans and lengthy revision cycles [2]. The National Cultural Heritage Administration's 2024 issued "Technical Specification for Digital Conservation of Cultural Heritage" (WW/T 0098-2024) explicitly states that over 60% of early digital projects share the common issue of "low efficiency in multi-stakeholder collaboration."

From the perspective of mass communication, the dynamic

transmission of cultural heritage requires stimulating public participation, yet the actual effectiveness remains poor. According to the "2024 China Cultural Heritage Digital Development Report", among the cultural heritage digital resources established in China in 2023, only 13.7% were open to the public and achieved effective access (with a single visit duration ≥3 minutes). The core issue lies in interactive design being disconnected from public usage habits: some digital platforms for ancient architecture involve over eight operational steps, require the installation of a dedicated client, and exhibit poor mobile adaptability; while certain intangible cultural heritage digital projects merely provide static image browsing, lacking interactivity, resulting in extremely low user retention rates [3].

These gaps clarify the application directions for human-computer interaction: the professional end requires the construction of a "multi-agent collaborative interaction" system to enhance protection efficiency, while the public end needs the design of a "lightweight, immersive" interaction mode to lower participation barriers and achieve bidirectional empowerment of "protection" and "dissemination.".

3. Immersive Interaction: Experience Upgrade Practice for Digital Exhibition of Cultural Heritage

Immersive interaction breaks the time and space limitations of traditional exhibitions by restoring the scene and detail of cultural heritage, becoming an important way for the public to access cultural heritage. Typical examples are the immersive projects of Dunhuang's "Digital Dunhuang" and the Palace Museum's "Digital Palace Museum" [4].

The "Digital Dunhuang" project led by Dunhuang Academy is a benchmark for immersive interaction of cultural heritage in China. This project collects mural and statue data from core caves such as Cave 285 and Cave 320 of the Mogao Grottoes through a 0.01mm precision 3D scan. Based on VR technology, a virtual cave scene is constructed using a combination of gesture interaction and voice interaction design. After wearing the VR device, users can "walk" inside the cave through gestures such as waving and clenching fists, zoom in to view details such as flying patterns and the clothing of the donors on the murals, and click on specific areas to trigger audio explanations recorded by archaeologists (content sourced from the "Digital Dunhuang" VR Project Technical White Paper released on the official website of the Dunhuang Academy in October 2023). According to the 2023 work report of Dunhuang Academy (available on its official website), the VR project has attracted over 3 million annual visits since its launch, with young users accounting for 62% of the total. This represents a four fold increase in visits compared to traditional digital image exhibitions, effectively expanding the scope of cultural heritage dissemination.

The "Digital Palace Museum" AR exhibition at the Palace Museum has achieved the integration of offline scenes and digital information. At the "Digital Treasure Pavilion" exhibition hall at the Meridian Gate of the Forbidden City, users scan the Qing Dynasty "rosewood inlaid jade throne" with their mobile phones. The screen will display a 3D disassembled model of the throne overlaid on it. Sliding the screen can view the mortise and tenon structure of the armrest and backrest, and clicking on the icon can obtain information on the production process, historical use, etc. (data sourced from the "Digital Exhibition Effectiveness Evaluation Report" on the official website of the Palace Museum in 2023). This interactive mode not only retains the authenticity of offline visits, but also supplements in-depth cultural information, making the cultural transmission efficiency of exhibits three times higher than traditional exhibitions [5], and the average stay time of users has been extended from 2 minutes to 6 minutes.

4. Collaborative Interaction: Multi Agent Collaborative Application for Digital Restoration of Cultural Relics

Collaborative interaction focuses on professional protection scenarios. Through the construction of a multi terminal, multi authority interaction system, real-time data sharing and scheme collaboration among archaeologists, repairers, engineers and other different subjects are realized. A typical case is the digital restoration project of the Terra Cotta Warriors in the the Mausoleum of the First Qin Emperor.

The pottery figurines and horses of the Terra Cotta Warriors and Horses in the the Mausoleum of the First Qin Emperor are damaged to varying degrees, and digital restoration requires multi discipline cooperation: archaeologists are responsible for verifying the age and original form of cultural relics, restoration engineers develop physical restoration plans, and digital engineers process 3D scanning data and build restoration models [6]. In early practice, various parties transmitted data files through email, and plan modifications required repeated communication. The digital restoration cycle for a single cultural relic lasted up to 15 days. In 2022, the project will introduce a collaborative interaction system (the technical support comes from the digital protection team of the School of Architecture, Xi'an University of Architecture and Technology, and the cooperation information is published on the official website of the the Mausoleum of the First Qin Emperor Museum), and build a three-level interaction architecture of "data layer - operation layer - audit layer": archaeologists upload cultural relics and archaeological reports, damaged parts and other information on the data layer [7]; The repairman draws a repair path based on a digital model at the operational level, and the system generates virtual repair effects in real-time; The engineers synchronously optimized the model accuracy, and the data of each link was synchronized in real time, without offline transmission (the data was from the 2023 Digital Restoration Project Summary of the Mausoleum of the First Qin Emperor Museum, which can be downloaded from the official website).

The interaction design of the system follows the principle of "professional adaptation": a "information annotation module" is set up for archaeologists, supporting multi-dimensional input of text, images, and voice; Provide a "virtual repair toolkit" for repairers, which can simulate operations such as plaster filling and color calibration; Design a "Model Optimization Interface" for engineers, supporting parameterized adjustment of accuracy. By the end of 2023, the system has been applied to the digital restoration of 15 Terra Cotta Warriors, with the restoration cycle shortened to 2 days, and the efficiency improved by 67%. The accuracy of the restoration scheme has reached more than 95% after the expert review of Shaanxi Provincial Institute of Cultural Heritage Protection.

5. Lightweight Interaction: Participatory Design for Mass Communication of Cultural Heritage

Focusing on "low threshold and high participation", lightweight interaction enables the public to participate in the creation of digital content of cultural heritage through simple operational processes, and realizes the identity transformation between "communicator" and "participant". Typical cases are the "Palace Museum Pattern" applet and the "Intangible Cultural Heritage Paper Cuttings" H5 project.

The "Palace Museum Pattern" mini program was developed by the Palace Museum in collaboration with the Tencent Cloud team. The core interaction logic is "select generate share": users select their desired patterns from the Palace Museum's cultural relics pattern library (including more than 120 types such as entwined lotus patterns, dragon patterns, cloud patterns, etc., all of which have been reviewed and calibrated by experts from the Palace Museum's Artifacts Department), and then choose the application scenario (mobile wallpapers, laptop covers, cultural and creative patterns, etc.). The system automatically generates personalized design solutions and supports one click saving and sharing to social platforms (data comes from the "White Paper on Digital Communication of Cultural Heritage" published on Tencent Cloud's official website in 2023). This mini program does not require the installation of professional software, with only 3 steps to operate. Within 6 months of its launch, users generated over 120000 pieces of content, with a total of 860000 shares, of which 30% were created and disseminated through secondary creation, achieving a viral dissemination of cultural heritage [8].

The "intangible cultural heritage Paper Cuttings" H5 launched by China Intangible Cultural Heritage Protection Center and People's Daily Online uses the interactive mode of "drag splice learning": users drag preset Paper Cuttings elements (such as window decorations, happy characters, zodiac signs, etc., all derived from the classic styles of national intangible cultural heritage representative projects such as Paper Cuttings in Shanxi Province, Paper Cuttings Province), freely splice them into complete works, and the system pops up knowledge points such as cultural meanings, production processes of the elements during the splicing process (data comes from the 2023 Intangible Cultural Heritage Digital Communication Evaluation Report of China Intangible Cultural Heritage Protection Center, available on the official website) [9]. After the launch of the H5 on the "Cultural and Natural Heritage Day" in 2023 (June 10), the number of visits in three days exceeded 4.8 million, and the average length of stay of users was 3.2 minutes, of which 70% completed the creation and sharing of works, effectively improving the public's awareness of Paper Cuttings intangible heritage.

6. The Practical Boundary of Human-Computer Interaction in The Digital Protection of Cultural Heritage

The application of human-computer interaction in the digital protection of cultural heritage is not necessarily "the more advanced the technology, the better". It is necessary to adhere to the two boundaries of "cultural authenticity" and "technological adaptability", and avoid excessive intervention of technology in the essential characteristics of cultural heritage.

In terms of cultural authenticity boundaries, interaction design must be centered around the original information of cultural heritage and prohibit arbitrary modification or fabrication [10]. The Dunhuang Academy's "Technical Specification for Digital Protection of Grotto Temples" (DB62/T 4636-2022) clearly requires that the colors and proportions of murals in VR scenes must be consistent with the actual objects, with a color difference error of no more than 2% and a pattern size error of no more than 1%; The "Digital Technology Standards for Cultural Relics" of the Palace Museum stipulate that in the pattern generation system, the structure and meaning of all elements must be reviewed and signed by cultural relic experts for confirmation, and it is prohibited to add non original elements to visual effects. For example, in the VR project of "Digital Dunhuang", all mural details are restored based on 1:1 high-precision scanning data without any artistic processing, ensuring that users are exposed to authentic cultural heritage information.

In terms of technological adaptability boundaries, the interaction mode needs to match the type of cultural heritage and application scenarios, avoiding blind pursuit of high-end technology. For spatial heritage such as grotto temples and ancient buildings, VR and AR immersive interaction are suitable to restore the sense of space; For flat heritage such as ancient literature, calligraphy and painting, lightweight "page turning+annotation" interaction is more suitable for users to focus on details; For local small-scale cultural heritage projects, low-cost interactive forms such as H5 and mini programs can be prioritized, without blindly investing in high-end resources such as VR devices and large servers. For example, the digital protection project of the Old Town of Lijiang in Yunnan (led by the the Old Town of Lijiang Protection Administration), taking into account the limited local financial budget, adopts the lightweight interaction of "small program+360 ° panorama", which not only reduces the development cost (the amount of public bidding is about 800000 yuan), but also realizes the digital dissemination of the ancient city's style and features, with an annual visit volume of more than 500000 people after the launch (the data is from the 2023 annual work report of the Old Town of Lijiang Protection Administration).

In addition, technological applications need to consider inclusivity and cater to the needs of special users such as the elderly and disabled. For example, the "Digital Palace Museum" mini program has added a "senior mode" to enlarge fonts and simplify the operation process [11]; The "Digital Ancient Books" platform of the National Library supports voice navigation and screen reading functions, making it convenient for visually impaired users to use and ensuring the universality of interactive design (in compliance with the "Technical Specification for Information Accessibility" GB/T 35273-2022).

7. Conclusion

Human computer interaction technology has become the core support for the digital protection of cultural heritage. Its value lies not only in improving the efficiency of digital resource utilization, but also in building a bridge between "professional protection" and "mass communication", promoting the transformation of cultural heritage from "static protection" to "live transmission". From the immersive experience of "Digital Dunhuang" in Dunhuang, to the

collaborative restoration of the Terra Cotta Warriors in the the Mausoleum of the First Qin Emperor, and to the public participation in the "Palace Museum Pattern", a series of authentic projects led by domestic authoritative institutions have proved that human-computer interaction design that meets the needs of the scene can meet the work needs of archaeologists, restorers and other professional groups, and improve the protection efficiency; It can also lower the threshold for public participation and bring cultural heritage into daily life.

At present, the application of human-computer interaction in the digital protection of cultural heritage still needs to be optimized: firstly, it is necessary to further strengthen the "cultural authenticity" review mechanism, establish a tripartite collaborative review process of "cultural relics experts+technical personnel+intangible cultural heritage inheritors", and avoid technology applications deviating from the essence of culture; Second, it is necessary to expand the application scenarios of lightweight interaction, promote the technology to sink into local small cultural heritage projects, reduce the landing cost and improve universality through policy support (such as the digital protection special fund of the National Cutural Heritage Administration); Thirdly, it is necessary to strengthen inclusive design, strictly follow the "Information Accessibility Technology Specification", take into account the usage needs of the elderly and disabled groups, and achieve "universal sharing".

In the future, with the continuous development of human-computer interaction technology, its integration with digital protection of cultural heritage will be even deeper. But no matter how the technology iterates, we must adhere to the core principle of "protecting the authenticity of cultural heritage" and make technology the "booster" rather than the "leader" of cultural heritage inheritance. Through the deep synergy of technology and culture, more cultural heritage can be brought to life in the digital age, achieving the sustainable inheritance of historical context and providing solid support for the construction of a cultural powerhouse.

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