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ИЗСЛЕДВАНИЯ ВЪРХУ ОПАЗВАНЕТО НА АРХИТЕКТУРНОТО НАСЛЕДСТВО И СТРАТЕГИИ ЗА УСТОЙЧИВО РАЗВИТИЕ, БАЗИРАНИ НА ЦИФРОВИ ТЕХНОЛОГИИ

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RESEARCH ON ARCHITECTURAL HERITAGE PROTECTION AND SUSTAINABLE DEVELOPMENT STRATEGIES BASED ON DIGITAL TECHNOLOGY

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Abstract:
In recent years, countries around the world have continuously increased their efforts to protect and inherit architectural heritage. The precision, sustainability, and adaptability of digital technology coincide with the principles of architectural heritage protection, making it one of the core technologies enabling this protection and inheritance. Based on the current status of digital protection and inheritance of the Forbidden City in Beijing, China, this article summarizes the practical methods of digital technology in three aspects: data collection and modeling, data storage and management, and virtual reality and its application. It also proposes strategies for the protection and inheritance of architectural heritage through the application of digital technology to interactive design, the construction of digital museums, and the intellectual property value-added of architectural heritage. This article aims to provide a Chinese solution for improving the digital protection and development of architectural heritage, as a reference.

Keywords:
Architectural heritage, digital technology,sustainable,adaptability

1. INTRODUCTION

As the world's largest and best-preserved wooden palace complex, the Forbidden City in Beijing embodies the material and cultural heritage of six hundred years of Chinese civilization and is a vital component of world cultural heritage. Since launching the "Digital Forbidden City" project in 2000, the Palace Museum has completed its transformation from basic digitization to intelligent preservation. This digitization of the Forbidden City embodies a trinity of "technology, culture, and sustainability." The application of digital technology focuses on three key areas: first, the precise virtual reconstruction of lost or severely damaged architectural heritage based on historical documents, drawings, and existing remains; second, the complete and accurate digital

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display and dissemination of existing architectural heritage; and third, the provision of new interactive experiences and diverse display and dissemination services to the public. The in-depth application of digital technology not only provides efficient technical support for the preservation and restoration of architectural heritage but also plays a positive role in cultural dissemination and public education, opening up new possibilities for the preservation and sustainable development of architectural heritage.

2. A REVIEW OF THE CURRENT STATUS OF DIGITAL TECHNOLOGY APPLIED TO THE ARCHITECTURAL HERITAGE OF THE FORBIDDEN CITY IN BEIJING

On the technical level: the Palace Museum has established the world's largest digital asset library of timber structures. Using 3D laser scanning (accuracy ±1mm) and BIM technology, holographic models of 98 core buildings have been completed (Li Li et al., 2021). AI algorithms automatically classify bracket arch components (with an accuracy rate of 92.3%), significantly improving archival efficiency (Palace Museum, 2023). In terms of preventive conservation, over 4,800 sensors monitor structural displacement and microbial activity in real time, and AI-powered risk warning models enable 85% advance prediction of beam and column deformation (Wang Renyu, 2020; Chen & Li, 2023). Virtual restoration technology significantly reduces the frequency of physical interventions. For example, the Hall of Mental Cultivation project used VR simulations of material aging to reduce on-site work by 30% (Architectural Heritage, 2022).

At the cultural and educational level:digitalization is driving a paradigm shift in cultural communication: the "Digital Cultural Relics Library" has made 68,000 artifacts available, dissolving physical boundaries and achieving "cultural democratization" (Liu Shuguang, 2021); the VR exhibition "Forbidden City: The Emperor's Palace" reconstructs historical context and enhances cognitive immersion (Murray, 2020); and cross-disciplinary collaborations, such as the Palace Museum-Tencent Digital Cultural and Creative Initiative, are activating cultural identity among young people (Huang Yang, 2022). The mobile app "Daily Palace Museum" has over 400,000 daily users, increasing knowledge acquisition efficiency by 60% (Palace Museum Education Center, 2023). However, the entertainment-oriented narrative has sparked controversy over the dilution of academic value (Wang Xiaolin, 2023).

At the economic level: Replacing physical exhibitions with digital ones has resulted in a 47% reduction in lighting energy consumption and a 32% reduction in temperature control energy consumption (Lin Huiyin Institute, 2021-2023); virtual tours replacing physical travel reduced CO_2 emissions by 12,000 tons in 2023 (Chinese Academy of Sciences data). Operational sustainability is reflected in the annual revenue from digital cultural creation exceeding 1.5 billion yuan, which will be channeled back into conservation funding (Palace Museum Annual Report, 2023), and open-source architectural data fostering global collaboration (e.g., the Sino-Italian timber structure conservation project).

3. PRACTICAL METHODS OF DIGITAL TECHNOLOGY IN THE PROTECTION AND INHERITANCE OF THE FORBIDDEN CITY

3.1. Data collection and modeling

Digital technology enables high-precision mapping and modeling of architectural heritage, providing accurate data support for conservation efforts. It also improves efficiency and reduces manual errors and risks. Currently, in architectural heritage conservation, technicians primarily use laser scanning and photogrammetry combined with 3D modeling for data collection and modeling.Laser scanning technology can quickly, massively, and accurately acquire 3D coordinate point cloud data of building surfaces. This point cloud data contains detailed information such as the building's geometry and spatial structure. Combined with 3D modeling, this collected architectural data can be used to construct high-precision digital models. This technology is often used for complex architectural structures. For example, the Beijing Palace Museum has conducted multiple high-precision laser scans of core palaces such as the Hall of Supreme Harmony, the Hall of Central Harmony, and the Hall of Preserving Harmony.

Scanners were deployed at hundreds of locations to capture the spatial coordinates (point clouds) of every surface inside and outside the building. Laser scanning technology can also be used for long-term monitoring of architectural heritage. [2]A sensor network throughout the Forbidden City continuously collects data, for example, "Dynamic change monitoring of Qianlong Garden Rockery". [3]Regular scanning and comparison of point cloud data from different periods allow analysis of building deformation, settlement, and other conditions, identifying damaged areas promptly. This assists researchers in assessing the extent of damage and provides a basis for implementing conservation and restoration measures. Photogrammetry is a technique that analyzes and processes photographic images to obtain geometric information and physical properties of objects. The combination of laser scanning, photogrammetry, and 3D modeling can significantly improve the efficiency and accuracy of data collection for architectural heritage. By using laser scanning to obtain high-precision point cloud data, supplemented by real texture information from photogrammetry, and finally integrating all the data through 3D modeling, a realistic and detailed digital model of architectural heritage can be built.

3.2. Data storage and management

Architectural heritage data includes a variety of data types, including documents, images, audio, video, and 3D models, as well as information on basic building information, structure and materials, conservation and restoration, data and analysis, and historical and cultural value. Traditional data storage and management methods use paper archives to store historical documents, drawings, photographs, and other materials. These archives require dedicated warehouses for categorized storage and numbering for easy retrieval and management. Regular inspection and maintenance are also required to prevent aging, damage, and fading, as well as to protect against insects, moisture, and fire, ensuring their safe storage.

Digital technology can be used to establish a unified database of architectural heritage information, storing a variety of structured data. In addition to traditional data such as documents, drawings, and photographs, it can also store video, audio, and 3D models. For example, the Palace Museum's "Digital Cultural Relics Library" not only contains cultural relics but is also gradually incorporating high-definition images and models of architectural components. The "Panorama Palace Museum" integrates high-resolution panoramic images and selected 3D scenes, forming a comprehensive digital archive for management, research, and application. The Palace Museum's ancient architectural knowledge graph platform systematically organizes data on the form, craftsmanship, and patterns of typical components such as brackets, painted patterns, and tile work. This facilitates identification of their era, regional characteristics, and evolutionary patterns, providing data support for dating and restoration research. These digital archives not only ensure long-term data preservation and dynamic updating, but also provide accurate data references for restoration work in the event of natural disasters or human damage to architectural

[2] Wang, Zhongjin, and Huan Liu. "Exploration of digital heritage strategy based on preventive conservation theory." The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 46 (2021): 845-849

[3] Guo, M., et al. "Dynamic change monitoring of Qianlong Garden rockery in forbidden city based on insar and LIDAR technology." The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 43 (2020): 1455-1463.

heritage.[4] For example, in the research and conservation project for the Hall of Mental Cultivation, stored data solved the challenge of precisely locating the dismantling and restoration of complex interior decorations (such as the Xianlou and Tongjinghua), fully documented traditional craftsmanship details and material information, and significantly improved the standardization and efficiency of project management.

3.3. Data display and dissemination

Virtual reality technology uses computers to generate virtual scenes, creating an immersive experience for users through image rendering, stereoscopic display, motion tracking, and interactive feedback. The continuous development and innovation of VR technology has provided powerful technical support for virtual experiences in various application scenarios, including exploring architectural spaces, engaging in interactive games, and reconstructing architectural heritage. The Palace Museum's Digital Cultural Relics Library and "Panoramic Palace Museum" project explores the use of knowledge graph technology to semantically associate entities and their relationships, such as buildings, components, people, events, documents, and research findings, to construct a knowledge network of the Palace Museum's architectural heritage. VR technology recreates historical scenes (such as Emperor Qianlong's time in the Juanqinzhai), opens previously undisclosed areas (such as the roof of the Hall of Supreme Harmony), and uses mobile apps to scan buildings, overlaying historical images, structural analysis, and restoration animations, bringing "dead" buildings to life. Leveraging technologies such as virtual reality (VR) and augmented reality (AR), high-definition digital exhibits, interactive games, and open data, these projects transcend physical limitations, create immersive and interactive experiences, and inspire the public to deeply participate in the understanding and recreation of cultural heritage.

4. RESULTS OF DIGITAL TECHNOLOGY EMPOWERMENT

4.1. Digital Museum

Digital museums are a new type of museum format that leverages digital technology to expand and extend the functions of physical architectural heritage. Through diverse applications, including digitized collections, virtual displays and interactions, online exhibitions and dissemination, and public outreach and education, they have profoundly transformed the display, interaction, education, and dissemination of architectural heritage. [5]Using databases, knowledge graphs, and AI technologies, they deeply mine and structure the vast amount of historical, artistic, and scientific information contained within the Forbidden City's architecture, constructing an explorable and growing "smart knowledge base." [6]For example, the "Ancient Architecture Gene Bank" systematically organizes the forms, craftsmanship, and patterns of typical components such as brackets, painted patterns, and tilework, identifying their eras, regional characteristics, and evolutionary patterns, providing data support for dating and restoration research. They semantically link architectural entities, components, individuals, events, documents, and research findings to form a networked knowledge structure (e.g., "Taihe Hall - Hexi Painted Pattern - Qing Dynasty Official Style - Craftsman's Regulations - Related Archives").

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[4] Li, Jiwei, and Yingchun Cao. "The Application of Virtual Reality Technology in Ancient Garden Restoration." 2016 7th International Conference on Education, Management, Computer and Medicine (EMCM 2016). Atlantis Press, 2017.

[5] Li, Jia, Jin-Wei Nie, and Jing Ye. "Evaluation of virtual tour in an online museum: Exhibition of Architecture of the Forbidden City." PloS one 17.1 (2022): e0261607.

[6] Wang, Yuting. "On the Artistic Expression of Traditional History Museums in the Digital Era." 2023 5th International Conference on Literature, Art and Human Development (ICLAHD 2023). Atlantis Press, 2023.

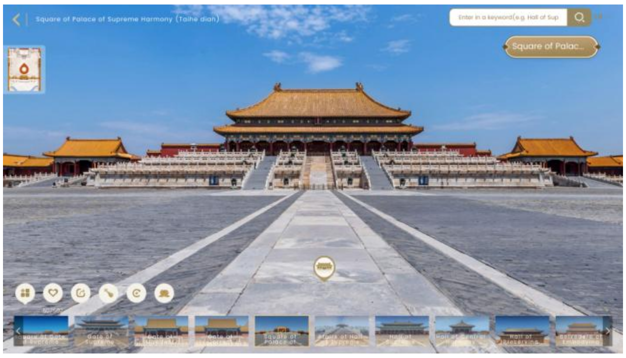

Figure 1. Square of Palace of Supreme Harmony [7]

Figure 2. Monitoring system[8]

4.2. IP industry value-added of architectural heritage

By exploring the distinctive elements of architectural heritage,shaping IP images,developing cultural and creative products, and creating digital content, we can uncover emerging business models within architectural heritage and maximize both economic and social benefits. [9]For example, ten iconic components, such as the ridge beasts of the Hall of Supreme Harmony, the Hexi colored paintings, and the glazed tiles, have been extracted to form a standardized vector image library. The Forbidden City Corner Tower Café transforms architectural mortise and tenon joints into a spatial design language, generating over 100 million yuan in annual revenue. Scenes like "Emperor Qianlong's Study" and "Cixi's Bedroom" have been transformed into storytelling IPs to support film and television production. Industry-wide IP collaborations are enabling consumption upgrades across all categories, such as digital art collections and virtual decorative items, to meet the consumption needs of young consumers in the virtual world. Empowered by digital technology, the project has successfully completed the triple transformation of "functional stripping - symbolic reinforcement - emotional binding", technically optimizing the protection and reuse of architectural heritage and reducing the bearing pressure of buildings; economically, it has formed a recycling mechanism, with an annual cultural and creative income of 1.5 billion yuan, of which 30% is invested in the construction of ancient building monitoring sensor networks; and culturally, it has expanded from "one-way knowledge output" to "immersive experience and living inheritance co-created by the public."

4.3. Interactive Design

In the preventive conservation project for the Hall of Supreme Harmony, we see digital technology surpassing traditional surveying and mapping. Laser scanning records the spatial coordinates and morphological details of every brick and tile, creating a permanent, high-fidelity digital archive of immovable cultural relics. A sensor network collects real-time data on temperature and humidity, structural displacement, and crack changes, correlating this data with the digital model. AI algorithms analyze data trends and predict potential risks (such as deformation of wooden components and subsidence of the platform), achieving "preventive measures" before they occur. In the discovering the Hall of Mental Cultivation Peoject, provides the audience with a more vivid and highly immersive experience through interesting and convenient multi-dimensional interaction, which is the intersection of digital art and media

[7] The Palace Museum (dpm.org.cn)
[8] http://english.scio.gov.cn/in-depth/2023-02/27/content_85130699.htm
[9] Liu, Luxiao. "Take the cultural and creative products of the Forbidden City as an example to explore the role of China’s cultural and creative industries in promoting traditional culture." Advances in Education, Humanities and Social Science Research 8.1 (2023): 306-306.

technology.Shan Jixiang, a director of the Palace Museum, explained that the concept of the Discovering the Hall of Mental Cultivation exhibition is to make the cultural relics come alive, letting people walk into the hall and feel the essence and charm of traditional culture (The Palace Museum, 2017)[10].

In order to effectively establish an emotional connection between users and architectural heritage, the Palace Museum combines the protection of architectural heritage with historical and cultural knowledge in terms of content[11]; in terms of form, it combines graphics, audio, video, and models to obtain richer content presentation; in terms of visual effects, it uses high-precision modeling technology combined with physical rendering technology to achieve realistic light reflection, refraction, and shadow effects, highlighting the building's sense of space and layering; in terms of environmental design, based on historical documents and archaeological research, it restores the appearance and environment of the architectural heritage, and creates a scene with a historical atmosphere by adding virtual characters, props, vegetation and other elements; in terms of link design, it uses animation technology to create dynamic historical scenes, such as the construction process of buildings, the occurrence of historical events, etc.; in terms of interactive design, it further utilizes VR or AR equipment to enhance the sense of immersion and interactivity through interactive design.

5. CONCLUSION

In summary, digital technology processes data through three primary methods: collection and modeling, storage and management, and display and dissemination. This data is then used to develop accurate information for project activities, achieving the preservation and value reproduction of architectural heritage. The completed and ongoing digital technology-enabled conservation and sustainable development of the Forbidden City in Beijing demonstrate that digital technology is not a replacement for tradition, but rather an enabler—enabling more scientific conservation, deeper understanding, broader participation, and sustainable inheritance.

The Forbidden City case embodies the three core values of digital preservation and development of architectural heritage. First, technology shifts conservation efforts from "rescue restoration" to "preventive intervention,"The Hall of Supreme Harmony monitoring system is a prime example,reshaping conservation logic and value dimensions, and innovating restoration techniques and research methods. Second, digital twins and knowledge graphs address the fragmentation of ancient architectural information. The Qianlong Garden BIM library even allows the "genetic" of each component to be traced, extending the heritage's lifecycle, reducing long-term maintenance costs, and ensuring the sustainability of cultural heritage. Third, open digital cultural resources enable the public to move from audience to co-creator, aiming to share cultural capital across humanity, empower research and education, and promote the reuse of cultural heritage.

As a significant World Cultural Heritage site, the Forbidden City's innovative application of digital technology not only paves new paths for its own preservation and inheritance, but also provides a step-by-step visualization experience for the conservation and sustainable development of architectural heritage worldwide. As a large developing country, China often faces the dilemma of prioritizing economic development. However, China's conservation and sustainable development of architectural heritage sites like the Forbidden City demonstrate that

[10] The Palace Museum, Duanmen Digital Museum of the Palace Museum Celebrated Its 92nd Anniversary With ‘Discovery · Hall of Mental Cultivation-Themed Digital Experience Exhibitor’, https://www.dpm.org.cn/show/246075.html, Dec 31 (2017)

[11] Lv, Weilu, et al. "Optimizing tourist facility layout in the Forbidden City using multi-source data analysis." npj Heritage Science 13.1 (2025): 132.

heritage can be cultural capital that promotes economic development and is the cornerstone of collective, ethnic, or national identity and a bond of social cohesion. Technological development presents us with a tremendous opportunity: to create new models, tools, and even partnerships to help preserve, manage, and enjoy humanity's collective cultural heritage. Emerging technologies and tools, such as digital technologies, can effectively transform local wisdom into a source of development, protect the narrative rights of cultural subjects, and provide an endogenous driving force for the sustainable and dignified development of collective, ethnic, or national culture.

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