

Research on the Communication of Dunhuang Grottoes Cultural Heritage Empowered by Digital Technology: A Case Study of the "Traveling around Dunhuang" mini-program

Yuewen Chen^{1, a}

¹Faculty of International Media, Communication University of China, Beijing, 100024, China

^akathychen1215@163.com

Abstract

The Dunhuang grottoes culture is a treasure of China's great traditional culture. However, up to now, the protection and dissemination of Dunhuang grottoes are facing a series of predicaments. The "Traveling around Dunhuang" mini-program jointly produced by Tencent and the Dunhuang Academy is one of the explorations to solve these predicaments. This study, based on the "use and Satisfaction theory", focuses on the practical paths and mechanisms of digital technology in enabling the dissemination of Dunhuang Grottoes' cultural heritage. Through the case deconstruction of the "Traveling around Dunhuang" mini-program, it reveals how technologies such as blockchain rights confirmation, AR interaction and 4K restoration meet users' cognitive, social and self-actualization needs; Analyze UGC content on platforms such as Weibo and Xiaohongshu in combination with the online ethnographic method, and extract users' creative translation strategies for Dunhuang cultural symbols. The study found that the technology-enabled "demand-behavior" loop reconstructed the model of cultural inheritance, while user-involved symbol reproduction promoted the contemporary revitalization of cultural heritage. The study provides a theoretical framework of "technology adaptation - user co-creation - meaning reconstruction" for the digital dissemination of cultural heritage, and also offers practical references for the innovative development of traditional culture in the context of global civilizational mutual learning.

Keywords

Digital technology; Dissemination of cultural heritage; Use and Satisfaction theory; Dunhuang Grottoes; User-generated content.

1. Introduction

1.1. Research background

The Dunhuang Grottoes, as a treasure of Chinese civilization, are of rich historical and cultural value. The sculptures, murals and statues in these grottoes are not only the pinnacle of art, but also the crystallization of the wisdom and creativity of the Chinese nation. However, due to the influence of the natural environment and historical changes, the Dunhuang Grottoes are facing serious conservation challenges. For example, the Mogao Caves are located in an arid region, and environmental factors such as dust in the air and drastic temperature changes can cause damage to the murals and sculptures. In addition, with the increasing number of tourists, excessive tourism activities have also put great pressure on the protection of these precious cultural heritages.

Against this backdrop, digital technology offers new possibilities for the protection and dissemination of the Dunhuang Grottoes' cultural heritage. Through digital means, not only can cultural heritage be preserved permanently, but also more people can appreciate and learn

about these precious cultural heritages without the constraints of time and space. In recent years, the Dunhuang Academy has worked with universities and research institutions at home and abroad to develop a complete set of key technologies and work processes suitable for the digital protection of the Dunhuang Grottoes and has fully launched the "Digital Dunhuang" project. The successful implementation of this project has laid a solid foundation for the digital dissemination of the Dunhuang Grottoes.

The "Traveling around Dunhuang" mini-program, jointly developed by the Dunhuang Academy and Tencent, is the first cultural and technological integration case in China that combines the appreciation of Dunhuang art, the issuance of digital collectibles, and user co-creation experiences. Through multimedia, networking and digitalization technologies, the mini-program breaks the limitations of time and space, presenting the treasures of Dunhuang to the public in a digital form. At the same time, with the rapid development of artificial intelligence (AI) technology, its application is becoming increasingly widespread in areas such as art education, cultural heritage protection and dissemination. AI technology can enrich the educational environment, optimize the learning process, and improve the efficiency and effectiveness of cultural heritage protection and dissemination. The combination of the Dunhuang Grottoes and AI technology opens up a new path for the dissemination and promotion of cultural heritage.

1.2. Literature Review

1.2.1. Construction of the Technical System for the Digital Conservation of Dunhuang

The digital conservation of the Dunhuang Grottoes began with the concept of "Digital Dunhuang" proposed by Fan Jinshi in the 1990s, and its technical core lies in building a full-chain technical system of "high-precision image acquisition - 3D modeling - data storage - intelligent analysis". Ding Xiaohong et al. pointed out that the Dunhuang Academy has improved the accuracy of mural images from 75DPI to 300DPI through its self-developed orbital orthobeam scatter coverage acquisition technology, and has achieved millimeter-level restoration of mural color and spatial structure by using laser point cloud and 3D scanning technology to correct lens distortion [1]. For complex architectural forms such as Buddhist temple courtyards, Wang Qiaowen proposed a methodology of "two-dimensional murals - three-dimensional parametric modeling - virtual reconstruction" based on BIM technology. Taking Cave 172 of the Mogao Grottoes as an example, she established a digital restoration model of Tang Dynasty Buddhist temple buildings, confirming that BIM technology can solve the problem of information discontinuity in mural architecture. Providing a replicable technical path for the digitalization of historical buildings [2]. In addition, the multi-dimensional heterogeneous data storage system developed by the Dunhuang Academy, through distributed storage and off-site backup technology, has enabled the secure management of 3D data of over 45,000 square meters of murals and 45 painted sculptures. Its technical standards have been extended to sites along the Belt and Road, such as the Kizil Grottoes in Xinjiang .

1.2.2. Artificial intelligence-driven revitalization and dissemination of cultural heritage

At the level of dissemination, AI technology is reconstructing the narrative logic of Dunhuang culture. Jiang Ni suggests that AI technology transforms the visual symbols in Dunhuang murals into interactive narrative language through a three-level architecture of "data mining - intelligent interpretation - multimodal interaction" [3]. For example, in the "Traveling around Dunhuang" mini-program, the "Today's Painting Language" module uses natural language processing technology to push mural stories that match the users' spatio-temporal situations every day, transforming static images into dynamic cultural dialogues [4]. Xu Di's bibliometric research shows that after 2016, the academic research focus shifted from "technology-oriented" to "audience-oriented", and AI-driven personalized recommendation systems (such

as the special push on Dunhuang mineral pigments) significantly enhanced the cognitive depth of young users [5]. In addition, the "Future Theater" project developed by a team from Tianjin Academy of Fine Arts reconstructs the visual style of caves from the Northern Liang Dynasty through an AI generative adversarial network (GAN) and enables dynamic interaction between user actions and mural elements through real-time rendering technology. This "technology archaeology + art creation" model has been evaluated as a "landmark breakthrough in digital humanities research" [3].

1.2.3. Immersive Experiences and cross-cultural communication mechanisms

The digital dissemination of Dunhuang culture has moved beyond one-way display to immersive experiences of "physical presence". Su noted that the Digital Cave of the Scriptures project has created an intertemporal participatory museum by integrating 8K dome films with XR technology, allowing users to "touch" cave documents through gesture recognition, and its multi-sensory collaborative design has increased cultural reception efficiency by 40 percent. In terms of cross-cultural communication, Zhao emphasized the "two-way collaboration" mechanism for the digital return of lost cultural relics: the joint data platform established by the Dunhuang Academy with institutions such as the National Library of France and the British Museum not only enables the digital sharing of 80% of overseas Dunhuang documents, but also eliminates cultural decoding barriers through an AI multilingual annotation system. The "Flying Sky Skin" social viral campaign designed by An Huili's team for non-Chinese speakers has achieved global secondary creation of cultural symbols through blockchain rights confirmation technology, reaching a cumulative exposure of 5 billion times, confirming the effectiveness of the "technology empowerment - community co-creation" communication model.

1.3. Research purpose

This study takes the "Traveling around Dunhuang" mini-program jointly developed by the Dunhuang Academy and Tencent as the core case, aiming to explore how digital technology reconstructs the dissemination logic of cultural heritage, with a focus on the empowerment mechanism of the innovative practice of digital collectibles and the in-depth application of AI technology for the cultural dissemination of the Dunhuang Grottoes. Through qualitative research methods, the following core issues are revealed:

At the technical path level: Analyze how the "Traveling around Dunhuang" mini-program breaks through the temporal and spatial limitations and one-way narrative mode of traditional cultural heritage dissemination through technological means such as blockchain rights confirmation, metaverse scene construction, and AI interaction, and realizes the digital "living inheritance" of cultural resources.

Audience behavior level: Explore how digital technology-enabled communication models can stimulate cultural identity and participation behaviors among the younger generation (such as social sharing and user co-creation), and analyze the underlying emotional resonance mechanisms and technology acceptance logic.

Practical strategy level: Summarize the experience and challenges of the "Cloud Tour of Dunhuang" case, provide reusable technology adaptation solutions and user operation strategies for the digital dissemination of other cultural heritages, and promote the sustainable development of traditional culture in the digital age.

Through the above research, this study aims to answer the core proposition of "how digital technology can reshape the dissemination ecosystem of cultural heritage through content innovation, experience upgrading and user engagement", and provide theoretical support and practical reference for the digital transformation of cultural heritage protection and dissemination.

2. Materials and Methods

Based on the "use and satisfaction theory," this study combines case studies and online ethnographic methods to systematically explore how digital technology can empower the dissemination of Dunhuang Grottoes cultural heritage from three dimensions: audience needs, technical practice, and dissemination effects.

2.1. Theoretical Framework: Practical transformation of the Use and Satisfaction theory

Based on Katz's classic theory, combined with the digital characteristics of the dissemination of Dunhuang culture, we build a three-dimensional analysis model of "demand - technology - behavior" :

The "Traveling around Dunhuang" mini-program was the first to meet users' cognitive needs. The Digital Dunhuang resource library offers high-definition images of 30 caves and online access to 6,500 documents, covering 78 countries around the world, with over 23 million visits. Users can learn about the history of the murals, artistic features (such as the digital interpretation of the Nine-colored Deer story) and conservation status (such as the layering comparison display of diseases). Meanwhile, the mini-program, relying on the multilingual search function of the "Dunhuang Studies Research Archive", integrates global academic achievements to promote the internationalization of Dunhuang studies.

The second is the satisfaction of social needs. Users can participate in the dubbing of animated dramas and design Dunhuang poetry scarves through the "Traveling around Dunhuang" mini-program, and share them on social platforms to form a secondary dissemination chain. For instance, the animated series "The Deer and the Informer" generated over 5,000 UGC content on its first day of release. The mini-program also has a lot of interactive ritual features to satisfy users' pursuit of ritual. For example, in the "Light Up the Mogao Caves" feature, users light up a virtual cave through blockchain technology, generate personalized lucky cards and share them, creating a collective memory of "lighting up the lamp online".

Finally, it fulfills users' need for self-actualization. Through the "Traveling around Dunhuang" mini-program, users can participate in the creation and design of cultural peripheral products, transforming from cultural viewers to cultural producers, thereby generating an identity as a cultural producer. For example, users can download mural materials through "Digital Dunhuang · Open Material Library" for secondary creation, and creators can share the revenue with the Dunhuang Academy, achieving the transformation from "consumer" to "producer". Users participating in the "Digital Donor" program can receive virtual MEDALS and exclusive rights by making small donations to support the protection of cultural relics, strengthening the sense of mission for cultural inheritance and also generating a strong spiritual resonance among users.

2.2. Case Analysis Method: Focus on the functional deconstruction of the "Traveling around Dunhuang" mini-program

Conduct an in-depth dissection of the functional modules, technical architecture and communication effects of the "Traveling around Dunhuang" mini-program.

The functional modules of the "Traveling around Dunhuang" mini-program are mainly designed using a strong interactive logic. When you open the mini-program, the first thing you see is classified navigation and knowledge popularization, intelligent recommendation of murals by dynasty and subject matter (such as the VR real scene of Cave 45 of the Tang Dynasty), and daily cultural knowledge push in combination with AI-generated "Today's Painting Language". One of the main features is to offer users an immersive experience of the beauty of the Dunhuang murals, restore the spectacular lighting scene of the Mogao Caves with AR

technology, and allow users to switch light perspectives in real time to experience the virtual scene of "a river of stars hanging". The mini-program also has a user participation mechanism, such as the "Dunhuang Animated Drama" dubbing function, where users can choose characters and invite friends to collaborate, and the generated works will be shared through social media. The mini-program has made innovations in its technical architecture. The first step is the use of blockchain for rights confirmation. Tencent's "Zhixin Chain" is used to generate a unique hash value for each lucky card to ensure the traceability of digital property rights, with evidence accumulated over 30,000 times. In the restoration and display of murals, 4K restoration and multispectral imaging were used to scan and restore the colors of the murals with high precision. For example, the nine-colored deer mural in Cave 257 recreated the details of mineral pigments from the Northern Wei Dynasty through multispectral technology, providing users with an ultimate visual experience.

After conducting a quantitative assessment of the dissemination effect of the "Traveling around Dunhuang" mini-program, we can find that its dissemination effect is very significant. First of all, the mini-program has a huge user base, with over 28 million visits and more than 10 million unique visitors in the first year of its launch. The second is the high user stickiness, with an average dwell time of 8.2 minutes and a purchase rate of 12.7 percent for digital cultural and creative products. The mini-program has also gained some international influence after its launch. At the Harvard University AR exhibition, viewers triggered dynamic dance performances by scanning murals, and the social media topic # Dunhuang AR# received over 120 million views.

2.3. Web Ethnography: The translation of cultural symbols from UGC content

By tracking social media platforms, analyze the language styles and cultural symbols that users spread spontaneously.

The language style analysis uses some quantitative methods. The first step was to collect the data. The UGC content was collected respectively from the top domestic user-sharing platforms Weibo (with 12,000 entries on the # Cloud Tour of Dunhuang # topic), Xiaohongshu (with 7,800 notes on "Dunhuang Outfits"), and Bilibili (with over 5 million views of secondary creation videos). Then, Python web crawlers and NLP techniques were used for semantic analysis to extract high-frequency words related to the Dunhuang topic such as "Flying apsaras", "Nine-colored deer", "Silk Road", and positive emotions accounted for 83.4% of the emotional tendencies.

Then there was an analysis of the cultural symbol translation strategy for user-generated content. In terms of visual design, users' understanding and love for Dunhuang culture have led to visual reconfiguration, integrating mural elements such as flying apsaras and lotus patterns into modern designs, such as a Xiaohongshu blogger who paired "Dunhuang colors" with Hanfu received over 100,000 likes. In terms of cultural content, users' participation has enabled narrative innovation in cultural dissemination, achieving cultural dissemination in a more novel way while attracting a large audience. The deep engagement of users has made them more identified with and responsible for Dunhuang culture, thus generating a stronger emotional resonance.

3. Results and Discussion

This study, based on the "use and Satisfaction theory", combines case studies, online ethnography and quantitative data to systematically reveal the internal mechanisms and practical paths of digital technology empowering the dissemination of Dunhuang Grottoes cultural heritage. The study found that the digital dissemination of Dunhuang culture has broken through the traditional one-way output model and formed a dynamic circular system

characterized by "demand activating technology, technology reconstructing behavior, and behavior feeding back culture". This process has not only reshaped the dissemination paradigm of cultural heritage, but also restructured the contemporary interpretation of cultural significance through audience participation. The specific conclusions unfold from three dimensions: theory, practice, and culture.

3.1. Theoretical dimension: Demand-driven technology adaptation mechanism

The practice of the "Traveling around Dunhuang" mini-program demonstrates the precise satisfaction of users' cognitive needs and technological empowerment. The "Traveling around Dunhuang" mini-program has achieved the knowledge transmission efficiency of high-precision technology. The blockchain rights confirmation technology, through the unique identification of hash values, and the 4K restoration technology for the multi-spectral restoration of mural colors have solved the problems of information distortion and authority in the dissemination of cultural heritage. The frequency of users' visits to the "Digital Dunhuang" resource library and the average duration of their stay indicate that technology-driven knowledge supply can effectively meet deep-level cognitive needs, especially the exploration of the historical evolution, development context and conservation techniques of the Dunhuang murals. At the same time, it has achieved a universal transformation of academic resources, allowing more users to learn about the academic knowledge and professional theories related to Dunhuang. The multilingual search function of the Dunhuang Studies Research archive has transformed the literature that was originally confined to academic institutions into public knowledge, promoting the transformation of Dunhuang studies from an "ivory tower" to a "mass".

The "Traveling around Dunhuang" mini-program offers opportunities for the explosive spread and behavioral transformation of users' social needs. The mini-program builds a social viral mechanism for content co-creation. Take the AR card sharing function of the "Traveling around Dunhuang" mini-program as an example. Users generate personalized virtual avatars (such as the "Digital Flying Apsara" that combines Tang Dynasty clothing with modern aesthetics) and share them on social platforms, forming a diffusion chain of "individual creation - community dissemination - public participation". The data shows that the secondary dissemination rate of user-generated content (UGC) is 43 percent, and the topic "DIY Dunhuang Fu Card" on Xiaohongshu has accumulated over 280 million views, confirming the creative transformation of social needs by digital technology. Ritualized interaction helps build collective memory. In the "Light Up the Mogao Caves" virtual lighting event, blockchain technology recorded millions of users' lighting actions and generated a "digital sea of lights" through timestamps and spatial coordinates, recreating the collective memory of ancient lighting ceremonies. This technology-enabled participation in the ceremony has given the online event a symbolic meaning of cultural heritage.

Mini-programs meet users' needs for self-actualization and help to reconstruct cultural identities. The user's identity enables a leap from consumer to producer. In the "Digital Dunhuang · Open Material Library", users download mural materials for secondary creation (such as commercial illustrations, costume designs) and share profits with the Dunhuang Academy through "revenue-sharing agreements", demonstrating that technological empowerment can activate cultural productivity. Through the mini-program, users can contribute their humble efforts to the conservation of the Dunhuang murals, thereby achieving a sustainable incentive of spiritual resonance. In the "Digital Donor" program, users receive virtual MEDALS and exclusive benefits (such as priority access to cave restoration progress) through small donations (minimum 1 yuan), forming a closed loop of "material support - spiritual satisfaction - behavioral continuation", highlighting the reinforcing effect of technology on cultural identity.

3.2. Practical dimension: The synergistic evolution of technology architecture and communication effect

The functional design of the "Traveling around Dunhuang" mini-program reflects the strategy of cultural translation. The popular translation of academic discourse, the AI-generated "Today's Pictorial Language" function (such as converting the Vajracchedika Sutra text into "Daily Zen sayings") and the intelligent summarization function of the multilingual literature library, through semantic analysis technology, transform professional academic texts into popular narratives, making profound cultural knowledge accessible to ordinary users. The interaction logic of the mini-program demonstrates a high degree of cultural adaptability. In the "guided by Dynasty" feature, the technical team designed an intelligent recommendation algorithm based on the evolution of the Dunhuang art style (such as the visual characteristics from the "delicate bones and clear images" of the Sui Dynasty to the "rich and luxurious" of the Tang Dynasty), embedding cultural logic deeply into the technical architecture.

The immersive experience feature of the mini-program has achieved the effect of emotional arousal. In the "cave lighting" scene recreated by AR technology, users can adjust the Angle of the light through gesture interaction to observe the visual effect of the murals under different lighting conditions. Emotional words such as "shocked" and "moved" appeared very frequently in user feedback, demonstrating that digital space helps enhance empathy. In the "Dunhuang Animated Series", users participate in narrative construction through voice interaction (such as voiceovers for the Nine-colored Deer character), and the generated content is integrated into the official knowledge base, forming a positive cycle of "user contribution - content upgrade - cognitive iteration".

3.3. Cultural dimension: Symbol reproduction and meaning reconstruction of user participation

User participation enables the modernization of visual symbols. In the "Dunhuang Color Outfit" notes on Xiaohongshu, users extracted the color spectrum of murals for fashionable matching, creating a visual dialogue of "traditional aesthetics - contemporary life", demonstrating a new way of interpreting traditional culture in the contemporary era. Many netizens have created secondary content and posted it on social media, innovating the narrative logic of the dissemination of Dunhuang culture. Many of them have also been reposted by the Dunhuang Academy, forming an incubation model of "folk creation - official certification".

3.4. Research Limitations and Future directions

Research limitations:

Risk of data bias: UGC content is affected by the platform's algorithmic recommendation mechanism (such as traffic bias in Weibo topics), and may not fully reflect real user behavior; Case studies are concentrated on top platforms (such as "Cloud Tour of Dunhuang"), and there is insufficient justification for the universality of small and medium-sized digital projects.

Lack of multi-faceted assessment of technology effects: Existing research focuses on user behavior data and lacks measurement of physiological indicators such as eye movement trajectories and brain waves, making it difficult to fully reveal the deep impact of technology on cognitive processes.

Future research directions

A comparative study of globalization: Comparing the digital dissemination paths of Dunhuang with Angkor Wat and Pompeii, extracting a universal framework for the digitalization of cultural heritage.

The cultural generation potential of AIGC technology: Exploring the intelligent restoration of damaged parts of murals by generative AI such as Stable Diffusion, and the ethical boundary definition of user participation.

Digital technology not only provides tools for preserving and revitalizing the cultural heritage of the Dunhuang Grottoes, but also reconstructs the logic of generating cultural meaning by activating the subjective participation of the audience. The dynamic model of "technology adaptation - user co-creation - meaning reconstruction" proposed in this study reveals the two-way mechanism of "technology adaptation needs and behavior feeding back to culture" in the digital dissemination of cultural heritage, providing a reusable methodological framework for global civilisational dialogue. In the future, with the evolution of technologies such as the metaverse and brain-computer interfaces, the digital dissemination of cultural heritage may enter a new stage of "sensory immersion - neural interaction - meaning co-creation", which requires more in-depth collaborative exploration between academia and industry in areas such as technology ethics and cultural sovereignty.

References

- [1] Wu, J. (2025). The Construction of Digital Dunhuang. China Archives News. Total issue 4244. Fourth edition
- [2] Wang, Q. (2024). Digital reconstruction of the Buddhist Temple Courtyard in Dunhuang Murals using BIM technology: A case study of the Buddhist temple courtyard in the murals on the north wall of the main chamber in Mogao Grotto-172. *Journal of Dunhuang Studies* (03), 65-75.
- [3] Jiang, N. (2024). Digital protection and dissemination of Dunhuang Art in the context of artificial intelligence. *Journal of Dunhuang Studies* (03), 90-97.
- [4] Zhao, Z., Wang, X. (2021). Digital communication of Material Cultural heritage from the perspective of media memory -- A case study of wechat mini program "Yuntour Dunhuang". *Journalism and Writing* (03), 99-102.
- [5] Xu, D. (2024). Research evolution and prospect of digital protection of cultural heritage in China: bibliometric analysis based on Cite Space. *Global Media Tribune* (05), 153-167.