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Preservation evaluation method of Chinese traditional shadow puppet relics based on pixel lattice and membership function

Xinyi Lei[1*], Long Li[1], Xinyu Liu[2] and Zhiyan Du[3]

Abstract

The conservation and preservation of shadow puppet artifacts is an important task that requires accurate assessment of their preservation status. Currently, there are many shadow puppet artifacts in collections with varying degrees of deterioration, and an easy-to-use and accurate deterioration assessment method is urgently needed. To address this, this paper proposes a method to convert the color rendering characteristics of shadow puppet artifacts in two-dimensional images into digital information, which is used to create a pixel lattice in processing software Adobe Photoshop. The quantitative signal of the shadow puppet image is extracted and used to calculate the offset of the overall or local chromaticity of the shadow puppet relative to the average chromaticity, allowing for the assessment of the degree of cortical variation and risk of deterioration. A membership function is established based on the observed values of shadow puppet color in the pixel lattice, and the discrete fuzzy set and its scoring index are specified to assign corresponding weight values to the regions with different chromaticity attributes in the pixel lattice.The method of computing scores using the membership function involves ordinary mathematical operations, the overall scoring values are used to comprehensively evaluate the preservation status of the shadow puppet artifacts. This paper establishes a preliminary technical standard for the preventive conservation evaluation of shadow puppet artifacts using pixel lattice and membership function, providing an important guideline for the quantitative and standardized virtual restoration of shadow puppets. The proposed method provides a new approach to quantitatively assess the preservation status of shadow puppets, which is essential for their efficient scientific conservation.

Keywords Cultural relics protection, Shadow puppet, Pixel lattice, Membership function, Deterioration assessment, Mathematical model

Introduction

Shadow puppet

Shadow Puppetry, also known as Leather-Silhouette Show, is a traditional form of Chinese folk drama that employs silhouettes of characters crafted from animal skins or cardboard to tell dramatic stories. With its roots dating back to the Han Dynasty, Shadow Puppetry reached its zenith during the Song Dynasty and remains a popular art form among the Chinese people today. In recognition of its cultural significance, "Chinese shadow puppetry" was inscribed on the United Nations' list of intangible cultural heritage in 2011, and the shadow puppet relics serve as tangible evidence of this enduring cultural legacy [1].

Chinese shadow puppetry is a widely distributed and unique art form with a complete system, distinctive national characteristics, and impressive aesthetic achievements. The shadow puppet is the primary

*Correspondence:
Xinyi Lei
459507456@qq.com
[1] Chengdu Museum, Chengdu 610000, China
[2] Xi'an Center of Geological Survey, China Geological Survey, Xi'an 710054, China
[3] Department of Cultural Relic and Museology, Fudan University, Shanghai 200000, China

physical carrier of this art, serving as a medium for storytelling, entertainment, and cultural expression. As China's museums continue to develop and the cultural relics collections are studied more in-depth, there is a growing appreciation for the importance of shadow puppetry to traditional social folk culture and art. As a result, shadow puppet artifacts are increasingly recognized as valuable exhibits and are being featured in museums. These artifacts are precious cultural and historical evidence that should be carefully preserved and passed down to future generations.

Previous research on shadow puppets has covered a range of disciplines, including historical, cultural, anthropological, and artistic examinations. For instance, in his study "History of Chinese Shadow Puppet Art," Wei. proposed a division of three regional genres of Chinese shadow puppets, employing detailed historical materials to explore the development of Chinese shadow puppets or leather-silhouette shows [2]. Lan. investigated the materials and production processes of Haining shadow puppets [3], while Cui. explored the production process of shadow puppets by examining the Tengchong shadow puppet as an example [4]. Meanwhile, Ni. among others, carried out morphological and folklore investigations to enhance and develop their findings [5]. Despite the range of research, the tools employed are mostly limited to fieldwork and documentary interpretation, and studies on heritage museology remain in the early stages, with only a few museums publishing catalogs of shadow puppet collections. Many museums possess little knowledge of shadow puppet artifacts, including them in their folklore or folk art collections. The lack of systematic and comprehensive research on shadow puppets is evident,. Existing research references mainly rely on the conclusions of leather relics, but there is a clear difference between shadow puppets and leather artifacts that requires further exploration. Wang. et al. initially explored the deterioration classification and grading of shadow puppet artifacts in the collection [6], but their method was only a vague, empirical generalization using macroscopic observation and analogy with other materials.

Due to the lack of a targeted conservation theory system, the preservation and protection strategy of shadow puppet collections is still in a primitive stage. Moreover, the number of shadow puppet artifacts in collections nationwide is so vast that it is impossible to count, with a single unit of the China Shadow Puppet Museum alone collecting over 300,000 pieces. Therefore, there is a long way to go to conserve them. Furthermore, due to the complex preservation history, most of the shadow puppet artifacts have varying degrees of damage and deterioration, making it urgent to carry out comprehensive conservation work.

Cultural relic mathematical model

Mathematical models have not been widely applied in artifact restoration. However, there are a few notable examples of the use of mathematical and physical models to quantitatively study artifacts. For instance, Liu et al. analyzed the vocal principles of The Dragon Washibasin using a non-flux line model [7]. Liu. et al. proposed an approach to address the balance problem between image completion quality and efficiency by finding an optimal patch throughout the candidate region surrounding the missing region with SSD [8]. Additionally, mathematical models have also been used in museum collection display studies and audience classification studies, such as those by Rudokas. et al., Zhen. et al. and Jiang. et al. [9–11]. There have also been case studies of frescoes by Pisu. et al., stone artifacts by León-Robles.CA et al., and bronze artifacts by Petiti. that used mathematical models to explore the nature of artifacts [12–14].

While a large amount of digital information is collected through sensors and natural science instruments to record the ontology and environmental data of cultural artifacts, there is a lack of connection between the digital information collected and artifact conservation in existing studies. This is because the methods of processing artifact information have not been thoroughly studied. Establishing this connection would allow for a convenient and accurate assessment of the preservation status of a large number of cultural objects. To address this issue, this paper focuses on Chinese Traditional Shadow Play as a typical category of heritage and the first entry point for this study. Furthermore, it is a flat cultural object with material characteristics and color expression strongly related to its preservation status, making it easy to establish a low-dimensional abstract model. Therefore, this study focuses on Shadow Play as the object of research, as it has representative and typical research characteristics that can be applied to other artifacts.

Research aim

To achieve effective preservation of shadow puppet heritage, it is essential to conduct systematic research combining natural science and technology. Conservation efforts for these cultural artifacts encompass evaluation assessment, preventive conservation, restoration, and virtual restoration research. Preservation assessment serves as the initial step in conservation research, providing a foundation for decision-making regarding conservation treatments. The utilization of mathematical models allows for accurate assessment of the artifacts' condition and preservation status, facilitating efficient scientific conservation of shadow puppet artifacts. The material characteristics and color expression of shadow puppets play a significant role in determining their preservation status. This inherent relationship enables the establishment of a concise abstract model for preservation assessment, which is technically advanced, cost-effective, easy to implement, and widely applicable. Moreover, the study of shadow puppets can serve as a representative and exemplary research pathway, potentially offering insights and approaches that can be applied to the conservation of other cultural artifacts.

Materials and methods

Artifact characteristics

The process of making shadow puppets involves two main stages: leather making and coloring. In the leather making stage, the epidermis, fat tissue, blood vessels, lymphatic vessels, and skin attachments are mechanically removed from the cowhide, leaving only the woven network structure of collagen fibers in the dermis. This process enhances the material's strength but does not tan it. As a result, shadow puppets have characteristics such as harder leather, good light transmission, and low fiber dispersion. General research methods used for tanned leather relics cannot be directly applied to the analysis of shadow puppet relics. Instead, targeted analytical methods need to be developed to study the preservation status of shadow puppet relics.

The coloring stage, on the other hand, involves the process of adding color to the collagen structure by mixing pigments with gelatin or hide glue boiled from shredded hides in a specific ratio and heating it. Shadow puppet generally includes five basic colors: white, yellow, red, blue, and black, which are used to construct different characters and scenes. To appreciate the special five-color effects of shadow puppets, they must be viewed under backlighting, which determines the light transmission requirements of pigment. Therefore, water-soluble vegetable pigments with excellent light transmittance are widely used for coloring shadow puppets instead of mineral pigments, which are almost lightproof. It is worth mentioning that the manufacturing techniques and materials of shadow puppets vary depending on the region, so even if the surface color of the shadow puppets appears the same, the pigments used may differ.

Currently, a large amount of the shadow puppets in museum collections are collected from folk sources, the most artifact's lack of key information regarding their production techniques and material selection hinders our ability to conduct batch analysis on these shadow puppet artifacts. In contrast, Chengdu shadow puppets have a clear origin and detailed technical information, and the sample properties are basically consistent, making them more suitable for conducting batch research and establishing standardized. Therefore, this study takes Chengdu shadow puppets as the research object and establishes a quantitative evaluation system for the preservation status of shadow puppet artifacts, ensuring the basic consistency of their properties.

Digital imaging

To further strengthen preventive conservation and support auxiliary restoration efforts, a precise assessment of the preservation status of shadow puppet artifacts is crucial. The current evaluation methods heavily rely on visual observation and subjective qualitative descriptions, lacking a robust guiding framework. Therefore, this paper proposes the utilization of digital imaging for a comprehensive and quantitative description of the preservation status of shadow puppet relics. To further enhance preventive conservation and support physical restoration efforts, it is essential to conduct accurate assessments of the preservation status of shadow puppet artifacts.

In their original state, shadow puppet materials exhibit homogeneity, at least within a small range, and their chromaticity is typically continuous. However, due to limitations in early preservation conditions, variations in environmental factors can lead to the deterioration of their appearance and shape. Fluctuations in temperature, humidity, light exposure, and other human factors within the storage environment can result in the aging of cultural heritage materials over time, causing issues such as color fading, mold growth, delamination, and cracks. These afflictions are often visually manifested as sudden shifts in surface color in shadow puppet artifacts. Under backlighting conditions, these color changes caused by deteriorations can be easily observed, and the images captured by digital cameras can effectively acquire this information and digitize it, thereby providing reliable materials for the accurate assessment of the preservation status of shadow puppet artifacts.

Mathematical model: pixel lattice and membership function

The mathematical model is a mathematical structure that captures the characteristics or quantitative relationships of a specific system or phenomenon using mathematical language, either in a generalized or approximate manner [15, 16]. In this study, a mathematical model is established to quantitatively describe the preservation status of cultural relics, exhibiting characteristics of objectivity, abstraction, efficiency, and accuracy. The quantification of the preservation status aims to provide precise guidance for the subsequent preventive conservation and physical and virtual restoration of cultural relics. Through mathematical modeling, the evaluation of cultural relics is no longer reliant on empirical judgment, enabling scientifically systematic and theoretically supported conservation practices [16, 17].

Mathematical modeling relies on structured data, and thus, the initial step in the modeling process involves converting cultural relic images into structured data. In this study, a pixel lattice approach is employed to facilitate this data transformation. High-definition digital cameras are utilized to capture backlight photographs of shadow puppet artifacts. In image processing software, pixels function as indivisible units, composing the two-dimensional digital image of the shadow puppet artifact.

The RGB color model, a standardized color system, encompasses all colors perceptible to human vision by manipulating the values of the red (R), green (G), and blue (B) color channels. These three components of the RGB color space are commonly represented as 8-bit integers in image processing software, providing 256 distinct values for each component, ranging from 0 to 255 [18–20]. It is worth noting that the three axes of the RGB color space are orthogonal, allowing for precise measurement of color deviations and variations within a three-dimensional coordinate system, in addition to absolute color coordinates.

The color information of any pixel can be uniquely expressed by its coordinates in the RGB color space. The distributions of pixel with color information expressed by RGB color space constitute a complete digital image for the shadow puppets. By mathematically describing the relationship between each part of the image and the surrounding chromaticity, a structured data framework for the chromaticity distribution on the surface of shadow puppet artifacts is constructed. As color discontinuity is a visible manifestation of deterioration in shadow puppets, the occurrence of significant chromaticity shifts in localized areas leads to abnormal changes in the coordinates of pixels within the RGB color space. Through mathematical computations and quantitative analyses of pixel lattice data, crucial information such as the location and severity of damage can be accurately extracted from cultural relic images.

The surface chromatic shifts of shadow puppets revealed by the pixel lattice models of digitized images would change with different shooting angles and lighting conditions (such as light source wavelength and luminous flux) while the absolute value of chromatic deviation can define the degree of damage to a shadow puppet artifact, it cannot compare the differences in preservation conditions between different artifacts. To address this problem, this paper establishes a normalized membership function to provide clear indicators and weights for describing the deterioration of shadow puppet relics, leading to construct a standard evaluation system. It converts the absolute values of physical system values into relative value relationships, it reduces the influence of the shooting methods and conditions on the analysis of digital images. More importantly, by normalizing the data, it undergoes dimensionless quantification, thereby enhancing the comparability of the data.

Theory and calculation

Quantification of Deterioration Based on Pixel lattice

Pixel lattice construction in digital imaging

Colors are composed of mixtures of different spectral colors in varying proportions, and we can determine the precise amounts of red (R), green (G), and blue (B) required to replicate each color. In this study, the coordinate values of pixels in the RGB color space represent the color signals of the shadow puppet artifact captured by the photoelectric image sensor [18]. Unlike the human eye, which is limited by the sensitivity of retinal receptors, devices and software can achieve stable and accurate color discrimination [19, 21]. The digital image of the Chengdu shadow puppet artifact is analyzed using image processing software, which breaks it down into various chromaticity and distribution features of individual pixels, forming a pixel lattice. Mathematical and statistical techniques are then applied to extract valuable information from these features, including the proportions of monochromatic regions, areas affected by deterioration, and areas within a specific chromaticity tolerance. By quantifying these aspects, it becomes possible to accurately assess the preservation status of the artifact and make reliable comparisons of assessment results.The reliability of this comparison lies in the dimensionless nature of the ratios obtained through the proportion method applied to the raw data. By normalizing the original data using the proportion method, all the indicators become unitless ratios, thus eliminating the absolute scale differences in the data. Consequently, the comparison of ratios is not affected by the quality of the image data, making it universally applicable and dependable.While it is true that digital image acquisition signals are influenced by factors like light sources and equipment limitations, and achieving complete uniformity in sampling across a wide range of samples is practically unfeasible, our approach effectively minimizes the impact of the original image on the analysis results and reduces the reliance on image quality standardization.

Pixel lattice deconstruction

The monochrome region of shadow puppet artifacts refers to the surface that is uniformly coated with either colored leather glue or remains uncolored, appearing as white. In the case of Chengdu shadow puppets, the five primary colors include the original white color of the leather, the yellow color of garcinia collagen dressing, the red color of cedar dressing, the blue color of anthocyanin collagen dressing, and the black color of carbon black collagen dressing. To establish a scientifically significant standard model, a statistically significant amount of data is required. Thus, this paper concentrates on the five fundamental colors found in the dressing area of shadow puppet artifacts: white, yellow, red, blue, and black. These colors possess well-defined compositions and are extensively utilized in shadow puppet artifacts, benefiting from a wealth of available research resources. These findings are based on preliminary folklore research conducted in this study, as targeted chemical analysis and detection research have not been carried out at present.

The determination of the original coloring area relies on manual tracing, considering folklore processes and color perception. Machine screening may not effectively identify severely discolored parts, highlighting the necessity of manual tracing to accurately outline the monochrome regions that closely resemble the artifact's "original state." Given the extensive preservation process, manual selection is indispensable, as programming alone cannot replace it. The discussion of each of the "five basic colors" separately is warranted due to variations in the composition of colored cortices and their optical properties.

The digital image of shadow puppet artifacts is represented by a pixel lattice matrix. The total number of pixels in the "five basic color" area of the pixel lattice involved in the calculation and study is calculated as follows:

$$N_0 = \sum_{k=1}^{m} N_k$$

Let k represent a region of a single color, such as white, yellow, red, blue, or black. N_k denotes the number of pixels in each monochrome region k. N_0 represents the total number of pixel points in the "five basic color" monochrome region k of the shadow puppet, not the number of pixels in the entire image after discarding the white background points. The number of "five basic color" monochromatic regions k contained in the pixel lattice is denoted by n.

To calculate the proportion of the area of a color's dressing on the artifact surface, the number of pixel dots contained within the dressing region is divided by the total number of pixel lattices. This proportion represents the area share of the selected area relative to the whole or other parts. This method is dimensionless and the obtained data transcends the influence of image clarity, pixel lattice data scale, and anomalous data, enabling quantitative calculations and cross-comparisons [15, 17]. The calculation formula can be expressed as:

$$P_k = \frac{N_k}{N_0} \times 100\%$$

This formula uses variables such as P_k, N_0 and N_k to represent different aspects of the pixel lattice. P_k represents the proportion of the monochromatic region k in the total five basic color area, N_0 represents the total number of pixel points in the monochromatic region k, and N_k represents the number of pixel points in each individual region k When analyzing a monochromatic region k, its impact factor must be multiplied by its corresponding area proportion k.

To analyze the pixel points in a monochromatic region$k$, only the points within the region are selected. The monochromatic standard point O_k is determined based on the average and actual offset of the distribution of the pixel points' chromaticity in the RGB color space. To make a comprehensive judgment, the standard point is combined with other surface characteristics of the shadow puppet, and must be determined through observational study and human judgment. However, this human judgment does not solely rely on subjective factors. Firstly, the average chromaticity value of the region needs to be considered, which can be found in Adobe Photoshop software as the automatically generated RGB three-dimensional coordinates (r, g, b) of each monochromatic region k. These coordinates represent the arithmetic average of the chromaticity of all pixels within region k Whether this coordinate value can be set as the standard point (O_k point) requires manual judgment. When the appearance of the artifact is relatively intact and the main idea of this method is the offset of the artifact's color relative to its own color level, this coordinate can be chosen as the standard point. However, due to uncontrollable factors caused by long-term preservation, such as the area, shape, proportion, and color variation degree of the deterioration, it is necessary to manually select the color coordinates that represent the "true colors" retained in the artifact. Nevertheless, as the method continues to develop and accumulates a large number of case data forming a database, the selection of the O_k point can be further freed from subjective limitations.

It is necessary to establish one standard point for each monochromatic region. Once the standard point O_k for a monochromatic region k has been determined, a set of color tolerance conditions i is established in the RGB color space. The color tolerance values represent the allowable range of color differences from the standard point. The set I, formed by the values of i, can be represented as follows:

$$\mathrm{I} = \{i | 10, 20, 30, 40, 50, \ldots\ldots, 150\}$$

To determine the surface area where the dominant color is present on the artifact, only pixel points that fall within a certain range [0, i] of color tolerance condition values in the RGB color space are selected, with the monochromatic standard point O_k as the origin. This value represents the proportion of the area where the dominant color is present on the artifact surface to the area of the monochromatic region k. The calculation formula is as follows:

$$P_{ki} = \frac{N_{ki}}{\mathrm{N}_k} \times 100\%$$

The formula uses three variables to calculate the proportion of the selected pixel area that meets a certain color tolerance condition: P_{ki}, N_k and N_{ki}.P_{ki} represents the proportion of the selected pixel area that falls within the color tolerance condition i in region k, while is the number of pixel points that can be selected within region k when the color tolerance is set to i relative to the monochromatic standard point O_k, and N_k is the total number of pixel points within region k. These variables are used in pixel lattice or color preservation analysis to determine the percentage of the artifact's surface area that meets the given color tolerance condition.

The variables i and j represent the color difference values in the RGB color space between the monochromatic standard point O_k and the pixel points in region k. The calculation equation for selecting points within the monochromatic region k that have a color tolerance condition between [j, i]] relative to the point O_k is given for i and j, such that $i > j > 0$.

$$\Delta P_{k(i-j)} = \frac{N_{ki} - N_{kj}}{N_k} \times 100\%$$

This equation, called the monochrome pixel color rendering ratio, calculates the value of$\Delta P_{k(i-j)}$. It represents the proportion of the area within the monochromatic region k relative to the entire RGB color space at the monochromatic standard pointO_k, subject to a color tolerance condition between [j, i]. In other words, measures the proportion of the surface area of artifacts that share similar preservation status, which can provide insight into environmental factors or conservation treatments and might be useful in evaluating the effectiveness of preservation strategies or assessing the overall condition of a collection of artifacts.

The calculation of $\Delta P_{k(i-j)}$ involves several variables, including the number of pixels N_{ki} within region k that fall within the interval [0,i] relative to the color tolerance of the monochromatic standard pointO_k, the number of pixels N_{kj} within region k that fall within the interval $[0, j]$ relative to the color tolerance of the point, the number of pixels ($N_{ki} - N_{kj}$) that can be selected within the interval [j, i] relative to the color tolerance of the point O_k, and the total number of pixel points N_k in the monochromatic region$k$.

To analyze color, damage or deterioration, and preservation information from shadow puppets, a pixel grid is used with dimensional reduction techniques to extract quantitative signals. The larger the values of j and i, the more severe the deterioration and the wider the corresponding area on the pixel grid. Conversely, a finer grading corresponds to a narrower definition domain and a smaller contained area. This approach evaluates the degree of cortical variation and the risk of degradation by directly calculating the offset of the puppet from the average chromaticity. When the properties of the cortical collagen weave's translucency and surface chromophores are consistent, smaller color tolerance settings can be used to select more representative pixel points. While some deterioration types may require alternative analysis methods, examining a large sample of shadow puppets can yield preliminary findings, and additional research is necessary to explore the aging behavior and overall evaluation of artifacts using the membership function described below.

Methodology examples

The process of creating and analyzing a pixel lattice from a digital image of a shadow puppet artifact can be illustrated through Figs. 1, 2, and Table 1. For instance, consider the artifact with the serial number 6Y1A7598, and its digital image of the flesh side. Firstly, the white background is removed, and a pixel lattice is generated to isolate the artifact image. Then, the proportion of the five basic color regions, namely white, yellow, red, blue, and black, can be quantified. In this case, the proportions are 37.61%, 38.27%, 6.64%, 6.77%, and 10.71%, respectively.

The distribution of monochrome pixel color rendering ratio $\Delta P_{k(i-j)}$ varies across different regions, as shown in Fig. 3. The response of each region to changes in color tolerance also varies depending on the value of i. Specifically, the red region has the fastest rate of change between i=50 and i=80, while the white region shows the fastest rate of change between i=120 and $i=150$. The black and blue regions have the same range of fastest rate of change, between $i=50$ and $i=80$, and the yellow region shows the fastest rate of change between i =80 and i=100. These differences can be attributed to the optical properties of the visible color gamut in the RGB color space and the preservation of coloring pigment skin gum and use of different coloring materials. Therefore, it is essential to conduct individualized analyses for each monochromatic region due to the significant differences in color rendering and light transmission.

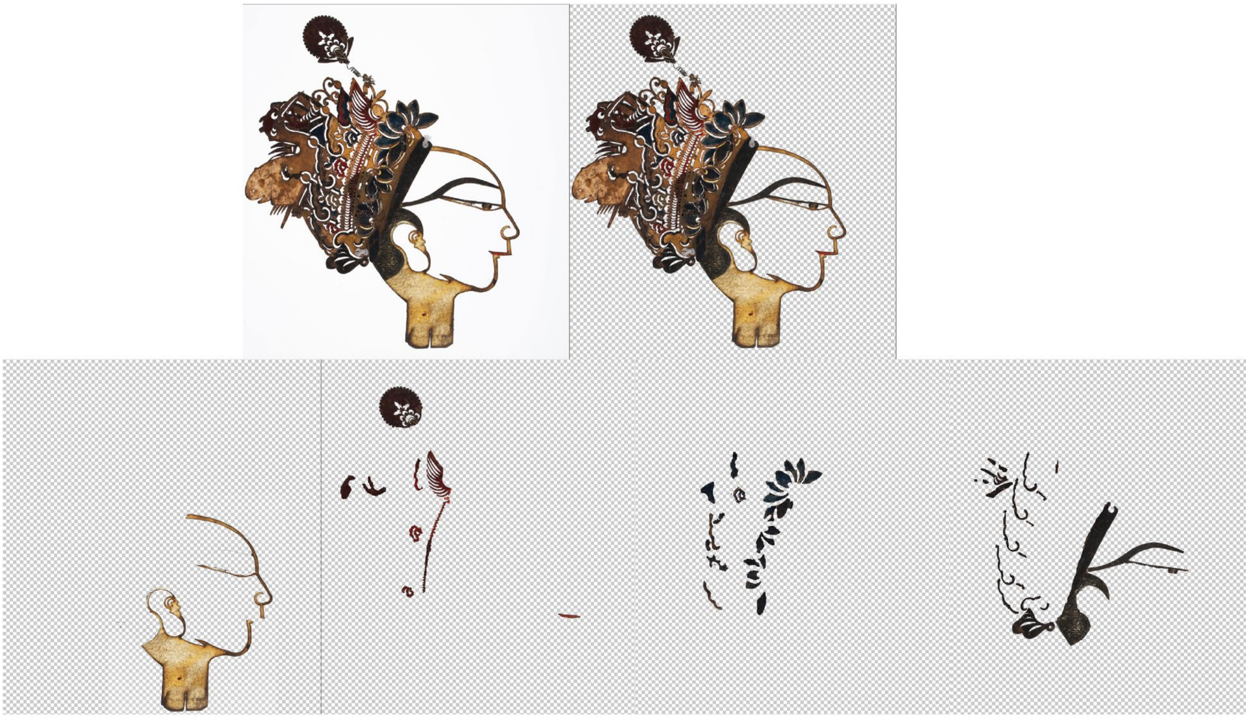

Fig. 1 The digital photo of shadow puppet artifact's flesh side (Serial Number: 6Y1A7598) and the pixels in each monochrome region of five basic color

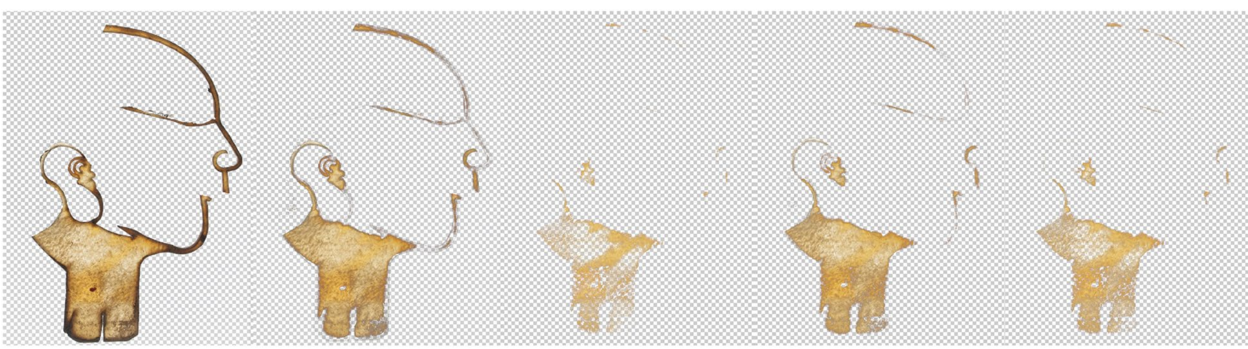

Fig. 2 Selection of pixel dots with different color tolerances within the white monochromatic region of the pixel lattice in the digital photo of shadow puppet artifact's flesh side (Serial Number: 6Y1A7598)

Each parameter in the evaluation of the artifact's preservation status depends on the pixel lattice system, involving area calculations and fuzzy clustering. Therefore, when considering the impact of indicators within each monochromatic region k on the overall artifact, it is crucial to consider the area ratio occupied by that region. For example, in the blue region, 81.56% of the area consists of pixel points with a color difference of 50 or less from the blue standard point in the RGB color space. Conversely, 14.52% of all pixel points have a color difference value greater than 50 from the standard point. Since the blue region accounts for 7.40% of the total area, the weighting impact of these values should be multiplied by 7.40% when evaluating the artifact as a whole.

Shadow puppet artifacts have two distinct surfaces, the flesh surface and the grain surface, which differ in material properties. When using imaging equipment to collect data, both sides of the plane are captured and can be compared and complement each other. However, it is important to note that the preservation status may vary between the two surfaces, even if the same color leather glue is applied. Differences in average color rendering, color retention,

Table 1 Deconstruction results of pixel lattice for digital photo of shadow puppet artifact's flesh surface (Serial Number: 6Y1A7598)

Relative to O_k point	Calculation item	White	Yellow	Red	Blue	Black
Monochrome region k	N_k	66854	68023	11810	12025	19027
	P_k (%)	37.61	38.27	6.64	6.77	10.71
Color tolerance i = 50	N_{k50}	8844	15645	4696	9807	16851
	P_k (%)	13.23	23.00	39.76	81.56	88.56
	$\Delta P_{K(50-0)}$ (%)	13.23	23.00	39.76	81.56	88.56
Color tolerance i = 80	N_{k80}	13093	32572	10261	11276	17815
	P_{k80}(%)	19.58	47.88	86.88	93.77	93.63
	$\Delta P_{K(80-50)}$ (%)	6.36	24.88	47.12	12.21	5.06
Color tolerance i= 100	N_{k100}	14436	63991	10827	11552	18071
	P_{k100}(%)	21.59	94.07	91.68	96.07	94.98
	$\Delta P_{k(100-80)}$ (%)	2.01	46.19	4.79	2.30	1.35
Color tolerance i = 120	N_{k120}	17880	68000	11070	11693	18276
	P_{k120}(%)	26.74	99.97	93.73	97.24	96.05
	$\Delta P_{K(120-100)}$ (%)	5.15	5.89	2.06	1.17	1.08
Color tolerance i = 150	N_{k150}	58200	68017	11240	11794	18445
	P_{k150}(%)	87.06	99.99	95.17	98.08	96.94
	$\Delta P_{k(150-120)}$ (%)	60.31	0.02	1.44	0.84	0.88
Total pixels	N_0	177739				

Monochrome region k: It represents a region of a single color, such as white, yellow, red, blue, or black

O_k: The monochromatic standard point O_k is determined based on the average and actual offset of the overall distribution of the pixel points chromaticity in the RGB color space for the single color region k

i/j: i and j represent the color difference value in the RGB color space between the monochromatic standard point O_k of the artifact and the pixel points in region k

Color tolerance 50: It represents the color difference value i=50 between the monochromatic standard point O_k of the artifact and the pixel points in region k in the RGB color space

N_k: The number of pixel points in each region k

P_k: The area proportion of the monochromatic region k in the whole five basic color area

P_{ki}: The proportion of the selected pixel area with a color tolerance condition of i in region k

N_{ki}: The number of pixel points that can be selected within region k when the color tolerance is set to relative i to the monochromatic standard point O_k

$\Delta P_{k(i-j)}$: It is named the monochrome pixel color rendering ratio, and it represents the proportion of the area within the monochromatic region k relative to the entire RGB color space at the monochromatic standard point, subject to a color tolerance condition between j and i

N_{k50}: The number of pixels that can be selected within region k with a color tolerance of i=50 relative to the monochromatic standard point O_k

P_{k50}: The proportion of the selected pixel area under the color tolerance condition i=50 in region k

$\Delta P_{k(50-0)}$: The monochrome pixel color rendering ratio represents the proportion of the area within the monochromatic region k relative to the entire RGB color space at the monochromatic standard point, under a color tolerance condition of [j, i] where i=50 and j=0

N_0: Denotes the total number of pixel points in the "five basic color" monochrome region k of the shadow puppet

and preservation status can be observed within the same monochromatic region on the flesh surface and the grain surface. Additionally, at a macroscopic level, the color coating may exhibit patchiness or the drawing pattern may become blurred, especially when multiple layers of color are applied. For instance (Fig. 4), applying another color on top of a large area of red color coating to outline a pattern with hide glue may result in a less clear outcome.

Quantitative evaluation assessment based on membership function

Membership function

Assessing the preservation status of shadow puppet artifacts is a challenging task due to the multitude of factors that can influence it. Moreover, the definition of "good preservation" is not always clear-cut, leading to a fuzzy evaluation process. Fuzzy mathematical methods can help overcome this issue by accurately quantifying the fuzzy relationship between the artifact samples and the "good preservation" event set. To achieve a comprehensive evaluation of the overall preservation status of shadow puppet artifacts, a membership function must be established in the pixel lattice of their images. This function should include scoring indices and assign corresponding weights to different attribute degrees in the various regions. By calculating the regional and overall scoring values, the preservation status can be classified and graded according to specific requirements [15, 16].

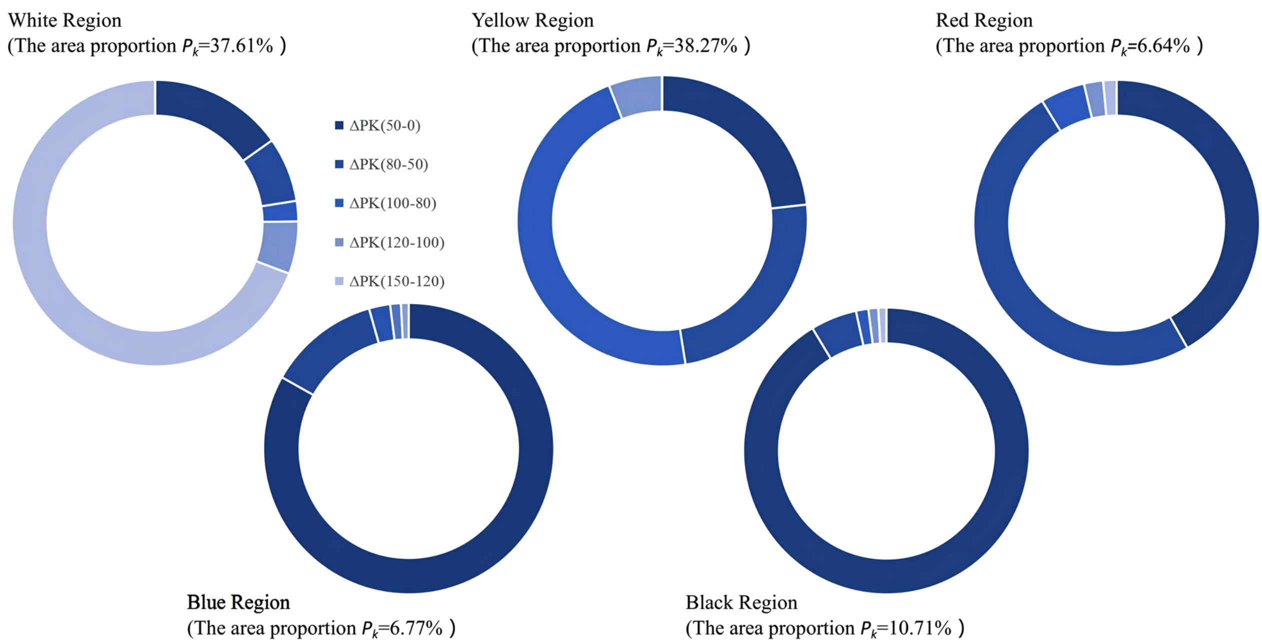

Fig. 3 The monochrome pixel color rendering ratio $\Delta P_{k(i-j)}$ values donut chart for each basic color monochrome region in digital photo of shadow puppet artifact's flesh side (Serial Number: 6Y1A7598). $\Delta P_{k(i-j)}$: It is named the monochrome pixel color rendering ratio, and it represents the proportion of the area within the monochromatic region k relative to the RGB color space at the monochromatic standard point O_k, subject to a color tolerance condition between j and i. $\Delta P_{k(50-0)}$: The monochrome pixel color rendering ratio which represent the proportion of the area within the monochromatic region k relative to the RGB color space at the monochromatic standard point O_k, subject to a color tolerance condition between 0 and 50. $\Delta P_{k(80-50)}$: The monochrome pixel color rendering ratio which represent the proportion of the area within the monochromatic region k relative to the RGB color space at the monochromatic standard point O_k, subject to a color tolerance condition between 50 and 80. $\Delta P_{k(100-80)}$: The monochrome pixel color rendering ratio which represent the proportion of the area within the monochromatic region k relative to the RGB color space at the monochromatic standard point O_k, subject to a color tolerance condition between 80 and 100. $\Delta P_{k(120-100)}$: The monochrome pixel color rendering ratio which represent the proportion of the area within the monochromatic region k relative to the RGB color space at the monochromatic standard point O_k, subject to a color tolerance condition between 100 and 120. $\Delta P_{k(150-120)}$: The monochrome pixel color rendering ratio which represent the proportion of the area within the monochromatic region k relative to the RGB color space at the monochromatic standard point O_k, subject to a color tolerance condition between 120 and 150

Consistency in color within a shadow puppet's monochromatic region indicates a uniform collagen weave and chromogenic chemistry. This allows for more precise pixel selection using smaller color tolerances on the pixel lattice. deterioration distribution and area share can be identified using color tolerance calculations, providing indicators of preservation status. Irregular variations from the average specificity may signal deterioration, and a membership function built on the pixel lattice can quantitatively represent these changes.

Significance of the membership function

To accurately assess the preservation status of cultural relics, a membership function is needed to convert discrete observations into definitive values. This function assigns nondimensional quantities to observations, resulting in a unique evaluation value that can be normalized to reduce ambiguity. This approach helps overcome the inherent ambiguity in assessing preservation status based on discrete observations of individual monochromatic areas and the overall condition of the artifact.

To achieve accurate assessment of preservation status in cultural relics, the affiliation function is built upon a pixel lattice, serving as the underlying framework in the quantitative model provided by the pixel dot lattice. The pixel lattice enables the calculation of monochromatic region areas relative to the whole artifact, removing dimensionality and facilitating objective and deterministic criteria for pixel selection under smaller color tolerances. Furthermore, it allows for clear delineation of the boundary between areas at risk of deteriorating deteriorations. The percentage of deterioration area, its location, and classification can be precisely defined, and the data can be made commensurable, enabling horizontal statistics and comparisons across different artifact samples.

To quantify the preservation status of artifacts, a membership function is used to assign values to the fuzzy set of preservation descriptions based on pixel points and the whole pixel lattice. The function uses a closed interval

Fig. 4 A digital photo of the shadow puppet cultural artifact (Serial Number: 6Y1A7717) with the grain and flesh sides depicted on the left and right

of [0,100] to represent the degree of pixel point affiliation with the ambiguous set, which is normalized by the area ratio. The closer the value is to 100, the better the preservation status, and the closer it is to 0, the worse. The values have physical meaning and are standardized and normalized to eliminate data differences. The "standard" is relative to its own level, extracted from the mathematical average and human experience [18, 19, 21].

Membership function construction

We denote the number of preservation status scores for the monochromatic region k as F_k. The formula for calculating it is as follows:

$$F_k = \sum_{i=1}^{n} y_{ij} \cdot \Delta P_{k(i-j)} = \sum\nolimits_{i=1}^{n} y_{ij} \cdot \frac{(N_i - N_j)}{N_k}$$

Here, the variable F_k represents the preservation status score calculated by the membership function for the monochromatic region k. Variables i and j represent the color tolerance selection condition of the set pixel points relative to the monochromatic standard pointO_k.$\Delta P_{k(i-j)}$ is the color rendering ratio of monochrome pixels, representing the area share of artifact color rendering within the monochromatic region k in the range $[j, i]$, relative to the color difference of the standard point O_k. In essence, this ratio represents the percentage of the monochromatic region that has a certain preservation status level.

y_{ij} is the weighting factor.The weighting factor represents how much weight should be given to the pixel points with different chromaticity levels when calculating the preservation status score. It can be interpreted as both the degree to which the set of pixel points of that class falls within a better criterion and as a description of the superiority or inferiority of the image represented by the pixel points of that class. In other words, it reflects the relative importance of each pixel point in contributing to the overall assessment of the preservation status of the cultural relic.

The score obtained by the set of pixel points in the tolerance interval $[j,\ i]$ is denoted by $[y_{ij} \cdot \Delta P_{k(i-j)}]$. The value of n corresponds to the number of categories used for the pixel color rendering gradation share. For each graded partition, the area share is multiplied by its respective weight, and the sum of these products is the preservation status score F_k for the monochromatic region k.

The preservation status score is a measure of how well-preserved shadow puppet artifacts are. A higher score means the artifacts are in better status. The score is based on the distribution of pixel colors in each monochrome region k, relative to a standard color point O_k. When there are more pixels with colors similar to the point O_k, the score is higher, indicating better preservation. This means the colors of the artifacts are consistent and the risk of damage and deterioration is lower. Conversely, a lower score F_k means the artifacts are in worse status, with less consistent colors and higher risk of damage and deterioration.

The closer the difference between i and j is to 0, the better the pixel set represents the surface preservation status. If given a higher weight y_{ij}, this class represents a better standard. However, the score decreases at a non-linear rate and is related to the difference between i and j. Higher differences between i and j cause the score to decrease faster. The first-order derivative of the score is larger, resulting in a smaller calculated fraction for that area share. The change function y_{ij} must contain a parabolic section according to the trend of the score F_k.

For each monochromatic region k, if the color difference between the pixel points in this range and the monochromatic standard point is small enough, the weight of the pixel points in this area is set to 100. This indicates that the colors are in good preservation status and meet the standard. However, when the color difference is greater than 20, a downward opening parabolic function is used to calculate the weight. The value of color difference $i-j=10$ is used in the calculation equation at this point. A larger color difference indicates more serious deterioration, and the weight decreases faster as the number of points decreases. This calculation is expressed as a segmentation function:

$$y_{ij} = \begin{cases} 100,\ i \leq 20 \\ ai^2 + bi + c,\ i > 20\ and\ \ i - j = 10 \end{cases}$$

The steepness of the y_{ij} curves in each monochromatic region k varies due to the combination of different colors' optical properties and material characteristics. The variation in the steepness of the y_{ij} curves in each monochromatic region k is reflected in the changes in the values of the quadratic term coefficient a, the primary term coefficient b, and the constant term c of the y_{ij} function. To determine these coefficients and typical values for each region k, several i values (maintaining $i-j=10$) and their corresponding y_{ij} values are assumed. Gaussian curve fitting is then performed, and the obtained quadratic function is verified for accuracy. Thus, the quadratic function coefficients and typical values vary for each region k and are determined by assuming different i values and corresponding Y values, performing Gaussian curve fitting, and verifying the obtained quadratic function. The results are shown in Table 2.

The parabolic segment is a curve that is symmetric with respect to $i=20$ and has its vertex at $i=20$. To calculate the i-values corresponding to the monochromatic regions y_{ij}=0 for the "five basic colors" of white, yellow, red, blue and black, the absorption and reflection characteristics of light waves in the "five basic colors" color gamut are taken into account. White light includes visible light across various wavelengths [18]. In this study, which is based on color imaging, a white light source which closely approximate equal-energy white was chosen as the external light source to accurately represent the colors of the cultural relics in the captured images. The light was uniformly projected onto the shadow puppet artifacts from behind, following a parallel optical path. When a higher light flux or longer wavelength light passes through the artifacts, under the same light source conditions, the artifacts absorb less light energy and transmit more light, resulting in lighter colors in the monochromatic regions [18–20]. This is because dark regions tend to absorb lower energy light more easily. The five basic colors, in order from lighter to darker, are white, yellow, red, blue, and black. Based on this characteristic, in this study, we define the i-values corresponding to the colors white, yellow, red, blue, and black when $y_{ij}=0$ as 150, 140, 130, 120, and 110, respectively.

The $[j, i]$ interval with small absolute values of i and j exhibits a higher rate of change in the monochrome pixel color rendering ratio $\Delta P_{k(i-j)}$, resulting in shorter and steeper parabolic curves y_{ij}. This corresponds to larger values of a and b. Conversely, in the $[j, i]$ interval with large absolute values of i and j, the resolution of chromatic aberration is lower, leading to longer and shallower parabolic curves y_{ij}.

Note that when the calculated value of the function is negative, the membership function y_{ij} should be set to 0. The membership function represents the degree to which the pixel's coloring phenomenon belongs to the fuzzy cluster, and is defined in the interval [0, 100]. A value of 0 indicates severe degradation and discoloration of the shadow puppet artifact at the corresponding point.

The preservation status score F of cultural relics is determined by considering the area calculation and the fuzzy clustering system. In order to accurately assess the impact of indicators within each monochromatic region k on the overall score, it is necessary to weigh the score of each region according to its corresponding area proportion P_k. The overall preservation status score is then obtained by summing up the weighted scores of all regions, taking into account their respective area shares in the overall artifact:

Table 2 Calculation formula and typical values of coefficients ***a***, ***b***, and ***c*** for each monochromatic region *k*

k	$i>20$ calculation formula $y_{ij}=ai^2+bi+c$			y_{ij}							
	a	*b*	*c*	$i\le 20$	$i=30$ $j=20$	$i=50$ $j=40$	$i=70$ $j=60$	$i=90$ $j=80$	$i=110$ $j=100$	$i=130$ $j=120$	$i=150$ $j=140$
White	-5.128×10^{-3}	1.025×10^{-1}	100	100	98.46	92.31	82.05	67.69	49.23	26.67	0.00
Yellow	-5.952×10^{-3}	1.190×10^{-1}	100	100	98.21	91.07	79.17	62.50	41.07	14.88	0.00
Red	-6.993×10^{-3}	1.399×10^{-1}	100	100	97.90	89.51	75.52	55.94	30.77	0.00	0.00
Blue	-8.333×10^{-3}	1.667×10^{-1}	100	100	97.50	87.50	70.83	47.50	17.50	0.00	0.00
Black	-1.010×10^{-2}	2.020×10^{-1}	100	100	96.97	84.85	64.65	36.36	0.00	0.00	0.00

Monochrome region *k*: It represents a region of a single color, such as white, yellow, red, blue, or black

i/*j*: *i* and *j* represent the color difference value in the RGB color space between the monochromatic standard point O_k of the artifact and the pixel points in region *k*.In the function y_{ij} are maintained such that $i-j=10$

y_{ij}: The weighting factor y_{ij} represents how much weight should be given to the pixel points with different chromaticity levels when calculating the preservation status score

Fig. 5 Digital photo of the shadow puppet cultural artifacts:No. 6Y1A4794 and No.6Y1A4499

$$F=\sum_{k=1}^{m}P_k\cdot F_k=\sum_{k=1}^{m}P_k\left(\sum_{i=1}^{n}y_{ij}\cdot\frac{(N_i-N_j)}{N_k}\right)$$

The preservation status of artifacts is evaluated using a membership function, which provides an overall assessment score represented by F. This score is calculated based on the membership function. The area share of monochromatic region k in the entire pixel lattice is represented by P_k, and the assessment score of the cortical preservation status of region k is denoted by F_k. There are m species of monochromatic region k.

After calculating the assessment scores of all monochromatic regions, the F-value is calculated to quantitatively evaluate the preservation status of cultural relics. A high F-value indicates superior preservation status, while a low F-value indicates inferior preservation status. This result serves as the foundation for further work on heritage conservation.

Results

Membership function analysis case

Table 3 presents the assessment scores obtained for 14 Chengdu shadow puppet artifacts in the collection using the membership function. It is observed that the scores vary among the monochromatic regions of the same artifact, which can be attributed to the use of different coloring materials and the effects of preservation

Fig. 6 Digital photo of the shadow puppet cultural artifacts: No. 6Y1A4630 and No. 6Y1A4487

history. These case studies serve to demonstrate the effectiveness and feasibility of the proposed method. The method involves disassembling the artifact images into pixel lattices and applying a comprehensive weighting of the membership function to scientifically assess their preservation status. This approach provides a reliable alternative to empirical judgment in monitoring the preservation status of cultural relics.

By analyzing the monochromatic regions of the 'five basic colors' in the cortical coloring of shadow puppet artifacts and utilizing digital information from various heritage resources, a theoretical database can be established to statistically assess the color preservation of these artifacts. This approach not only offers simplicity and scalability but also holds immense potential for broader applications in the field of cultural heritage conservation. It expands the utilization of information data and provides a straightforward and adaptable method that can be applied to various categories of cultural relics.

The mathematical model employed in this study expresses the relationship between the physical variables of cultural relics using mathematical language, enabling the investigation of their movement patterns and facilitating a precise understanding of the underlying fuzzy system. While the focus of this paper is on shadow puppets, the process and methods utilized to establish the mathematical model can be extrapolated to other types of cultural relics. The steps involved in building the model encompass creating a quantitative model, evaluating the values within the model, and abstracting the results in a quantitative manner, enabling effective research on cultural relics using the mathematical model (Figs. 5 and 6).

Discussion

The method of analyzing and evaluating a digital image using Adobe Photoshop software for the division of monochromatic regions k and the establishment of the pixel lattice is relatively efficient. Researchers only need to perform basic image extraction operations, and data collection can be easily obtained through panel options. Calculating the score value F_k and F in the set membership functions simply requires inputting the collected pixel lattice data into the predetermined calculation formula, and the calculation is automated. Overall, the method is straightforward, cost-effective, and time-efficient.

Compared to existing methods for assessing the preservation status of cultural relics, the proposed approach in this paper offers significant advantages. Currently, existing methods mainly focus on component analysis and surface morphology analysis. Techniques such as X-ray Fluorescence (XRF) and Fourier Transform Infrared Spectroscopy (FTIR) are used for non-destructive analysis of cultural relic samples' components, while High-Performance Liquid Chromatography and Thermal Stability Analysis are used for destructive analysis. However, regardless of whether these methods are applicable to biological materials like shadow puppets, they come with expensive equipment purchase and operational costs. Considering the vast number of shadow puppet artifacts found in museums across China, conducting a comprehensive survey and assessment of their preservation status using these methods is practically infeasible.

Similarly, techniques based on high-precision 3D scanning, Scanning Electron Microscopy (SEM), and optical microscopy also face cost-related challenges. Additionally, employing overly precise instruments for all relics generates a large amount of data, leading to the need to

Table 3 Membership function analysis of selected Chengdu shadow puppet artifacts

Sample		White	Yellow	Red	Blue	Black	Total score *F*
6Y1A7644	P_k(%)	74.77	3.70	9.14	8.92	3.47	82.11
	F_k	92.23	79.84	83.30	28.41	27.54	
6Y1A0813	P_k(%)		68.61	55.93	69.97	48.10	85.92
	F_k		10.40	6.76	30.38	52.46	
6Y1A4566	P_k(%)	41.51		29.04		29.45	80.70
	F_k	64.22		22.79		59.99	
6Y1A6377	P_k(%)	47.76		20.50		31.74	73.66
	F_k	77.45		83.15		72.33	
6Y1A7717	P_k(%)	38.93		30.64		30.42	91.16
	F_k	81.94		89.11		75.30	
6Y1A4754	P_k(%)	33.27		16.63	19.62	30.48	87.86
	F_k	92.43		90.41	96.87	69.31	
6Y1A6188	P_k(%)	15.67	42.95			41.37	78.77
	F_k	93.73	86.93			69.30	
6Y1A4794	P_k(%)	28.76		26.22	22.10	22.91	79.47
	F_k	92.91		64.83	73.13	54.34	
6Y1A6377	P_k(%)	53.13		46.58		0.29	61.34
	F_k	90.73		91.67		89.17	
6Y1A7582	P_k(%)	33.20		35.84	29.95	1.01	85.81
	F_k	94.46		94.27	73.12	80.12	
6Y1A6377	P_k(%)	13.68	16.04	47.86		22.41	82.11
	F_k	94.24	72.77	76.62		78.23	
6Y1A4629	P_k(%)	4.00	35.85	3.06		57.08	85.92
	F_k	85.40	71.76	80.96		83.82	
6Y1A4630	P_k(%)	74.92	2.03	16.42		6.63	80.70
	F_k	58.46	65.20	72.84		64.18	
6Y1A6377	P_k(%)	47.79		33.13		19.08	73.66
	F_k	86.02		84.19		88.08	

P_k: The area proportion of the monochromatic region *k* in the whole five basic color area

F_k: It represents the score number of the cortical preservation status assessment in the monochromatic region *k* calculated by the membership function

F: It represent the overall assessment score of the artifact

omit some data during practical analysis, making high-cost and high-precision image analysis unnecessary in practice.In contrast, the proposed method in this paper maintains accuracy while controlling costs, making it suitable for widespread application. It can provide reliable results without the need for excessively expensive equipment, making it a feasible and cost-effective choice for evaluating the preservation status of shadow puppet artifacts.

Conclusions

Pixel lattice and membership function in conservation

The extensive digital data collected from cultural heritage conservation endeavors holds immense potential when thoroughly analyzed and effectively utilized. By not only recording and transmitting this data through images but also using it as a foundation for assessing damage to shadow puppet heritage, we can significantly advance the long-term, stable, and secure conservation of cultural heritage collections. As data continues to accumulate, the evaluation criteria for determining the pixel lattice and membership function will become increasingly defined, ultimately leading to the establishment of a technical standard system for the preventive conservation of shadow puppet cultural relics. This innovative approach has the capacity to serve as a model for the conservation of various other types of cultural relics. Its implementation has the potential to make substantial contributions to the protection and preservation of cultural heritage on a global scale.

Virtual restoration with pixel lattice

The concept of virtual restoration has gained popularity in the field of heritage conservation, although its application to shadow puppet artifacts is still in the experimental stage. However, the pixel lattice and membership function offer valuable guidance for standardizing virtual restoration practices. By employing the pixel lattice model, it becomes possible to establish monochromatic standard points O_k and pixel points with a defined tolerance (i). These elements enable accurate calculations of the damaged area within the artifact.

The monochrome pixel color rendering ratio ($\Delta P_{k(i-j)}$) plays a crucial role in assessing the extent and severity of damage in a graded manner at each location. Notably, when there is a significant change in the monochrome pixel color rendering ratio, indicating a chromaticity shift, it signifies evident deterioration and the potential spread of damage. Utilizing this model, specific points requiring repair can be identified, and simulations can be conducted to restore color anomalies to their target chromaticity. This approach enables a scientific and quantitative approach to virtual restoration for shadow puppet artifacts, particularly in terms of precise chromaticity restoration, which may not be achievable through other methods.

Folklore research with pixel lattice

The pixel lattice model not only serves as a guiding framework for virtual restoration but also presents a novel approach to folklore color research. It introduces a quantitative tool that complements existing folklore research methods, allowing for a more in-depth study of the craftsmanship associated with shadow puppet artifacts. By analyzing pixel values and membership functions, valuable insights into color usage and distribution patterns in shadow puppetry can be gained. This approach holds great potential for advancing our understanding of the historical and cultural contexts surrounding these artifacts. It provides a means to explore the intricacies of color application in shadow puppetry, shedding light on the artistic techniques employed by shadow puppet artisans. Additionally, the findings derived from this model can inform future restoration and conservation efforts, ensuring a more accurate and culturally sensitive approach to the preservation of shadow puppet heritage Additional file 1.

Outlook

In the future, through statistical analysis of a substantial volume of sample data, it will be possible to establish a systematic theory that links the color tolerance of shadow puppet artifact images with the assessment of damage. This theory will lay a solid foundation for the long-term and comprehensive conservation of these cultural relics. Furthermore, it can serve as a pioneering guide for the conservation practices of small and medium-sized museums across the country, which often possess similar collections but may lack professional expertise and resources.

By adopting the established theory and technical standards, these museums will be better equipped to effectively preserve their cultural heritage and share their valuable cultural resources with the public. This will contribute to the broader dissemination and appreciation of shadow puppetry, enriching the cultural landscape and fostering a deeper understanding of this traditional art form.

Abbreviations

SSD	Single Shot multibox Detector,a deep learning object detection framework represented by YOLO algorithm that transforms object detection into a regression problem
microCT	Micro computed tomography, also known as micro CT, is a non-destructive 3D imaging technique that allows for a clear understanding of the internal microstructure of a sample without damaging it
RGB color system	The RGB color system is a color standard in the industry, which obtains a variety of colors through changes in the red (R), green (G), and blue (B) color channels and their superposition. RGB represents the colors of the red, green, and blue channels. This standard includes almost all colors that can be perceived by human vision and is one of the most widely used color systems

Supplementary Information

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Additional file 1: Raw data of example calculation.

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Author contributions

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Declarations

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