

Programmatic Reconstruction of Suzhou Embroidery Stitches and 3D Design Application for Digital Twin

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Abstract:

As a national-level intangible cultural heritage, Suzhou embroidery is faced with the dilemma of inheritance fault and communication difficulties in the contemporary context. Most existing digital protection methods stay at the level of static image recording, which is difficult to effectively restore its stitch logic and physical characteristics of silk threads. This paper proposes a method for reconstructing Suzhou embroidery techniques oriented to three-dimensional digital applications. Firstly, shape grammar is used to systematically sort out typical Suzhou embroidery patterns, extract and classify feature primitives, and establish a parametric form library. Then, with the node-based workflow of Adobe Substance 3D Designer, core stitches such as plain stitch and sheathed stitch are transformed into adjustable programmatic algorithms. Finally, combined with the PBR physical rendering system, the semantic transformation of Suzhou embroidery from two-dimensional patterns to three-dimensional digital assets is realized, and application verification is completed in digital fashion design. The research shows that the programmatic technical path can not only restore the visual characteristics and silk texture of Suzhou embroidery with high precision, but also endow traditional patterns with sustainable regenerative capacity through parametric means, providing a referable systematic solution for the digital protection and living inheritance of intangible cultural heritage handicrafts.

Keywords:

Suzhou Embroidery Digitalization; Programmatic Modeling; Intangible Cultural Heritage Protection; Pbr Materials; Shape Grammar

1. Introduction

Suzhou embroidery, originating from Suzhou, is known as one of China's "Four Famous Embroideries" together with Cantonese embroidery, Hunan embroidery and Sichuan embroidery. It was included in the first batch of national-level intangible cultural heritage lists in 2006. It takes "flatness, neatness, fineness, density, evenness, smoothness, harmony and luster" as aesthetic standards, covering themes such as flowers, birds, landscapes, figures and allusions [1]. It flourished especially in court costumes of the Qing Dynasty, representing the highest achievement of traditional Chinese embroidery craftsmanship.

However, the contemporary inheritance of Suzhou embroidery is confronted with practical dilemmas: the acquisition of core techniques highly relies on personal instruction and hands-on demonstration from masters to apprentices with a long learning cycle; most existing digital works only stay in static photo archiving, which can neither restore the undulating texture and silky luster of embroidery threads, nor systematically express the stitch logic, nor facilitate lightweight communication and interactive display on the Web.

With the increasing maturity of digital twin, programmatic generation and physical rendering technologies, the digitalization of intangible cultural heritage has the technical conditions to leap from “visual reproduction” to “logical reconstruction”. Focusing on the programmatic reconstruction of Suzhou embroidery techniques, this paper parses pattern structures through shape grammar, simulates stitch rules through node programming, restores silk texture with the PBR material system, and finally applies digital achievements to three-dimensional fashion design, exploring a feasible path for the living inheritance and cross-border application of Suzhou embroidery in the digital space.

2. Historical Evolution and Artistic Characteristics

Suzhou embroidery originated in the Wu and Yue regions, and continued to evolve through the Song, Yuan, Ming and Qing dynasties, reaching its artistic peak under the promotion of the royal family in the Qing Dynasty. Suzhou embroidery in the Qing Dynasty was widely used in dragon robes, court utensils and noble costumes. Embroidery craftsmen continuously improved their techniques under the strict royal standards, making Suzhou embroidery in this period perfect in stitch types, color systems and pattern design.

The aesthetic characteristics of Suzhou embroidery are summarized by eight characters: “flat, neat, fine, dense, even, smooth, harmonious and lustrous”, which is not only a technical requirement for the accuracy of stitch arrangement, but also an aesthetic standard for the overall visual presentation. The natural luster of silk threads refracts through different stitch directions, forming a unique anisotropic reflection effect, which is an important visual marker distinguishing Suzhou embroidery from other embroidery types.

Suzhou embroidery creation follows the philosophy of “learning from nature”, and is good at transforming natural ecology into pattern language. It has a wide range of themes with both narrative and decorative properties: floral patterns express emotions through objects, animal patterns carry auspicious meanings, figure themes integrate historical allusions and opera stories, and landscape themes present the artistic conception of literati paintings, forming a complete visual coding system.

2.1. Analysis of Main Stitches

Suzhou embroidery has a wide variety of stitches with different functions. Plain stitch (uniform stitch) is the most basic stitch of Suzhou embroidery, including three variants: straight plain stitch, horizontal plain stitch and oblique plain stitch, distinguished by needle movement direction [2]. Plain stitch requires neat stitch arrangement, with needle entry and exit points within the pattern range, and embroidery threads shall not overlap or expose the base fabric. Large-area plain stitch filling is called “spread embroidery”, which is often used as the base layer for other stitches. Due to its strong regularity, plain stitch is the most suitable basic stitch for

programmatic parametric modeling. Sheathed stitch realizes natural color gradient transition through nested multi-row stitches, and is often used for subjects requiring layered sense such as petals and feathers. The digital simulation of its gradient effect is one of the key research directions of this study. Random stitch expresses rich light and dark relations with crossed and overlapping stitches, influenced by Western realistic painting, and is mostly used in realistic embroidery and painted embroidery to pursue three-dimensional visual effects, which is an important embodiment of the integration of Chinese and Western techniques in Suzhou embroidery in the Qing Dynasty. Special stitches such as scale engraving stitch and grabbing stitch are used for fine depiction of specific pattern parts, such as fish scales, wings and other details [3].

2.2. Classification of Pattern Themes

The themes of Suzhou embroidery in the Qing Dynasty can be divided into four categories: floral themes represented by peony, lotus, plum, orchid, bamboo and chrysanthemum, with patterns mostly radial or rotationally symmetric, suitable for parametric expansion after primitive extraction; animal themes such as dragon, phoenix, qilin and crane, with smooth lines and clear skeleton structure, convenient for three-dimensional processing; figure themes mainly based on historical allusions and opera stories, with painted embroidery focusing on freehand brushwork and realistic embroidery pursuing realism, both representing different interpretations of traditional painting spirit by Suzhou embroidery; landscape themes drawing on the composition of literati paintings, presenting spatial hierarchy through well-spaced stitch arrangement.

3. Limitations of Existing Protection Methods

Traditional protection methods of Suzhou embroidery are mainly physical collection and image recording, with obvious limitations [4]: first, two-dimensional photos cannot capture the anisotropic luster changes of embroidery threads caused by different stitch directions; second, static archive records are difficult to convey the internal logic of stitch arrangement, and non-professionals cannot acquire technical knowledge from images; third, high-resolution image files are bulky, leading to low transmission efficiency on mobile and Web terminals.

The root cause of the above problems is that the existing digitalization only stays at the level of “visual retention” and fails to touch the “craftsmanship logic” of Suzhou embroidery. The knowledge system constituting the core of Suzhou embroidery techniques, such as stitch arrangement rules, physical properties of embroidery threads and pattern generation grammar, has not been effectively digitally expressed.

3.1. Technical Feasibility of Programmatic Reconstruction

The maturity of digital twin and programmatic generation technologies provides practical conditions for solving the above problems. Node-based programmatic modeling platforms such as Adobe Substance 3D Designer allow designers to transform complex craftsmanship experience into adjustable algorithm parameters; the PBR (Physically Based Rendering) material system can accurately simulate the optical physical properties of silk threads; normal mapping and height mapping technologies can restore high-precision surface details on lightweight models, effectively solving the contradiction between model volume and rendering quality. The combination of the three makes it possible to transform Suzhou embroidery from

a “pixel set” into three-dimensional digital assets with thickness, luster and physical characteristics [5].

3.2. Core Value of Digital Inheritance

The programmatic digital reconstruction of Suzhou embroidery is valuable not only at the technical level, but also in the substantial promotion of three dimensions: lowering creation barriers, expanding application scenarios and constructing knowledge systems.

The learning of traditional Suzhou embroidery requires years or even decades of professional training, while programmatic smart material balls allow designers to change stitch density, color schemes and silk texture in real time by adjusting parameters, enabling designers with cross-disciplinary backgrounds to create and explore within the framework of Suzhou embroidery language, effectively expanding the participating groups of Suzhou embroidery art. Digital Suzhou embroidery assets can be directly applied to emerging scenarios such as digital clothing, virtual fashion, web interactive design and online virtual exhibitions, breaking through the physical constraints of physical embroidery products in material loss, space limitations and communication scope, and realizing cross-regional and cross-media cultural communication. By solidifying stitch logic and pattern generation rules through algorithm models, perceptual manual experience is transformed into a researchable, testable and sustainable knowledge structure, providing a new entry point for interdisciplinary research of art [6], design and computer science, and fundamentally promoting the transformation of intangible heritage inheritance from “human memory” to “systematic knowledge”.

4. Digital Implementation Path of Suzhou Embroidery

The technical implementation of this study is divided into three progressive links: pattern deconstruction and primitive library construction, programmatic stitch reconstruction, cross-platform rendering and application, corresponding to the complete workflow of “analysis-modeling-output”.

4.1. Pattern Deconstruction and Parametric Primitive Construction

The starting point of digital transformation is the structural analysis of traditional patterns. This study introduces Shape Grammar as an analysis tool to systematically disassemble typical Suzhou embroidery patterns such as peony, phoenix and lotus, and identify their constituent units, combination rules and transformation logic.

Specifically, taking the peony pattern as an example, its primitives can be decomposed into: petal arc contours (mainly S-curves), petal stacking relations (rotational symmetry with decreasing layers), and stamen filling mode (radial dense arrangement). By quantifying the geometric parameters (curvature, rotation angle, scaling ratio, repetition times) of each type of primitive, a parametric adjustable primitive library is established, laying a logical foundation for the subsequent programmatic laying on digital fabrics.

The establishment of the primitive library follows two principles: first, coverage, trying to cover the core visual units of the main themes of Suzhou embroidery in the Qing Dynasty; second, composability, each primitive should have interface specifications for splicing with other primitives to support the algorithmic generation of new patterns. In the node workflow of Adobe Substance 3D Designer, the above

primitives are solidified in the form of Shape nodes and Transform nodes, forming reusable parametric modules.

4.2. Programmatic Stitch Reconstruction Based on Node Programming

Stitch reconstruction is the technical core of this study. Its goal is not to generate approximate visual effects, but to build a material model with correct optical properties based on the physical logic of stitches [7].

4.3. Parametric Generation of Embroidery Thread Units

The visual characteristics of a single embroidery thread include the rounded volume of the cross-section and the fibrous gradient texture of the surface. In Substance 3D Designer, the Capsule shape node is used to construct the cross-section model of a single silk thread; the Levels node is used to control the dynamic range of height information, simulating the three-dimensional form of the embroidery thread with a raised center and narrowed sides on both sides; the Gradient Linear node is used to superimpose the color gradient along the fiber direction, restoring the unique luster transition effect of natural silk fibers [8].

The above parameters are set as externally adjustable, so that designers can modify the embroidery thread thickness, cross-section curvature and fiber texture in real time in the final material ball without going deep into the node interior.

4.4. Topological Simulation of Plain Stitch Arrangement

Plain stitch is the basic stitch of Suzhou embroidery, and its digital simulation needs to restore the overall order of stitch arrangement and slight randomness at the micro level. The Tile Sampler node is used to arrange embroidery thread units in a matrix, and the X/Y density parameters are adjusted to control the stitch spacing; the Rotation parameter is used to set the uniform direction of embroidery threads, simulating three variants of straight plain stitch, horizontal plain stitch and oblique plain stitch; on this basis, controllable random disturbances are introduced to the arrangement density and rotation angle, and the Luminance Random parameter is used to control the brightness difference between units, so that the final effect retains a sense of handcraft in the overall neatness and avoids the mechanical uniformity unique to computer-generated graphics as shown in Figure 1.

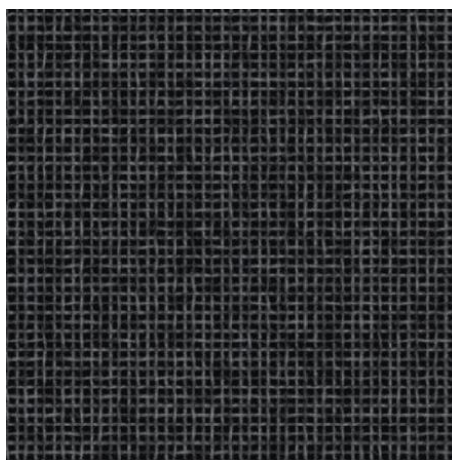


Figure 1. Tile Diagram.

The simulation of sheathed stitch adds multi-layer offset stacking on the basis of plain stitch, and realizes the gradient blending effect by adjusting the color range and transparency mixing of each layer. Its mathematical expression is as follows:

$$C_{\text{final}} = \alpha \cdot C_{\text{warp}} + (1 - \alpha) \cdot C_{\text{weft}}$$

Where α is the mixing weight coefficient and C represents the color channel value of the corresponding layer.

4.5. Topological Simulation of Plain Stitch Arrangement

The core visual feature of Suzhou embroidery silk threads is anisotropic reflection. The luster performance along the embroidery thread direction and perpendicular to the embroidery thread direction is completely different, which makes the Suzhou embroidery surface present rich shimmer changes under different light angles.

To restore this feature, the Directional Blur node is used to directionally process the noise information in the normal map, so that the spatial distribution of roughness is consistent with the embroidery thread direction; in the PBR output channel, precise mapping is performed on the Roughness and Metallic channels respectively, and the moderate activation of the Metallic channel can effectively enhance the unique luster depth of silk, simulating the shimmer effect of real silk threads under dynamic light sources as shown in Figure 2.



Figure 2. 3D rendered image.

4.6. Topological Simulation of Plain Stitch Arrangement

After the stitch material is completed, it needs to be loaded on the three-dimensional clothing model to complete the overall digital effect. Firstly, the basic three-dimensional clothing model is constructed in Maya, focusing on the surface topology of the clothing area covered with Suzhou embroidery patterns to ensure the accurate pattern proportion after UV expansion; then, UV splitting and texture baking are completed in Adobe Substance 3D Painter, generating a complete PBR texture sequence including ambient occlusion map, normal map and base color map; finally, the texture sequence is imported back to the model[9], and a multi-light source scene is configured in Marmoset Toolbag for final rendering to verify the visual performance of Suzhou embroidery patterns under dynamic lighting as shown in Figure 3.

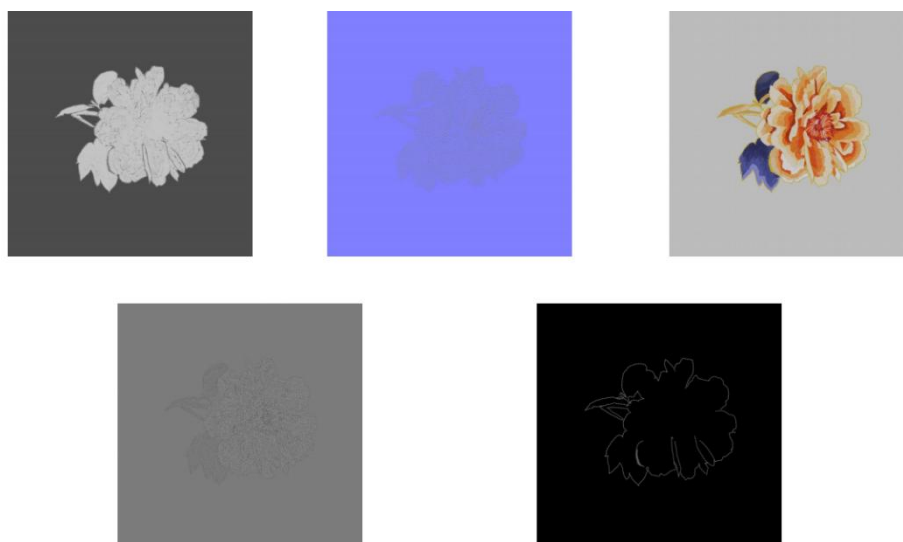


Figure 3. *PBR texture sequence.*

For the three-dimensional texture demand of Suzhou embroidery patterns, normal map and Displacement Map are used cooperatively. The normal map is responsible for the lighting direction information of the embroidery thread cross-section, and the displacement map is responsible for the geometric deformation of the embroidery thread higher than the base fabric. The superposition of the two can restore high-precision three-dimensional embroidery texture on low-polygon models .

4.7. Topological Simulation of Plain Stitch Arrangement

In Adobe Substance 3D Designer, the above stitch reconstruction node network is integrated into a set of Smart Material with a unified parameter interface. Designers can quickly switch stitch styles by adjusting core parameters without touching the interior of the nodes.

Parametric material balls significantly improve the design efficiency of Suzhou embroidery patterns. Effects that need to be adjusted by changing threads and stitches in traditional embroidery can be previewed in real time and parameter snapshots recorded at the digital end, greatly reducing the technical barrier for cross-border designers.

4.8. Topological Simulation of Plain Stitch Arrangement

The carrying of high-fidelity three-dimensional assets on the Web side is a practical bottleneck for the digital communication of Suzhou embroidery. This study adopts the strategy of “low model + high-precision texture” to solve this contradiction:

At the model level, the number of geometric faces is compressed as much as possible, and the morphological details are transferred to the texture layer; at the texture level, formats such as mview are used for encapsulation and compression under the premise of ensuring resolution; at the rendering level, a simplified multi-light source scheme is configured on the Web side, and AO maps are used to make up for the lack of real-time lighting and maintain the visual hierarchy s shown in Figure 4.



Figure 4. *MVIEW file rendering.*

After the above optimization, the model file size can be controlled within the acceptable range of the Web side, while retaining the three-dimensional sense of Suzhou embroidery texture and silk luster, realizing efficient communication of intangible heritage content on mobile and web terminals.

5. Conclusions

This paper focuses on the core issue of programmatic reconstruction of Suzhou embroidery stitches, and systematically explores the complete digital path from pattern deconstruction to three-dimensional application. The main conclusions of the research are as follows:

First, shape grammar can effectively support the structural analysis of Suzhou embroidery patterns, and the extracted parametric primitives have composability and scalability, laying a logical foundation for the algorithmic generation of patterns;

Second, the node programming-based stitch reconstruction scheme can restore the arrangement rules of core stitches such as plain stitch and sheathed stitch at the physical logic level, and combined with the PBR material system, it can accurately simulate the anisotropic luster characteristics of silk;

Third, the lightweight strategy of “low model + high-precision texture” effectively balances the contradiction between rendering quality and Web-side carrying capacity, providing a feasible solution for cross-platform communication of digital Suzhou embroidery assets.

Existing research still needs to be expanded. At present, programmatic materials are still insufficient in expressing complex stitches, and some manual technical details are difficult to be fully parameterized; in addition, the reverse transformation path from digital achievements to physical embroidery production has not been deeply discussed[10]. Future research can be further promoted in the directions of stitch algorithm optimization, 3D printing-assisted embroidery design and virtual reality interactive display, so as to promote the digital protection of Suzhou embroidery intangible heritage to a more complete and sustainable development form.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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Author Contributions

Conceptualization: Qi Xia, Xinyue Zhang; Methodology: Qi Xia; Software: Qi Xia; Validation: Qi Xia, Xinyue Zhang; Formal analysis: Qi Xia; Investigation: Xinyue Zhang; Resources: Qi Xia, Xinyue Zhang; Data Curation: Qi Xia; Writing – original draft preparation: Qi Xia, Xinyue Zhang; Writing – review and editing: Qi Xia; Visualization: Xinyue Zhang; Supervision: Qi Xia, Xinyue Zhang.; Project administration: Xinyue Zhang; Funding acquisition: Qi Xia.

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