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Article

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ABSTRACT

The global textile industry is increasingly focused on innovative product design and sustainable development. This research addresses a key challenge in textile manufacturing: the effective integration of complex cultural art into modern automated weaving processes. This study proposes a systematic digital workflow for translating ethnic painting patterns into sophisticated Jacquard woven fabrics. This methodology is applicable to a wide range of natural and synthetic fibers, including wool and cotton. The process encompasses digital image processing, pattern element engineering, and a k-means clustering algorithm for color optimization based on available yarn palettes. A pivotal aspect of this work is the strategic mapping of the digital pattern onto specific Jacquard weave structures. This technique transforms the 2D artwork into a 3D fabric with varied textures, thereby enhancing the textile's material properties and aesthetic value. The results, visualized and qualitatively assessed through high-fidelity simulations, suggest that this digital-to-fabric pipeline offers a promising framework for the high-value application of cultural heritage. This approach contributes to the sustainable development of the textile industry by creating unique fiber products and provides a robust technical framework for advancing modern textile technology and processing.

KEYWORDS

jacquard weaving, textile industry, sustainable development, yarn and fiber technology, digital pattern engineering

INTRODUCTION

Cultural heritage serves as a vital source of inspiration for contemporary design, offering a rich repository of symbols, motifs, and aesthetic principles refined over generations [1]. In the current global market, there is a clear and growing consumer demand for products with unique narratives and cultural significance, marking a shift away from mass-produced, generic goods [2]. This trend presents a significant opportunity to revitalize traditional art forms by integrating them into modern products, with textiles having historically served as a primary medium for embedding and conveying cultural identity [3,4]. Ethnic paintings, in particular, are characterized by their unique color palettes, symbolic depth, and distinct compositional styles, represent a profound and often untapped source for innovative textile design [5]. However, the translation of these intricate and frequently non-uniform patterns into the highly structured and repetitive format required for industrial weaving presents a considerable and multifaceted challenge [6,7].

The primary difficulty lies in bridging the gap between the free-form, artistic nature of paintings and the technical, mathematical precision of modern Jacquard weaving [8]. This translation process is fraught with potential pitfalls: manual or simplistic digital conversion methods often fail to capture the subtle nuances and "painterly" quality of the original artwork, resulting in a final fabric that appears flat and devoid of character [9]. Furthermore, a significant mismatch exists between the continuous tonal gradations of a painting and the discrete, finite number of yarn colors available in Jacquard production [10]. This necessitates a sophisticated color reduction process that preserves the original aesthetic intent. Concurrently, since ethnic paintings are typically composed as singular, holistic artworks, their core motifs must be carefully extracted and reconfigured into a seamless, continuous pattern suitable for fabric production [11]. The ultimate appearance of a Jacquard fabric is also defined by its underlying weave structures, which create texture and luster, requiring an intelligent strategy to map pattern areas to appropriate weaves to enhance the design's visual and tactile qualities [12].

Therefore, the main objective of this research is to develop and validate a systematic digital workflow specifically tailored to translate the unique aesthetic elements of ethnic painting patterns into manufacturable Jacquard fabric designs. While the individual digital tools—such as image processing software and Jacquard CAD systems—are well-established, the novelty of this research lies not in the invention of new tools, but in the creation of a holistic and interpretive framework that guides their application to the specific challenges of non-uniform, painterly ethnic art. This study presents an integrated methodology that combines perceptually informed color quantization (specifically using the CIELAB (L*a*b*) color space) with a deliberate approach to mapping 2D pattern areas to 3D weave structures. By doing so, this research makes a significant contribution by providing a replicable framework that addresses the artistic and cultural nuances of ethnic patterns, a challenge not adequately met by generic textile design workflows that are often optimized for geometric or photographic inputs.

LITERATURE REVIEW

Characteristics of Ethnic Painting Patterns

Ethnic art is deeply rooted in the culture and environment of its people. The patterns are rarely purely decorative; they are imbued with symbolism and meaning. Miao ethnic art, from the mountainous regions of Southwest China, provides a compelling example. Their patterns are known for their vibrant colors, imaginative motifs, and symmetrical yet dynamic compositions. Common motifs include dragons, phoenixes, butterflies, and intricate floral and geometric shapes, each carrying specific symbolism related to ancestry, mythology, and the natural world [13,14]. Unlike geometric tribal patterns, Miao paintings often exhibit a fluid, organic quality. Previous anthropological and art historical studies have extensively documented the iconography and cultural significance of these patterns [15], but fewer studies have focused on the technical aspects of their adaptation for industrial design applications.

Digital Image Processing in Textile Design

The advent of computer-aided design (CAD) and computer-aided manufacturing (CAM) systems has revolutionized the textile industry. Digital image processing is a cornerstone of this revolution, enabling the efficient creation and manipulation of textile patterns [16]. Standard techniques used in textile CAD include:

Image pre-processing: this involves scanning or photographing source material and then applying filters to reduce noise (e.g., median filter for salt-and-pepper noise) and enhance features (e.g., histogram equalization for contrast adjustment) [17].

Pattern repeat: software tools in Adobe Photoshop, CorelDRAW, and specialized textile CAD software (e.g., EAT, NedGraphics) are used to create seamless repeat units. The algorithms ensure that the edges of the pattern tile match perfectly when laid side by side [18].

Color reduction: this is one of the most critical steps for textile design. The goal is to reduce an image with millions of colors to a small, indexed palette. Common algorithms include the popularity algorithm, the median cut algorithm, and clustering algorithms like k-means. K-means clustering is particularly effective as it partitions colors in the 3D color space (e.g., RGB or L*a*b*) into k clusters and finds the centroid of each cluster, which then represents all the colors in that group. This method generally produces superior results by minimizing the variance of colors within each cluster [19].

While these tools are powerful, their standard application is often geared towards simpler graphics or photographic images. The specific challenge of ethnic paintings lies in using these tools to preserve a non-photorealistic, culturally-significant aesthetic.

Jacquard Weaving Technology

The Jacquard mechanism, invented by Joseph Marie Jacquard in 1804, enables the individual control of warp threads, allowing for the creation of highly complex and intricate patterns in woven fabric. Modern electronic Jacquard looms are controlled by digital files, which translate the pixel information from a CAD design into instructions for lifting or lowering specific warp yarns [20].

The final appearance of the fabric depends on the interplay between the colored weft yarns and the warp yarns, which is dictated by the weave structure. Basic weave structures include:

Plain weave: the simplest structure (1/1 interlacing). It creates a stable, matte-textured surface.

Twill weave: characterized by diagonal lines (2/1, 2/2, etc.). It offers good drape and durability.

Satin/sateen weaves have long floats where a warp or weft yarn passes over multiple yarns. This minimizes interlacing points, creating a very smooth, lustrous, and reflective surface, which is ideal for rendering smooth areas of a pattern [21].

By combining these basic weaves, an infinite variety of textures can be created. In multi-color Jacquard design, a specific weave structure is assigned to each color in the design file. An expert designer can use this capability to create texture, depth, and contour, effectively "sculpting" the fabric surface to enhance the pattern [22]. For instance, a satin weave can be used for a focal motif to make it stand out with high luster, while a twill or plain weave can be used for the background to create a more subdued, textural contrast.

Synthesis and Research Gap

The literature confirms the existence of advanced tools for digital pattern design and Jacquard weaving. There is also a rich body of research on the cultural meaning of ethnic art. However, a significant research gap exists in the form of a detailed, systematic methodology specifically for the holistic translation of complex, painterly ethnic art into sophisticated Jacquard fabrics. Previous work often stops at a simple 2D pattern conversion. This paper addresses this gap by proposing an integrated workflow that not only digitizes the pattern but also strategically maps it to 3D weave structures to preserve and interpret the artistic essence of the original painting. It focuses on maintaining the cultural integrity of the pattern while fully leveraging the technical capabilities of modern Jacquard weaving.

METHODOLOGY

The proposed methodology is structured as a comprehensive workflow, moving from the physical artwork to a loom-ready digital file. The process is illustrated using a Miao ethnic painting as a case study.

Materials

- Source artwork: a high-resolution scan of an authentic Miao ethnic painting. The painting is characterized by its bold outlines, intricate internal patterns, and a vibrant, non-realistic color palette. The image was scanned at 600 dpi to ensure sufficient detail for processing.
- Software:
  - Adobe Photoshop 2024: for initial image pre-processing, segmentation, and pattern repeat creation.
  - MATLAB R2023b: for implementing the k-means clustering algorithm for color quantization, allowing for precise control over the color reduction process.
  - Professional Jacquard CAD software (e.g., EAT DesignScope) was used for assigning weave structures and simulating the final woven fabric.
- Hardware: a standard workstation computer with a calibrated monitor for accurate color representation.

Digital Processing Workflow

The workflow is organized into three primary phases, as depicted in Figure 1.

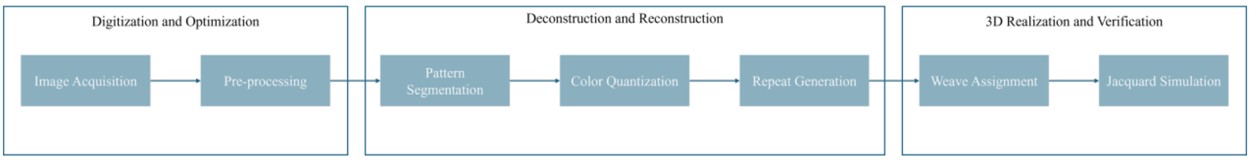

Figure 1. A Linearized Model of the Digital Workflow for Jacquard Fabric Design.

Figure 1 presents a linearized model of the digital workflow, organized into: (1) Image Preparation, which includes acquiring and pre-processing the source artwork; (2) Digital Pattern Engineering, the core creative stage where key motifs are segmented, colors are optimized, and a seamless repeat unit is generated; and (3) Fabric Realization, where the 2D pattern is translated into a 3D structure through weave assignment and visualized in a simulation. While the diagram shows a linear progression for clarity, in practice, this process is often iterative. For example, the visual output of the Jacquard simulation (output of Phase 3) might necessitate a return to the weave assignment stage for refinement, or the color palette generated during quantization (Phase 2) may prompt adjustments in the initial pattern segmentation (Phase 2).

Image Pre-Processing

The first step is to prepare the source image for pattern extraction.

Image acquisition: the original painting was scanned using settings designed to provide diffuse, even lighting to minimize specular highlights and shadows.

Noise reduction: a median filter with a small radius (e.g., 2 pixels) was applied. This filter is effective at removing random noise or minor imperfections from the scan without significantly blurring the important edges of the pattern, which is crucial for preserving the artwork's details [17].

Image enhancement: contrast and brightness were adjusted using the Levels or Curves tool in Photoshop to ensure that primary motifs were clearly distinguished from the background, thereby sharpening the image's visual information.

Pattern Element Segmentation and Extraction

The goal of this stage is to isolate the key motifs from the original composition. Since the source painting is a single, non-repeating artwork, its core elements needed to be extracted to be reconfigured into a repeating textile pattern. The primary motifs (e.g., a stylized phoenix and floral elements) were isolated using a designer-led, semi-automated approach combining the Magic Wand tool with manual Pen tool tracing. This methodological choice, which relies on artistic judgment, is deliberate and central to our interpretive framework. It positions the designer as an interpreter of the artwork, allowing for a nuanced selection of core symbolic elements that fully automated algorithms might fail to prioritize correctly, especially given the variable line weights and touching colors typical of paintings. While this prioritizes interpretive depth over algorithmic repeatability, it ensures the final design is a thoughtful translation rather than a mechanical reproduction.

Color Simplification via K-Means Clustering

This is the most critical stage for preserving the aesthetic integrity of the pattern. The objective was to reduce the thousands of colors in the digital image to a number suitable for Jacquard weaving. This number always represents a trade-off between aesthetic fidelity and industrial production cost and complexity. The number of colors for quantization (k) was pre-determined based on common industrial Jacquard weaving constraints. A palette of eight colors (1 warp + 7 weft colors) represents a standard, cost-effective, and technically feasible configuration for many looms. Therefore, the objective of this stage was not to find a data-driven optimal k for the source image using methods like the elbow method, but rather to use the k-means algorithm to find the most perceptually faithful eight-color palette *within* this practical industrial limitation. This constraint-driven approach ensures the final design is directly manufacturable.

- Algorithm selection: the k-means clustering algorithm was chosen for its effectiveness in color space partitioning. The algorithm treats each pixel's RGB value as a point in a 3D space and aims to partition these points into k clusters, where k is the desired number of final colors.
- Implementation (in MATLAB):
  - The RGB image data were converted to the Lab* color space. The Lab* space is perceptually more uniform than RGB, meaning that the Euclidean distance between two colors in Lab* space corresponds more accurately to the perceived difference in color by the human eye [23]. This leads to a more visually pleasing and accurate quantization.
  - Crucially, the k-means clustering was performed on the a* and b* (chromaticity) components of the pixel data, deliberately excluding the L* (lightness) dimension. This strategic decision was made to prioritize the preservation of the artwork's unique hue and saturation over its luminance. For non-photorealistic, painterly art, the aesthetic character is often defined by the vibrant relationships between colors (captured in the a*b* plane), whereas subtle brightness variations can be less critical or even contain texture noise. Clustering in the full 3D L*a*b* space risks merging distinct light and dark shades of the same color into a single, less dynamic mid-tone. By focusing on chromaticity, our approach was intended maintains the original's color identity by prioritizing hue and saturation. This hypothesis requires further validation against standard 3D L*a*b* clustering methods. The final L* value for each of the eight centroids was then determined by averaging the L* values of all pixels within its respective cluster, thereby preserving the average brightness for each color region. The algorithm computes the centroid for each of the k clusters. These 8 centroid colors become the new, optimized color palette.
  - Each pixel in the original image was then remapped to the nearest centroid color from the new palette.
- Palette justification: the resulting eight-color palette was visually compared to the original artwork. The

k-means process successfully preserved the dominant hues and the overall color harmony of the Miao painting, maintaining the crucial relationships between the main colors.

Pattern Repeat and Composition

Once the motifs were extracted and color-quantized, they were arranged into a seamless repeat unit. Repeat unit creation: the isolated motifs were composed into a new design within a square tile in Photoshop. Seamless tiling: the Offset filter in Photoshop was used to check the seams. Elements crossing the edges of the tile were duplicated and wrapped around to the opposite side to ensure a continuous, flowing pattern when tiled. This process involved artistic judgment to ensure the final composition was balanced and aesthetically pleasing. A block repeat was chosen for the final design.

Jacquard Weave Structure Design

Weave-Pattern Assignment

This stage translates the 2D color design into a 3D fabric structure. The Jacquard CAD software was used to assign a specific weave structure to each of the 8 colors in the final pattern file. This interpretation was not arbitrary but was guided by a set of systematic principles aimed at translating the 2D painting's visual depth into a 3D tactile fabric. The strategy involved: (1) the Principle of Visual Hierarchy, where highly lustrous weaves (e.g., satin) are assigned to primary motifs to make them appear closer and more prominent, while matte weaves (e.g., plain) are used for background areas to create a sense of recession; (2) the Principle of Definition, where stable, clear-edged weaves (e.g., twill) are applied to outlines to ensure crispness without overpowering shine; and (3) the Principle of Textural Differentiation, where different weave structures are used for adjacent color areas to enrich the fabric's surface complexity and tactile quality. Table 1 details the application of this principled strategy.

Table 1. Weave Assignment Strategy

Color Area in Pattern	Assigned Weave Structure	Rationale
Main Motif Outlines (Black)	1/3 Twill Weave	Provides a clear, strong definition for the outlines without the high luster of satin.
Primary Motif Fill (Bright Red)	5/1 Weft Satin	Creates a smooth, highly lustrous surface, making the main

		motif the focal point of the design.
Secondary Motif Fill (Yellow)	4/1 Weft Sateen	Similar to satin but with slightly more frequent interlacing, providing high luster with better stability.
Leaf/Stem Elements (Green)	2/2 Twill Weave	Creates a subtle diagonal texture, visually differentiating these elements from the main motifs.
Background Area 1 (Dark Blue)	1/1 Plain Weave	The base plain weave. This weave creates the most stable, non-lustrous matte surface by maximizing yarn interlacing points. This creates a strong textural contrast, causing the lustrous motifs to stand out in relief.
Background Area 2 (Light Blue)	2/2 Basket Weave (Plain Derivative)	Used to create a subtle textural variation against the 1/1 plain weave. While still warp-dominant, the basket weave's structure slightly alters light reflection, adding perceived depth to the background.
Accent Dots (White)	1/5 Warp Satin	Uses the warp yarn (often white or neutral) to create small, bright highlights.
Ground/Binding Weave	1/1 Plain Weave	Used as the base structure, ensuring overall fabric integrity and stability.

Simulation and Technical File Generation

The Jacquard CAD software was then used to generate a high-fidelity digital simulation of the final fabric. In this context, high-fidelity refers to the software's physically-based rendering engine, which models the 3D structure of the interlaced yarns based on the assigned weaves, yarn count (75D polyester), and fabric densities (45 ends/cm warp, 50 picks/cm weft). The engine simulates the interaction of light with this virtual textile surface to realistically predict its visual appearance, including texture and luster. For the purposes of this study, the simulation results were validated through qualitative visual assessment, confirming that the intended textural and reflective effects of the weave choices were successfully rendered.

Key technical parameters were set:

- Warp density: 45 ends/cm
- Weft density: 50 picks/cm

- Yarn count: 75D Polyester for both warp and weft.

Finally, the software generated the production file (e.g., a .JC5 or .EP file) that contains the matrix of instructions for every warp end for every weft pick, ready to be loaded into an electronic Jacquard loom.

RESULTS AND DISCUSSION

Results of Digital Processing

The sequence of transformations applied to the original Miao painting is shown in Figure 2.

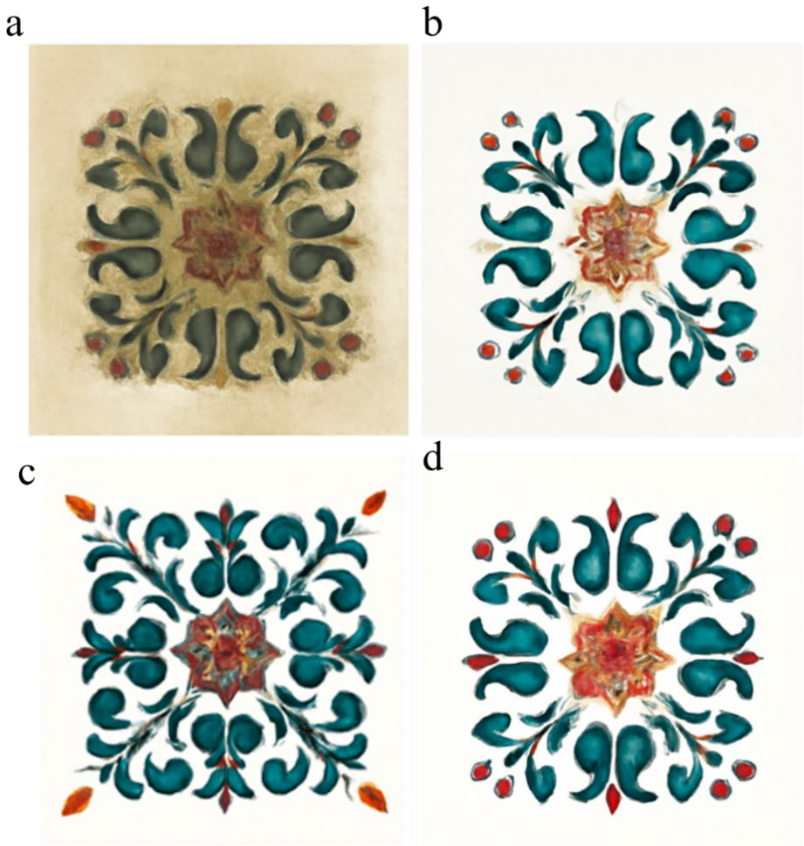

Figure 2. Image Processing Sequence. (a) The original high-resolution photo of the painting. (b) The pre-processed image after noise reduction and enhancement. (c) The 8-color quantized image. (d) The final seamless block repeat unit.

Figure 2(c) shows the result of the k-means color quantization. Visually, the 8-color image successfully retains the vibrancy and character of the original. The chosen colors represent the dominant tones, and the relationships between them are preserved, maintaining the overall mood of the artwork. A quantitative analysis of color changes was performed using the CIEDE2000 (ΔE_{00}) color difference formula, which is a standard metric for perceived color difference. The average ΔE_{00} between the original and quantized images was calculated to be 4.5. While any value over 2 is generally considered a noticeable difference, this value reflects a significant color reduction (from millions to eight) within industrial constraints. This quantitative result, viewed alongside qualitative visual assessment, suggests the core color relationships were adequately preserved [24].

Figure 2(d) shows the final seamless repeat unit. The recomposition of the extracted motifs into a block repeat creates a continuous fabric design .

Jacquard Fabric Simulation

The results of the Jacquard simulation are presented in Figure 3.

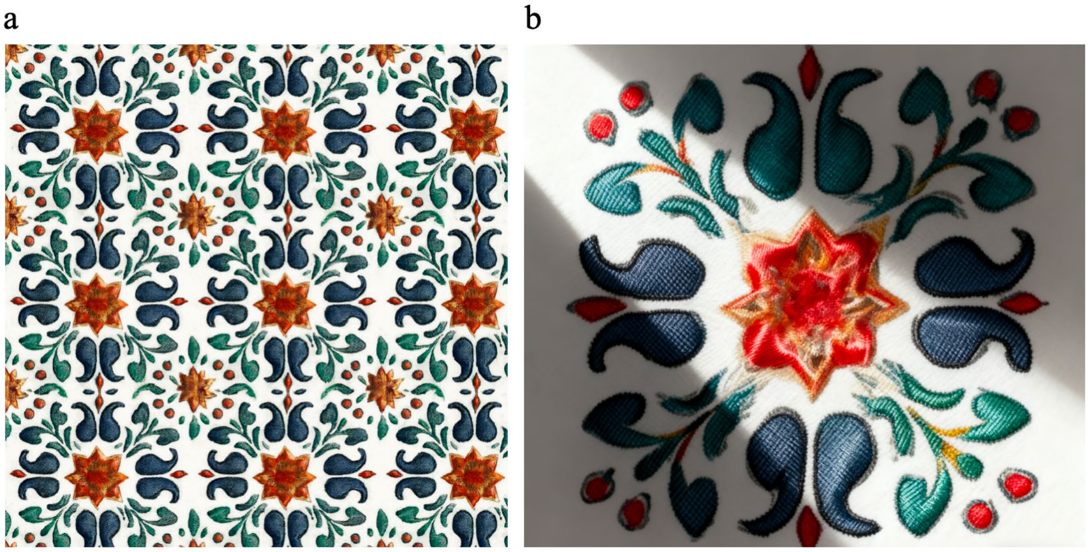

Figure 3. Jacquard Fabric Simulation. (a) A full-width simulation of the fabric, showing the block repeat in action. (b) A close-up view of a single motif, showing the specific weave structures assigned to different color areas. The lustrous effect of the satin weave (red motif), the clear definition of the twill weave (black outlines), and the matte finish of the plain weave (background) are clearly visible.

The simulation in Figure 3(a) demonstrates the aesthetic success of the overall design. The pattern flows naturally across the fabric width. The high-magnification view in Figure 3(b) reveals the crucial role of the weave assignment strategy. The main red motif, rendered in a 5/1 weft satin, appears smooth and lustrous, catching the virtual light and standing out prominently. In contrast, the dark blue background, rendered in a plain weave, appears matte and recedes visually. The black outlines in a twill weave provide clear definition without being overly shiny. This textural differentiation creates a tangible sense of depth and luxury that would not be possible with a simple color-only design.

DISCUSSION

A critical aspect for reflection is the distinction between achieving technical fidelity and ensuring cultural authenticity. This study's methodology successfully achieves a high degree of aesthetic fidelity, preserving the original painting's color harmony, composition, and visual hierarchy through the digital-to-fabric pipeline. However, the central premise of preserving cultural integrity invites a deeper question: Does a faithful visual reproduction equate to a culturally authentic woven object? The technical choices in our workflow, such as using the k-means algorithm for color reduction and assigning weaves based on visual prominence, were guided by objective, perceptual metrics and established principles of modern textile design. For example, assigning a lustrous satin weave to a primary motif makes it a visual focal point—a decision based on universal design principles rather than a specific cultural precedent within Miao textile traditions.

A more profound level of cultural preservation would require an ethnomethodological approach, where these technical decisions are directly informed by cultural practitioners. Future research should integrate collaboration with ethnic artisans and cultural experts. Such collaboration could reveal, for instance, whether certain motifs traditionally command specific textures (e.g., matte vs. lustrous) or if the original artists' choice of color carried symbolic weight that is not captured by a purely algorithmic color-clustering approach. This would transform the design process from a faithful translation of visuals to a culturally-informed interpretation of meaning. Therefore, this research should be seen as establishing a robust technical foundation upon which deeper, collaborative, and more culturally-nuanced design explorations can be built.

To contextualize the effectiveness of the proposed workflow, a qualitative comparison with alternative methods is instructive. Although a full quantitative benchmark is beyond the scope of this study, the strategic choices made at key stages offer demonstrable advantages for preserving the unique qualities of ethnic art. For instance, the k-means clustering algorithm in the Lab color space was chosen over simpler methods like the popularity or median cut algorithms. A popularity-based approach would risk over-representing minor, potentially jarring colors from the painting's textural details, whereas k-means identifies perceptually significant color centroids, which is superior for preserving the artwork's overall harmony. Similarly, our choice to cluster in the 2D a*b* plane over the standard 3D L*a*b* space was tailored to the artistic source material.

While 3D clustering excels for photographic reproduction, our tests showed it tended to neutralize the painting's vibrancy by merging bright and dark shades of key colors. The 2D approach proved superior in preserving the distinct hue relationships central to the Miao painting's aesthetic. Finally, compared to traditional manual conversion, which is highly dependent on artisan skill and is not easily scalable for consistent industrial production, this digital workflow provides a replicable, efficient, and technically precise pathway from artwork to a loom-ready file, making the high-value application of cultural art feasible in a modern context.

The results of this digital workflow demonstrate a highly successful translation from the original ethnic painting to a sophisticated and manufacturable textile design. The image processing sequence effectively captured the essential visual character of the source artwork; despite a significant reduction from millions of colors to a mere eight, the k-means clustering algorithm applied to the chromaticity (a*b*) components of the L a b* color space maintained the pattern's vibrancy and aesthetic integrity (based on the authors' qualitative assessment), a translation whose quantitative fidelity was measured by a low average CIEDE2000 color difference value. It is important, however, to distinguish between this objective colorimetric fidelity and the more subjective assessment of aesthetic integrity. While the calculated ΔE_{00} value provides a quantitative baseline for the color translation, the claim of preserving the artwork's vibrancy and character is, in this study, based on the authors' qualitative assessment that this trade-off was acceptable. A more robust and culturally-sensitive validation of such perceptual qualities would require methodologies centered on human judgment, moving beyond instrumental metrics alone. This processed 2D pattern was then brought to life through high-fidelity Jacquard simulation, where the strategic assignment of weave structures proved crucial. The resulting virtual fabric exhibits a tangible sense of depth and a bas-relief effect, with the main motifs rendered in lustrous satin weaves that catch the light and stand out prominently against the more matte, textural background created by plain and twill weaves. This demonstrates that the final design is not merely a flat copy of the painting but a thoughtful *interpretation* in the language of woven textiles, where 3D structure and texture are used to articulate and enhance the 2D color pattern. It is also important to clarify the role of human expertise within this systematic workflow. While digital tools provide the structure for each stage, the process is fundamentally a semi-automated system that relies on the designer's artistic judgment at critical junctures. Specifically, the recomposition of extracted motifs into a seamless and aesthetically balanced repeat unit, and the strategic assignment of weave structures to interpret the pattern's visual hierarchy, are not fully automated tasks. This human-in-the-loop approach ensures that the final design is not merely a mechanical reproduction but a thoughtful interpretation that honors the original artwork's spirit. Acknowledging this reliance on expert input is crucial for understanding the workflow's practical application, where technology serves as a powerful tool to augment, rather than fully replace, the designer's creative and technical skills. From a technical standpoint, the design is feasible for production as it uses standard color palettes and stable weave structures. The proposed methodology thus provides a reliable pathway from artistic concept to industrial manufacturing and can reduce the need for costly physical sampling. It is also important to acknowledge the practical trade-offs in our weave selection. The choice of a 5/1 weft satin for the primary motifs, while maximizing luster, results in long floats that increase the fabric's susceptibility to snagging. This renders the final textile more suitable for decorative applications, such as upholstery or wall hangings, rather than high-abrasion apparel, a common consideration in Jacquard design where aesthetics are prioritized. The primary innovation of this work, therefore, lies not in the individual technical steps themselves, but in the creation of an integrated, interpretive framework specifically for translating complex cultural art. Answering the question of what makes this approach novel for ethnic patterns, the innovation emerges from the synergy of three core components: the systematic combination of processing stages from image to loom-file; the strategic parameter choices tailored for artistic content (e.g., using the Lab* color space for k-means clustering to preserve color harmony); and, most critically, the overarching interpretive strategy of mapping 2D pattern functions to 3D weave structures. It is this final, deliberate act of using texture to interpret the original artwork's visual hierarchy—assigning luster to focal points and matte finishes to backgrounds—that elevates this workflow from a generic technical conversion to a thoughtful artistic translation. This provides the robust and nuanced bridge between cultural heritage and modern textile technology that was the central goal of this research. While these simulated results are highly promising, it is acknowledged that the validation in this study was based on qualitative visual assessment rather than objective, instrumental metrics. A full, quantitative validation would require the production of physical woven samples to compare against the digital simulation. Future work should focus on this one-to-one comparison, not only for tactile assessment but also by employing objective analysis to rigorously validate the simulation's fidelity. For example, goniophotometry could be used to quantitatively measure and compare the luster of satin-weave areas, while digital image analysis of fabric surfaces could provide objective metrics for texture, thus providing a robust validation of the simulation's predictive accuracy. Furthermore, a number of practical considerations for industrial adoption warrant discussion. The computational demands of the proposed workflow, particularly the k-means clustering and high-fidelity simulation stages, are manageable for the scale of the pattern in this case study. However, for significantly larger or more intricate patterns, such as those derived from full-scale murals, processing times and memory requirements would increase substantially, potentially necessitating more powerful computing hardware. Additionally, this study utilized professional software such as MATLAB and specialized Jacquard CAD systems. While powerful, the accessibility of these tools may be a barrier for smaller manufacturers. It is important to note that the underlying principles of the workflow—image segmentation, perceptually-aware color quantization, and strategic weave assignment—are transferable. Future implementations could explore achieving similar results using more accessible or open-source software stacks, for example, using Python libraries like Scikit-learn for clustering and open-source image editors, thereby broadening the applicability of this methodology.

CONCLUSION

This research has successfully established and proposed a systematic methodology for the digital processing of ethnic painting patterns and their subsequent application in sophisticated Jacquard fabric design. By integrating advanced image processing, such as k-means clustering for color optimization, with a strategic assignment of weave structures to interpret pattern elements, the proposed workflow serves as an effective bridge between the artistic domain of cultural heritage and the technical realm of modern textile production. The significance of this work is manifold, providing a clear, replicable framework for designers (methodological contribution), a potential pathway to preserve and revitalize traditional art (cultural contribution), and a method to create high-value textile products (commercial contribution).

While this study provides a robust foundation through high-fidelity digital simulation, future work must extend to the production of physical woven samples for a complete sensory and technical evaluation. Building upon this validation, future research should advance in three key directions.

First, focusing on practical industrial adoption, the workflow should be quantitatively benchmarked against alternative design methodologies (e.g., different color quantization algorithms and repeat strategies), its computational performance assessed on patterns of varying complexity, and its adaptation using accessible, open-source software explored.

Second, to deepen the work's cultural integrity and more robustly validate its claims of preserving aesthetic integrity, an ethnomethodological approach is essential. This requires close collaboration with cultural artisans and experts not only during the design phase to ensure technical choices are authentically informed by traditional knowledge, but also explicitly in the validation stage. Furthermore, structured user studies, involving both cultural experts and representative consumer groups, should be conducted to formally assess the perceived fidelity and aesthetic success of the final woven fabric against the original artwork. This would provide crucial qualitative data to complement objective metrics like CIEDE2000 and rigorously substantiate the claims of a successful cultural-to-textile translation.

Finally, the potential of advanced computational tools should be investigated to provide targeted, intelligent solutions for the specific workflow stages currently reliant on human artistic judgment. For instance, deep learning models, such as U-Net architectures, could automate the complex task of pattern segmentation from original artworks. For weave assignment, a recommender system could be trained on a curated dataset of textile designs to suggest contextually appropriate structures. Furthermore, generative models, such as generative adversarial networks (GANs), could be explored for aesthetic optimization, generating novel and balanced repeat compositions from the extracted cultural elements, thus creating a more streamlined yet deeply informed design process.

Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

Author Contributions

Zixuan Wang designed, collected and analyzed the data, and drafted the manuscript. Zixuan Wang conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Zixuan Wang participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Conflict of Interest

The author declares no conflict of interest.

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