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Research on Innovative Design of Ancient Chinese Architectural Polychromy Based on AIGC: A Case Study of Song Dynasty Architectural Polychromy Patterns

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Abstract

Ancient Chinese architectural polychromy embodies profound cultural significance and aesthetic value. However, it faces two main challenges: the evolving demands of contemporary design and the discontinuity in traditional craftsmanship transmission. This study focuses on polychrome patterns of the Song Dynasty and proposes a framework for their digital preservation and innovative redesign based on Artificial Intelligence-Generated Content (AIGC) technologies. Grounded in canonical texts such as the Yingzao Fashi (营造法式, Treatise on Architectural Methods), the research systematically analyzes the formal, chromatic, and symbolic characteristics—termed “form–color–meaning”—of Song Dynasty architectural polychrome decoration. A representative dataset was constructed, comprising typical pattern types such as Huawenjin (花纹锦, Floral Brocade), Suowenjin (琐纹锦, Interlocking Brocade), Qushuijin (曲水锦, Meandering-Stream Brocade), Jingdijin (净地锦, Plain-Ground Brocade). By combining Stable Diffusion v3.5 with the LoRA fine-tuning mechanism (including a human–machine collaborative feedback loop), the framework integrates multidimensional evaluations of cultural semantics and aesthetic quality into its iterative optimization cycles, the approach achieves high-fidelity structural reconstruction and deep semantic expression. Experimental results demonstrate that the model excels in structural reconstruction and stylistic emulation. The generated patterns exhibit robust cultural adaptability and innovative design capacity across applications such as virtual exhibitions, cultural–creative products, and interactive education. The developed "Songfeng Caiyun" (宋风彩韵, meaning 'Song-style Aesthetic Chroma') intelligent platform further validates the proposed framework’s feasibility for digital conservation, creative redesign, and cross-media dissemination of traditional Chinese ornamental art.

1. Introduction

Traditional architectural polychromy is a quintessential manifestation of China’s built heritage. It embodies pre-modern artisans’ mastery of chromatic symbolism and cultural semiotics through structured decorative systems. These intricate motifs span zoomorphic figures, botanical emblems, and cosmological geometries. They function as visual rhetoric, encoding hierarchical structures and moral philosophies within components such as dougong brackets and ceiling caissons.

The Song Dynasty marks a pivotal stage in this development, characterized by the institutionalization and standardization of polychromy. During this period, decorations featured clear forms, standardized compositions, and a calm, elegant palette, reflecting a high degree of cultural rationality and aesthetic awareness. Canonical works such as Yingzao Fashi (营造法式, Treatise on Architectural Methods) codified color compositions, pattern systems, and compositional methods. These norms, combined with their symbolic logic, provide a robust foundation for integrating traditional decoration with contemporary digital preservation technologies.

Against a backdrop of rapid urban renewal, fading traditional crafts, and evolving modern aesthetics, architectural polychromy is facing multiple challenges: skill loss, imbalanced inheritance mechanisms, and shifting design demands. Consequently, leveraging emerging technologies—especially AIGC (Artificial Intelligence-Generated Content)—for digital preservation, intelligent regeneration, and contemporary expression has become crucial in architectural heritage protection and design innovation. AIGC technologies have now made significant strides in image synthesis, semantic transfer, and style reconstruction, positioning them as key drivers of cultural heritage design.

This paper focuses on the pattern composition and aesthetic features of Song Dynasty architectural polychromy, presents an AIGC-based pattern generation system tailored to Song Dynasty polychromy styles. Through image recognition, Stable Diffusion models, and LoRA fine-tuning, we extract, classify, and semantically label typical patterns. Directed LoRA models enhance structural fidelity and cultural adaptability. We then develop a pattern redesign system for automated generation across multiple scenarios, demonstrating its value in education, cultural experiences, and product innovation.

2. Research Status

Chinese ancient architectural polychromy is both a functional and ritualized decorative art, forming a unique visual language in historic timber-framed buildings. In the 20th century, Liang Sicheng catalogued China’s architectural forms and decoration, highlighting polychromy’s significance in structural and symbolic contexts. Later scholars have explored its evolution and cultural value from the perspectives of structural aesthetics, decorative logic, and social rituals (Zhang and Chen, 2016; Tang, 2021).

During the Song Dynasty, Yingzao Fashi (营造法式) codified hierarchical distinctions, spatial layouts, motif systems, and color schemes, establishing standardized norms (Li, 2020). Scholars have since analyzed the tripartite “center–border–auxiliary” composition of Song Dynasty architectural

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polychromy, illuminating its semiotic logic and the interplay between ritual propriety and aesthetic expression (Yuan and Shi, 2023; Shen, 2024). In pedagogical contexts, researchers have examined how ancient polychromy informs modern curricula, emphasizing its role in cultural-identity reconstruction and the integration of aesthetic education with cultural literacy (Wang and Luo, 2019).

In recent years, AIGC technologies have shown strong potential for digital preservation and creative redesign of traditional Chinese patterns (Liu, 2025). Some studies have applied AIGC to automate extraction and 3D parametric modeling of Shu embroidery, revitalizing heritage motifs (Li and Zhang, 2024). Additionally, AIGC has been used to analyze and artistically redesign ancestral-hall ridge decorations (Zhang et al., 2024). In architectural polychromy, it supports the generation of patterns grounded in historical documentation and field data, enabling virtual restoration of interior scenes (Yi et al., 2024).

Although significant progress has been made—both domestically and internationally—in AIGC-assisted reconstruction, style transfer, and digital redesign of traditional polychromy, focused research specifically on Song Dynasty architectural polychromy designs remains limited. A comprehensive framework integrating cultural-semantic annotation, generative models, and human–AI collaborative workflows is not yet established. Users commonly encounter issues such as insufficient understanding of pattern structures, semantic distortion in control mechanisms, and weakened cultural adaptability. Future work should address cultural-context interpretation, style-control methods, and cross-platform generation systems to advance the intelligent revitalization of Chinese architectural polychromy.

3. Artistic Characteristics of Song Dynasty Architectural Polychromy

3.1 Historical Evolution and Functional Transformation

From its origins through the Song Dynasty, architectural polychromy evolved from a wood-protective function to an aesthetic and status-symbolic expression. Yingzao Fashi, an authoritative Song treatise on architecture, detailed regulations and pigment-mixing methods for polychromy. It prescribed strict norms for decorations in palaces, ancestral temples, and high-grade residences. With increased social stability and the rise of urban culture, polychromy transitioned from mere protection to cultural expression, becoming a key medium for conveying Confucian rituals and the scholarly aesthetic within architectural spaces.

3.2 Color Composition and Technical Application

Song-era polychromy predominantly employed blue, green, and red pigments, complemented by white and yellow to form a calm, well-layered palette (Chen, 2002). Primary pigments included mineral-based stone blue, stone green, and cinnabar, along with small amounts of plant-derived gamboge. Color mixing techniques yielded composite systems such as “grass color,” “lining color,” and “mixed color,” enabling gradients, overlapping, and filling effects (Wu, 2023). Recession-focused coloring enhanced gloss and texture, producing a visually serene, elegant, and three-dimensional effect.

3.3 Composition Methods and Pattern Systems

Compositional design in the Song Dynasty emphasized symmetry, balance, and standardization, adopting a three-part “center–border–auxiliary” structure. Yingzao Fashi specifies six principal polychromy modes, each tied to spatial hierarchy and building grade. Pattern expressions favored auspicious and longevity-symbolic motifs—such as climbing-branch flowers, double-lion reunion motifs, and round-nest medallions—while stressing reuse of forms, combinatorial composition, and decorative unity. This clear classification provides a structured semantic template for subsequent AIGC-based pattern splitting and parametric modeling.

3.4 Cultural Connotations and Ritual Symbolism

Song Dynasty polychromy rigorously adhered to Confucian ritual codes. Its color choices, pattern arrangements, and application processes displayed clear gradation and symbolism. Yingzao Fashi codified permissible polychromy forms, chromatic combinations, and decorative extents, embodying the feudal ritual order in architectural art. For example, Wucai bianzhuang (五彩遍装, Five-Color Full Decoration) with its vibrant polychromy was predominantly used in high-ranking structures like imperial palaces and ancestral temples, embodying polychromy’s association with authority and solemnity in such designated settings. Motifs—such as dragons, phoenixes, peonies, pomegranates, and climbing-branch lotuses—conveyed concepts of nobility, wealth, fertility, and longevity. The integration of scholar-official culture with Buddhist and Taoist thought further cultivated an elegant, tranquil aesthetic, emphasizing harmony between heaven and humanity and a serene communion with nature (Chen and Liu, 2015).

4. AIGC - Based Design Model Architecture for Song Dynasty Architectural Polychromy Patterns

4.1 Design Approach and Model Architecture

4.1.1 Design Approach: This study establishes a deep-learning–based redesign workflow for Song Dynasty architectural polychromy motifs. It aims to achieve digital preservation and innovative regeneration via AIGC (Artificial Intelligence–Generated Content) technologies. The workflow includes three core modules. First, data preparation and processing; second, model training; and third, integration and application of pattern generation system. (Figure 1).

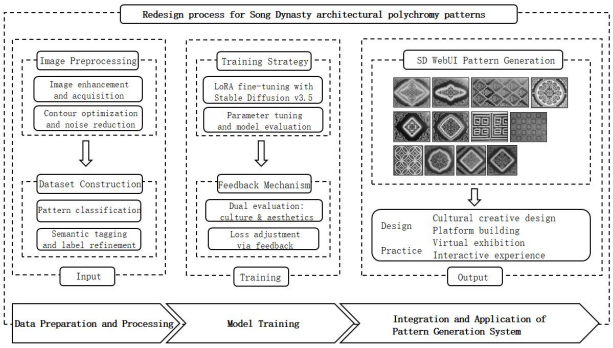

Figure 1. Redesign process for Song Dynasty architectural polychromy patterns.

During the data-preparation phase, Song Dynasty polychrome patterns were systematically categorized into four archetypal

classes: Huawenjin (花纹锦, Floral Brocade), Suowenjin (琐纹锦, Interlocking Brocade), Qushuijin (曲水锦, Meandering-Stream Brocade), Jingdijin (净地锦, Plain-Ground Brocade). Image quality was enhanced through denoising, geometric rectification, and standardization protocols, while a hierarchical labeling strategy was implemented to construct a high-fidelity dataset.

In the model-training phase, Stable Diffusion v3.5 (SD v3.5) was adopted as the base architecture, with four specialized LoRA (Low-Rank Adaptation) models fine-tuned for each motif category. Iterative parameter optimization and loss-function monitoring (e.g., perceptual loss, style loss) were conducted through multi-stage experimental cycles, ensuring that generated outputs were aligned with Song-era artistic conventions.

The finalized LoRA models were deployed via the SD WebUI platform to enable automated, diversity-driven pattern regeneration. Validation of outputs combined traditional aesthetic metrics—grounded in Yingzao Fashi compositional principles—with quantitative Fréchet Inception Distance (FID) scores. This two-pronged validation established a scalable technical architecture for cultural-product development and virtual-exhibition systems. Further extensions include a dedicated AIGC-assisted co-creation platform featuring virtual exhibitions, interactive design interfaces, and modular cultural-innovation workflows.

4.1.2 Model Architecture: This architecture comprises two components: a Stable Diffusion–based generative foundation model and a LoRA fine-tuning module. The Stable Diffusion backbone delivers robust, high-fidelity image synthesis, while LoRA enables lightweight, style-specific adaptation. Combined, they form an accurate and efficient framework for generating Song Dynasty architectural polychromy patterns.

(1) Stable Diffusion - Based Foundation Model Architecture

Stable Diffusion (SD) is a deep-learning, diffusion-based model with powerful image-generation capabilities. Its principle originates derives from noise inversion in non-equilibrium thermodynamics: by gradually removing random noise, it produces high-quality images that satisfy semantic constraints. This offers a novel technical path for regenerating Song Dynasty polychromy patterns. It consists of three core modules: first, the Text Encoder, which uses the CLIP model, converts text prompts into mathematical representations understandable by computers; second, the Image Information Creator, based on a UNet structure, denoises step-by-step according to a diffusion scheduler to generate potential image representations; and third, the Image Decoder restores low-dimensional images from the latent space into high-resolution images. Through successive semantic encoding, diffusion modeling, and latent-space optimization, SD achieves reliable mapping from noise to high-fidelity images, establishing the foundation for AIGC-driven pattern redesign.

(2) Transfer Model Architecture Based on LoRA

Building on SD's image generation capabilities, this study introduces LoRA (Low-Rank Adaptation) fine-tuning to optimize for the highly stylized target of Song Dynasty polychromy. LoRA is a lightweight and efficient fine-tuning technique designed to enhance the customization capabilities of large-scale pre-trained models in specific domains.

LoRA operates by freezing the original model parameters W_0 and introducing a low-rank update $\Delta W=BA$, where $B \in R^{d\times r}$, $A \in R^{d\times r}$, with rank much smaller than d ($r \ll d$). This reduces the number of parameters needing update from $d\times d$ to $d\times r + r\times d = 2\times d\times r$, significantly lowering both fine-tuning cost and computational resource requirements. LoRA modules are inserted into the cross-attention layers of the Stable Diffusion model—i.e., the key components where prompt semantics interact with image structure—to maximize retention of the pre-trained model’s generalization capacity while endowing it with strong style-specific adaptation. For example, in the regeneration of Song Dynasty architectural polychromy, LoRA focuses on learning the structural features of typical motifs such as Huawenjin (花纹锦, Floral Brocade), enabling precise synthesis of patterns that conform to the Song semantic framework. The forward pass is given by $h = (W_0+\Delta W)x = (W_0 + BA)x$. During inference, the low-rank increment matrices learned during training are directly added to the original pre-trained weights, forming a new weight matrix, $W_{new} = W_0 + BA$, without additional model structural adjustment or repeated computation, thereby preserving the original model’s inference speed. Moreover, because W_0 remains unchanged, LoRA avoids catastrophic forgetting under small-sample training, enhancing the generated images’ style consistency, detail fidelity, and cultural adaptability.

Overall, with its compact size (2 MB–200 MB) and excellent plug-and-play compatibility, LoRA bridges the broad applicability of general-purpose diffusion models and the style customization required in vertical domains. It thus provides a viable and scalable technical pathway for the intelligent redesign of Song Dynasty architectural polychromy patterns.

4.2 Data Preparation and Processing

4.2.1 Image Preprocessing: The polychromy pattern samples used in this study were drawn from the following authoritative sources: Ornamental Patterns of Ancient Chinese Architecture (《中国古代建筑纹样》), Liang Sicheng’s Commentary on Yingzao Fashi (《梁思成营造法式注释》), Research on Colored Paintings in Yingzao Fashi (《营造法式彩画研究》), History of Ancient Chinese Architecture (《中国古代建筑史》), and Studies on Yingzao Fashi (Vol. 3) (《营造法式の研究（第 3 卷）》). All images were first subjected to image-quality enhancement and threshold-based segmentation. Next, curve optimization and noise suppression were applied to ensure that the final pattern samples combined clear outlines with high fidelity of detail. These processed images thus provided high-quality inputs for subsequent model training.

During the image acquisition phase of polychrome motifs, a series of image processing techniques were employed to optimize image quality and improve segmentation precision. Original samples frequently exhibited challenges, such as low luminance, uneven color saturation, and substrate texture interference. To address these issues, adaptive histogram equalization and Contrast-Limited Adaptive Histogram Equalization (CLAHE) were first applied for localized luminance and contrast enhancement, significantly improving detail visibility. Subsequently, local threshold segmentation and Otsu's algorithm were used to isolate motifs from backgrounds, ensuring crisp contour delineation and structural continuity.

To mitigate line discontinuity and localized noise artifacts during preliminary motif extraction, morphological operations and image smoothing techniques were systematically applied.

Python-based implementations of morphological opening (erosion followed by dilation) eliminated small-scale noise while preserving primary linework integrity. Gaussian blurring was then employed to smooth jagged or coarse edges, effectively reducing high-frequency noise. Finally, binarization processing accentuated all edge and line features, achieving standardized and high-definition motif representations (Figure 2).

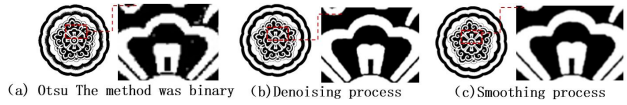

Figure 2. Image preprocessing workflow demonstration.

4.2.2 Dataset Construction and Pattern Labeling

Considering the diversity and complexity of Song Dynasty architectural polychromy, this study develops a systematic classification methodology and data-labeling strategy along two key dimensions—textural and geometric—for four principal pattern categories: Huawenjin (花纹锦), Suowenjin (琐纹锦), Qushuijin (曲水锦), Jingdijin (净地锦). A structurally coherent, sample-rich dataset was then constructed, providing subsequent models with high-standard semantic labels and robust data structures (Figure 3).

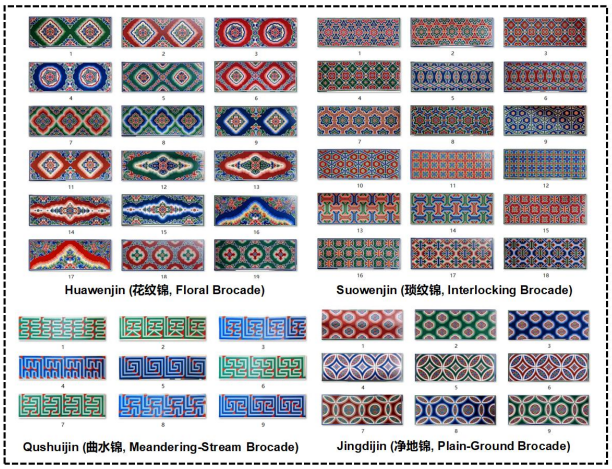

Figure 3. Example of the pattern dataset.

To enhance classification accuracy, Local Binary Patterns (LBP) were employed to capture detailed textural differences, while Histogram of Oriented Gradients (HOG) and edge-direction analysis were used to extract line and geometric shape information. An end-to-end convolutional neural network (CNN) training approach, combined with data augmentation, was adopted to improve the model's robustness and generalization ability. Post-processing techniques, including morphological opening and connected-component analysis, were applied to ensure the clarity and coherence of the pattern structures.

For pattern labeling, all images were standardized to a uniform size of 512×512 pixels to eliminate dimensional discrepancies between images, thereby optimizing the batch processing workflow and ensuring consistent feature understanding during model training. A two-step labeling strategy combining "automatic extraction" and "manual optimization" was employed. The WD (Waifu Diffusion) ViT Tagger v3 model was used to automatically extract style features and detail tags from the images, generating corresponding text prompts to serve as training labels. Following the initial automatic labeling, Booru Dataset Tag Manager was utilized for manual review and refinement to enhance the semantic accuracy and precision of the labels. This ensured precise learning of pattern styles by the LoRA model during the training phase.

4.3 Model Training

To achieve precise customization of Song Dynasty architectural polychromy patterns, this study employed the officially released Stable Diffusion v3.5 model and performed LoRA fine-tuning on the Stable Diffusion WebUI platform using a robust training strategy. This approach maximized the model’s learning capacity while effectively mitigating overfitting and underfitting. Critical parameters were meticulously adjusted throughout training to ensure stability and effectiveness. Multiple rounds of evaluation and comparison were then conducted to identify the optimal model for pattern generation. The experiments were carried out on an AMD Ryzen 9 5900HX CPU, NVIDIA GeForce RTX 3060 GPU, and Windows 11 OS, with Python 3.10.8 as the programming language.

The model was trained for 15 epochs, with the U-Net module using a learning rate of 1×10^{-4} and the text encoder set to 1×10^{-5}. A cosine-with-restarts scheduler adjusted the learning rate to accommodate the requirements of different training stages. TensorBoard monitoring (Figures 4 and 5) illustrated stable training dynamics, showing smoothly decreasing loss curves alongside the scheduled learning-rate changes, thereby validating the effectiveness of the training strategy. The AdamW-8 bit optimizer was chosen to minimize GPU memory consumption during large-scale parameter updates. To bolster learning from limited data, each dataset was cycled through ten times. Intermediate checkpoints were saved every three epochs, yielding five models for comparative performance analysis. Custom X/Y/Z scripts generated visualizations of style reproduction, image clarity, and geometric consistency, and computed SSIM and FID metrics to identify potential issues and guide timely parameter tuning. Ultimately, four LoRA models demonstrating superior stylistic expressiveness and structural fidelity were selected as the primary generators for Song Dynasty polychromy pattern regeneration (Figure 6).

To enhance cultural precision and artistic fidelity, a human-machine collaborative feedback mechanism is embedded within the training loop: following each iteration of LoRA fine-tuning, representative generated samples are evaluated from two dimensions—"cultural consistency" and "aesthetic quality." These evaluation scores, after normalization, are transformed into weighted penalty terms and incorporated into the original loss function. This approach guides subsequent iterations toward higher cultural fidelity without altering the predefined training schedule or hyperparameter settings. Consequently, the regenerated Song Dynasty patterns can not only accurately render structural details but also faithfully reflect the ritual symbolic meanings embedded in the original designs.

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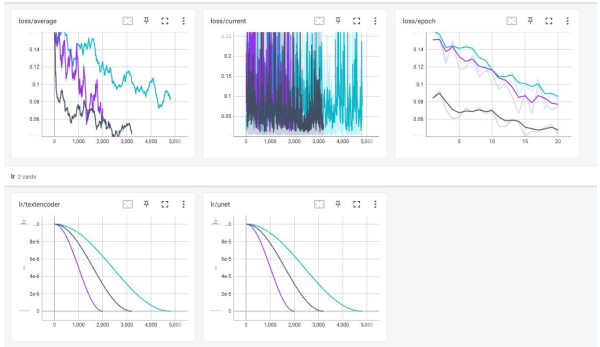

Figure 4. TensorBoard training visualization.

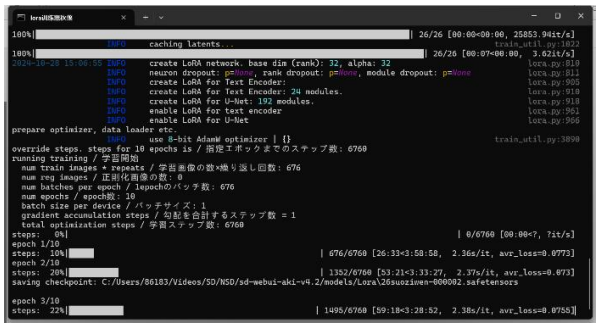

Figure 5. Example of LoRA fine-tuning training process.

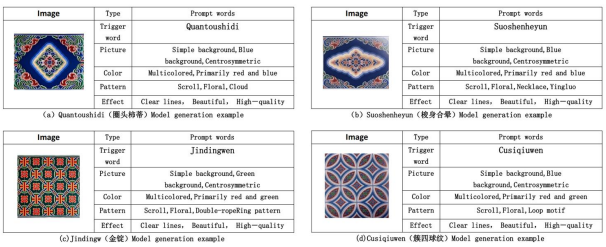

Figure 6. Four selected LoRA models.

4.4 Integration and Application of Pattern Generation System

This study further integrated the fine-tuned LoRA model into a Stable Diffusion WebUI-based platform, thereby establishing an intelligent generation system for Song Dynasty architectural polychromy that integrates visualization, interactivity, and extensibility. The system is designed with a standardized RESTful API and secured by a token-based access control mechanism to ensure safe, cross-platform invocation and deployment of pattern images. The frontend interface, developed with the Vue 3 framework, provides an intuitive user experience and features a multimodal control panel—including color selection, pattern density adjustment, rotation angle control, and aspect ratio modification. Users can generate patterns interactively via sliders and preset options, with real-time visualization of the results. Additionally, the system incorporates an auto-completion module for prompt formulation and a semantic analysis engine, markedly enhancing the model’s capacity to interpret and execute natural language instructions.

To ensure the cultural accuracy and artistic quality of the generated content, the platform incorporates an Active Learning mechanism and an Online Fine-Tuning strategy that automatically adjust model parameters based on user feedback, enabling the generative model to continually evolve and self-adapt. Furthermore, by leveraging LoRA’s multi-dimensional weight fusion capability, the system orchestrates coordinated control over distinct stylistic elements, ensuring that the final outputs retain traditional characteristics while satisfying modern aesthetic standards (Figure 7).

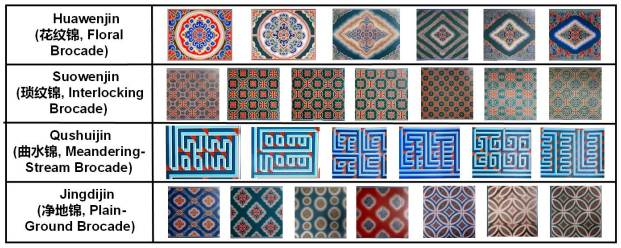

Figure 7. Examples of generated polychromy patterns.

The system has been applied to the Songfeng Caiyun (宋风彩韵, meaning 'Song-style Aesthetic Chroma') online platform, where experimental implementations have been conducted in virtual exhibitions, cultural and creative product design, and interactive experience projects. The generated patterns have demonstrated excellent performance in style simulation, detail fidelity, and user acceptance, fully demonstrating the practical value and developmental potential of AIGC technology in the intelligent redesign of traditional colored paintings.

5. Innovative Design Practices Using Song Dynasty Architectural Polychromy Patterns

After constructing and optimizing an AIGC-based model for redesigning Song Dynasty architectural polychromy patterns, this study explored the model's applicability in practical design scenarios through multi-dimensional and cross-platform innovative design practices. The study examined the model's transformation pathways in education, virtual exhibitions, and cultural and creative development, thereby verifying the effectiveness and feasibility of AIGC generation technology in the digital regeneration, creative redesign, and cross-media communication of traditional architectural polychromy.

5.1 Development of an AIGC-Based Polychromy Learning and Creation Platform

At the educational level, the constructed Songfeng Caiyun (宋风彩韵) intelligent platform establishes an integrated pedagogical workflow that bridges AI-aided design, structural deconstruction, automated generation, and offline manual craftsmanship. The platform combines natural language prompt input with style embedding mechanisms, enabling users to generate personalized Song Dynasty architectural polychromy patterns through keyword-driven interactions.

The platform integrates semantic analysis and cultural gene matching modules to dynamically collect users' multidimensional behavioral data during the creative process. These data are then transformed into structured feedback signals and transmitted in real time to the online fine-tuning module. This approach ensures that generated content retains historical authenticity while achieving high-level aesthetic adaptability and stylistic consistency.

The platform’s design systematically incorporates Song Dynasty aesthetic principles: its interface architecture emulates the layered logic of traditional dougong (斗栱) bracketing systems, while its color synthesis engine reconstructs classical pigment hierarchies, such as vermilion (朱红), cyan-green (青

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绿), and gold-tracing (金 描) palettes. These features collectively enhance user immersion in classical artistry and cultural identification (Figure 8).

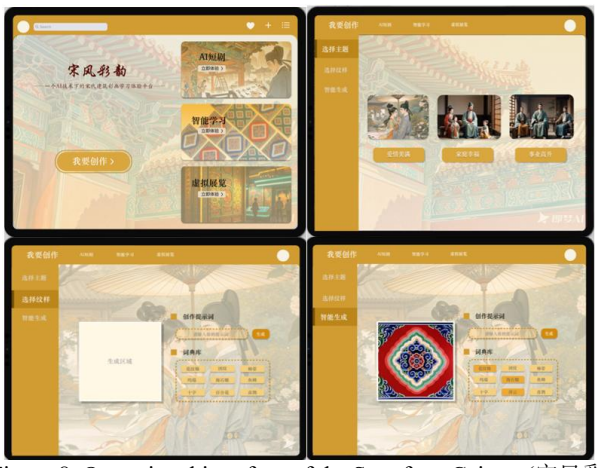

Figure 8. Operational interface of the Songfeng Caiyun (宋风彩韵) intelligent generation platform.

The AI-Assisted Design system supports the generation of complex patterns (e.g., "Tuanke Baozhao (团窠宝照，Roundel Baozhao Motif)—Vermilion Base with Cyan-Green Contour (朱红底 - 青绿轮廓)"). Its comprehensive workflow encompasses semantic keyword parsing, layered motif synthesis, style-transfer-driven parameter tuning, and end-to-end image export for seamless integration into creative applications (Figure 9).

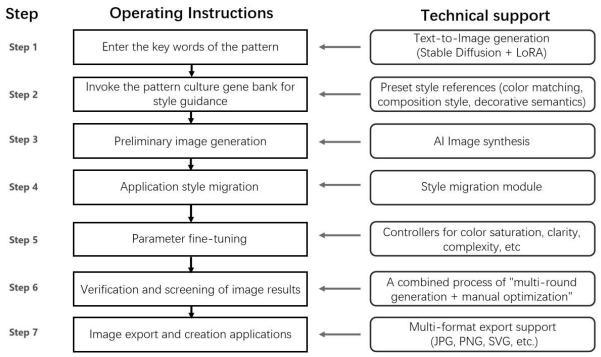

Figure 9. Operation flowchart of the AI-assisted design system.

In addition to these features, the platform integrates an AI-generated short animation module powered by Runway’s video synthesis engine. This module combines virtual character storytelling, animated demonstrations of traditional craftsmanship, and interactive scripting. By embedding virtual representations of Song Dynasty artisans, reconstructions of polychromy production processes, and culturally immersive narrative sequences, the system enables scenario-based experiential learning. Representative works such as A Day as a Craftsman and Memories of Liang and Lin allow users to intuitively explore the historical evolution and technical essence of architectural polychromy (Figures 10 and 11). This approach effectively addresses common challenges in intangible cultural heritage communication—namely, low accessibility, poor memorability, and limited practical relevance.

The platform’s intelligent learning module employs computer vision and deep learning technologies to enhance user understanding, study, and practice of Song Dynasty architectural polychromy. Specifically, it includes:

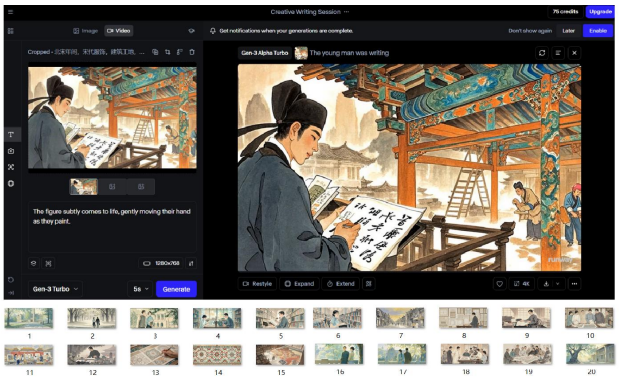

Figure 10. AIGC video generation on the Runway platform.

Figure 11. Video clip of "Memories of Liang and Lin".

①AI-Powered Polychromy Style Recognition: After uploading images, users can rapidly obtain detailed analyses of polychromy categories, historical periods, and technical characteristics, satisfying their cognitive needs during visits to ancient buildings.

②In-Depth Teaching and Interactive Exploration: Combined with AI-generated step-by-step analyses, users can delve into the study of polychromy composition, color matching, and production techniques. Future plans include launching educational games to further enhance learning outcomes through interactive experiences.

③Integration of Knowledge and Practice: Beyond theoretical understanding, users can learn to design and practice polychromy creation. By utilizing AI-generated motifs and traditional toolkits, users are empowered to create their own polychrome artworks on-site. This transition from “AI generation” to “individual creation” significantly enhances user participation and achievement in art education (Figure 12).

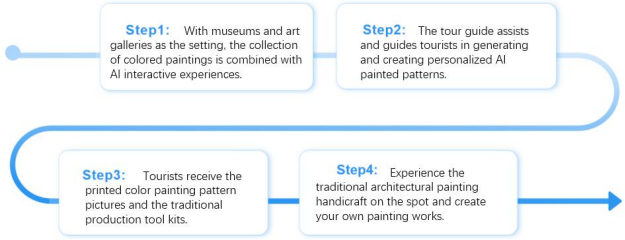

Figure 12. User on-Site polychromy creation experience flowchart.

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5.2 Development of Virtual Exhibition and Interactive Display System

At the interactive communication level, this study developed an immersive virtual exhibition system for Song Dynasty architectural polychromy based on the TouchDesigner platform, aiming to expand the display pathways of AI-generated patterns and enhance their public cultural impact. The system transforms generated motifs into immersive exhibition experiences through 3D puzzle assembly, dynamic layering, real-time color evolution, and gesture-based user interaction. It allows viewers to actively control pattern evolution in real - time, achieving 3D pattern display and interactive communication (Figure 13).

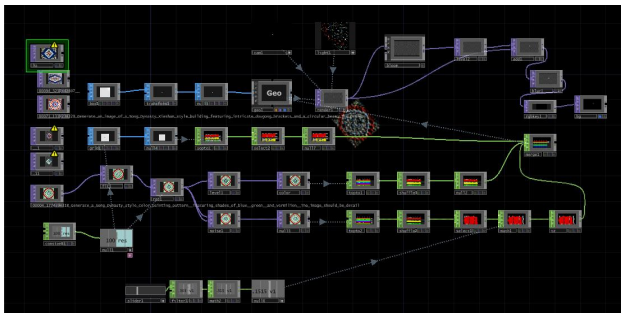

Figure 13. Interactive visualization programming of the "Tuan Ke Bao Zhao" motif using TouchDesigner.

Building on the high-resolution outputs generated by the LoRA model, the system transforms polychromy pattern data into hierarchically structured interactive units. Users can manipulate these pattern elements in real time through gesture-recognition devices such as Leap Motion, enabling operations such as rotation, scaling, and splicing. Additionally, users can mix and recombine components based on individual aesthetic preferences to construct personalized motif compositions.

The system further incorporates a pattern evolution timeline, which visualizes the dynamic development process from “motif initialization” to “element construction,” “border generation,” and “color overlay.” This feature helps users intuitively comprehend the technical logic and cultural semantics underlying Song Dynasty pattern construction.

The system also integrates an online synchronized exhibition interface, which can be embedded into digital museums, virtual galleries, and university teaching platforms. This enables a dual-platform dissemination model that combines physical-space exhibition with digital-space co-creation, thereby expanding the accessibility and cultural influence of Song Dynasty polychromy art and fostering a deeper integration between traditional artistic heritage and emerging media technologies.

5.3 Development of Cultural Creative Product System and Application of Pattern Redesign

At the cultural and creative practice level, the study used generated Song-style polychromy patterns as themes, translating traditional patterns into contemporary visual and consumer contexts through graphic language and cross-media redesign. Following the "from life to culture" concept, high-frequency, strong-medium products like canvas bags and pillows were chosen as carriers, with designs focusing on graphic expression, cultural communication, and functional utility.

The pattern translation process rigorously preserves the symbolic semantics intrinsic to traditional motifs: the Quantou Shidi (圈头柿蒂， Circular-framed Persimmon Calyx motif) pattern embodies auspiciousness, while the Quantou Hezi (圈头合子， Circular Medallion with Ruyi Center), though visually akin to Quantou Shidi, features a central ruyi (如意) petal configuration symbolizing peace, prosperity, and fulfillment. The Tuanke Baozhao (团窠宝照， Roundel Baozhao Motif) further conveys cyclical harmony and perpetual vitality. Through modernized layout composition and functional zoning, the packaging design embodies the refined elegance of Eastern aesthetics while aligning with contemporary users’ aesthetic preferences and usage habits.

Leveraging the unique capabilities of AI-generated patterns, the team established a unified Visual Identity (VI) system to enhance brand recognition within competitive product categories. For example, in scarf and necktie design, the traditional Cusi Qiuwen (簇四球纹, Clustered Four-Ball Motif) was algorithmically extended into a proprietary heraldic emblem representing the brand. The patterns were adapted using the currently popular Morandi color palette, increasing their compatibility with modern aesthetic sensibilities. This approach establishes a distinct visual symbolic system that strengthens consumer memory and fosters a sense of cultural belonging (Figure 14).

Product design emphasized practicality, selecting materials and processes based on structural rationality and functional convenience. For example, in the structural design of stationery sets, biodegradable recycled paper and partitioned card slots are employed, with QR codes linking to original prompts and cultural background information, thereby enhancing the product’s educational and cultural value. The project also developed a “one-object-one-pattern” customization platform, allowing users to generate unique patterns via custom prompts or reference images, and enabling parameterized pattern embedding into clothing, furniture, and spatial decorations through API integration.

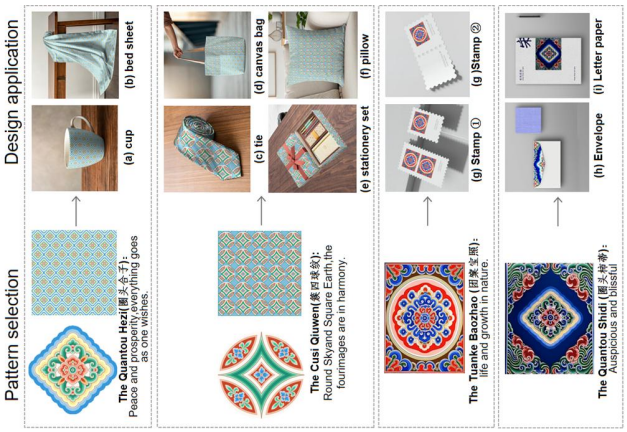

Figure 14. Examples of cultural and creative product design.

In the design process, the product not only preserves the aesthetic characteristics of "regulatory principles and craftsmanship" inherent in Song architectural polychromy but also integrates contemporary color trends and functional design philosophies. This fusion reinvigorates traditional visual language within modern contexts, while establishing replicable technical frameworks and empirical evidence for the "digital revitalization of intangible heritage" and "design-driven heritage preservation" of Song architectural polychromy.

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
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6. Conclusion and Future Directions

This study focuses on Song Dynasty architectural polychromy and proposes an AIGC-based generative design system, validated through a structured analysis of “form–color–meaning,” a high-fidelity pattern dataset, and LoRA-based fine-tuning of Stable Diffusion v3.5, including a human–machine feedback mechanism. The framework integrates semantic labeling, aesthetic evaluation, and weighted loss control to enable high-fidelity reconstruction and semantic generation of representative patterns such as Huawenjin (花纹锦), Suowenjin (琐纹锦), Qushuijin (曲水锦), and Jingdijin (净地锦). A complete pipeline – from static pattern acquisition to dynamic image generation – was implemented using the SD WebUI and TouchDesigner platforms.

At the theoretical level, this study establishes an integrated paradigm of “visual structure–semantic annotation–generative modeling.” This paradigm embeds the cultural codes of Song Dynasty polychromy into the training and inference processes of generative AI, thereby enabling the digital reconstruction of traditional decorative “cultural genes.” At the methodological level, it develops a symbolic modeling framework that combines standardized image acquisition, hierarchical prompting, and lightweight LoRA tuning to achieve a balance between cultural semantics and formal aesthetics. At the practical level, the system has been deployed through the “Songfeng Caiyun” platform and applied in education, immersive exhibitions, and cultural and creative design, shifting architectural polychrome preservation from static display to interactive experience.

While initial results are promising, further work is needed to address challenges in complex composition and semantic depth. Future research will explore the integration of multimodal vision–language models (e.g., BLIP, GIT) and the development of collaborative annotation frameworks with feedback loops, to further enhance the potential of AIGC in digital heritage preservation and creative regeneration.

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