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An Atlas-based Approach for Appearance-aware Virtual 3D Restoration and Simulation of Fading in Fugitive Textiles

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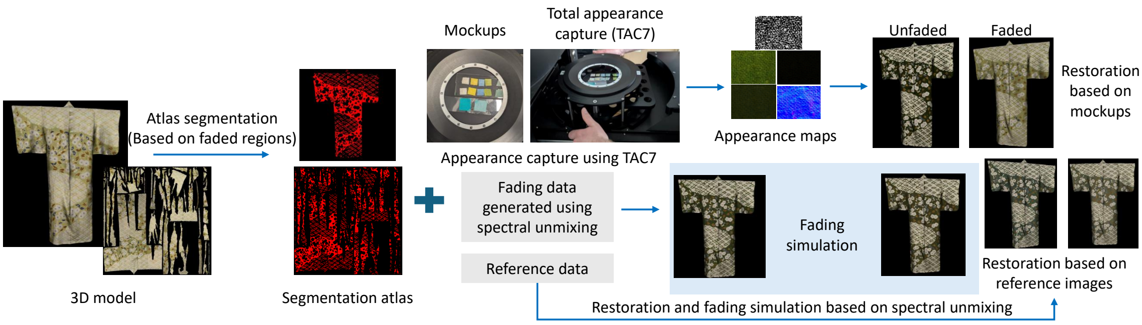

Figure 1: *Segmentation of fugitive colors in the UV-parameterized 3D model is achieved using a 2D parameterized atlas. This segmented atlas facilitates fading simulations and appearance-aware restoration of fugitive colors, guided by mockups, fading data, and reference images.*

Abstract

Simulating the discoloration of cultural heritage garments provides valuable insights into their history and supports their preservation. For this purpose, digital methods provide innovative solutions that can leverage the realism of aging processes without causing damage to the artifact. In this work, we propose a method to render color changes in two fugitive textiles housed at the Victoria and Albert Museum. We use a combination of novel atlas-based material segmentation and color restoration approaches to transfer appearance from textile mockups to the 3D models of the garments. The fading effects are induced with accelerated aging on mockups that are chemical proxies of the historic garments, with their aging monitored colorimetrically and spectrally, and their appearance measured with a total appearance capture device. Our proposed approach generates a colour-cue-based segmentation map over a 3D surface, followed by appearance transfer to segmented regions from mockups and fading simulations from spectral unmixing, along with appearance-aware restoration optimized using a reference image. By facilitating appearance-aware fading simulation in virtual 3D models in an interactive app, our approach supports a realistic visualization of colour change in the past and the future. We evaluate our method on two heritage garments - a 20th-century kimono and a 19th-century Victorian dress featuring different fabrics (silk and cotton) and dyed with natural and synthetic materials. In accordance with data collected through scientific analysis measurements, the proposed method effectively transfers a visual appearance that is both plausible and consistent with the data, providing both specialists and lay audiences with a range of fading simulations to support interpretation and restoration decisions.

CCS Concepts

• ***Computing methodologies*** → ***Reflectance modeling; Image-based rendering;*** *Image manipulation;* ***Hyperspectral imaging;***

1. Introduction

Understanding and preserving heritage textiles is essential to any culture's identity and traditional craftsmanship. As these historical garments deteriorate and age, there is an urgent need for effective preservation and restoration methods to avert the loss of significant cultural artifacts. The challenge of accurately restoring

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the original appearance of these textiles, combined with the risk of secondary damage from physical intervention, underscores the necessity for innovative solutions that promote the longevity of these items [DL24]. Recently, advancements in three-dimensional (3D) reconstruction, 3D modeling, and virtual simulation have gained prominence, showcasing the potential of digital methods for restoring and preserving heritage costumes. In the digital restoration and reconstruction process, computer graphics software is essential for generating 3D clothing from two-dimensional (2D) images and prototypes. With the development of computer technology, 3D digital technologies, including 3D scanning, virtual reality (VR), and augmented reality (AR), have been increasingly applied to research in the field of cultural heritage [SPMPL22, DKL*24, KMM18]. Digital restoration serves as a practical alternative, facilitating the preservation and online dissemination of these garments while minimizing direct physical contact with delicate materials. This strategy not only safeguards the physical integrity of the clothing but also improves access to and awareness of cultural heritage for future generations. Recent advancements in learning-based 3D scene

Figure 2: *(a) Kimono and Victorian dress from the V&A collection. (b) 3D models of the Victorian dress and kimono created using photogrammetry.*

representations, particularly those utilizing volume rendering techniques such as Neural Radiance Fields (NeRF) [MST*20] and rasterization methods like 3D Gaussian Splatting (3DGS) [KKLD23], have demonstrated significant potential in photorealistic novel view synthesis applications. These methodologies have facilitated various extensions, including material asset generation [JTL*23], 3D style transfer [SGW24a, LZX*24], scene segmentation [QLZ*23], and spectral scene representation [SGW24b], thereby enhancing the versatility and effectiveness of 3D modeling techniques. Nevertheless, despite their advantages, methods based on these representations often struggle with issues such as halos, ghosting artifacts, and inadequate mesh quality. This is particularly problematic in cultural heritage contexts, where achieving high-fidelity reconstructions is crucial. In the field of polychromy, atlas-based segmentation has been employed alongside learning-based methods and high-quality scans to produce high-fidelity reconstructions [SKR*24]. We utilize a UV-parameterized texture map over the 3D surface created by commonly used 3D software packages like Blender to generate a 2D parameterized segmentation map by segmenting the texture based on colour segmentation and thresholding. This parameterized segmentation map, which we refer to as a segmentation atlas, is employed to colorize the heritage clothing in the fugitive regions in an appearance-aware manner. We used two real-world examples ––the Myriad Green Leaves silk kimono and a Victorian dress (see Fig. 2a) from the collections of the Victoria and Albert Museum (accession numbers FE.422:1-1992 and T.7&A-1926, respectively, dyed with fugitive materials). The Myriad Green Leaves silk kimono [FFM92], created by Furusawa Machiko in 1992 using the traditional Japanese resist-dyeing method of shibori with natural dyes, features a dominant green colour achieved by first dyeing the fabric with yellow (Miscanthus tinctorius) and then over-dyeing with indigo. Our technique provided various representations of the original green color, as the kimono has faded from vibrant green to paler colour observed after its 2020 display under halogen and LED lights. The V&A also houses a calico printed cotton dress [Pot85] produced in 1887 by Edmund Potter & Co., renowned for using engraved copper rollers and early synthetic dyes, featuring a design inspired by Japanese kamon circular emblems and Indian chintz. Although the specific dyes used remain undocumented, the blue-green, almost turquoise background has significantly faded due to environmental exposure, with brighter hues preserved in protected areas beneath the bodice flaps. Various representations of the turquoise colour were created using our virtual 3D reconstruction. In summary, the main contributions presented in this work are:

- An atlas-based approach for segmenting fugitive colors in heritage clothing, utilizing a 2D parameterized segmentation map to restore or simulate fading effects based on various sources of evidence, including spectral data, mockups, and reference images (see Figure 1). To the best of our knowledge, this is the first atlas-based restoration approach for heritage clothing, utilizing a 2D parameterized segmentation map.
- A web-based application developed using WebGL that enables the application of different data types (such as mockups and reference images) to fugitive regions, assisting experts in gaining a deeper understanding of restoration and fading processes (Demo video of the application). Additionally, we demonstrated the effectiveness of our application by restoring and simulating fading for two real-world examples: the kimono and the Victorian dress from the V&A.

2. Related Work

3D virtual reconstruction of heritage clothing: Heritage clothing reconstruction can be categorized into two main approaches. The first involves replicating an existing garment with a known original appearance, facilitating the digital reconstruction process thanks to detailed information about the garment's structure, color, and fabric. The second approach entails recreating garments that no longer exist, such as those illustrated in paintings, described in historical texts, or represented by clothing patterns. The absence of specific details in these cases poses considerable challenges for researchers, making the digital reconstruction process more intricate and time-consuming [DL24]. Recent advancements in digital reconstruction techniques from known original appearances have enabled the detailed modeling of various heritage garments, including traditional opera and folk costumes, while also addressing the complexities posed by damaged historical clothing [LZZL22, LWG*23, KNGT18, YZ23, LZZ22, WLJ*22, MWM21].These methods not only preserve and disseminate cultural heritage but also provide insights into historical clothing usage, making 3D reconstruction an essential tool in research and cultural preservation [LLZ23].The digital reconstruction of historical clothing with an unknown original appearance, such as those depicted in paintings, murals, and other artifacts, is a complex task that requires careful consideration of various factors, including style, size, fabric, color, and pattern blocks. Researchers must also account for the manufacturing technologies of the past and how they influence the final reconstruction [ZK19]. For instance, Kuzmichev et al. [KMM18] developed methods to parameterize historical pattern blocks and account for fabric deformations, enhancing the accuracy of virtual 3D models. Furthermore, interactions between clothing layers and objects must be carefully modeled to ensure that the reconstructed garments align closely with their historical prototypes [MKM19, KMMP18]. In our case, we focus on reconstructing the kimono and Victorian dress that exist but have experienced colour fading in specific areas. We employ an atlas-based approach to segment and restore these regions, as well as simulate fading. To the best of our knowledge, this is the first application of an atlas-based method segmenting material regions and segmentwise restoration simulation for reconstructing virtual heritage clothing.

Atlas generation and 3D atlas-based segmentation: Surface parameterization, a heavily researched field, frequently employs UV-maps for texturing [HLS07, SPR06]. Single-patch parameterization techniques typically target disk-like surfaces and prioritize area preservation, conformality, isometry, and injectivity, all while minimizing inevitable distortions. An adaptive strategy allocates more texture area to regions of importance. To reduce distortions, global parameterization techniques introduce seams to convert a surface into one or more disks, trading Gaussian curvature within patches for line curvature at their boundaries. Atlas-based UV-map methodologies map each disk onto an individual chart [SWG*03, ZSGS04, PTC10], while alternative approaches map the entire surface onto a singular chart [GGH02, PTSZ11]. Atlas-based 3D segmentation is widely used in medical imaging, as demonstrated by the work of David et al. [WAA*17]. Additionally, combining atlas-based and learning-based approaches effectively produces semantic shading and stylization in polychromy [SKR*24]. Since texture-based segmentation operates seamlessly in UV space, we applied this technique to segment the fugitive colors of heritage clothing, ensuring appropriate appearance in both the fugitive and non-fugitive regions.

Spectral unmixing and fading simulation: Hyperspectral imaging (HSI) analysis was proved to be useful for material characterization in historic textiles. A hyperspectral image has typically more than one hundred channels, that embed the spectral properties of the material captured, at pixel level. These high-dimensional data facilitates spectral unmixing techniques, where a hypespectral image is decomposed into a basis of independent elements, that describe the distinct materials in the captured scene. Grillini et al. (2024) [GdFP*24] focus on the application of hyperspectral imaging to study pre-Columbian textiles, highlighting the ability of spectral unmixing techniques to non-invasively map dyes and fibers, and revealing manufacturing processes and burial conditions of archaeological artifacts. Similarly, Vlachou-Mogire et al. (2023) [VMDGH23] demonstrate the utility of HSI in characterizing and mapping materials and dyes on historic tapestries, using spectral angle mapping (SAM) to identify and differentiate between various dyes and fibers, thus providing insights into the original colour palettes and conservation needs. In a review of computational techniques for virtual reconstruction of fragmented archaeological textiles, Gigilashvili et al. (2023) [GLG*23] emphasize the role of spectral analysis in automating the reconstruction process and reducing manual labor. While spectral unmixing has been explored in the study of historic textiles, to the best of our knowledge, there is no approach similar to ours, that simulates aging in textiles based on a hyperspectral image of a detail of the textile and accelerated aging data of mockups that imitate the textile's chemical composition.

3. Dataset

Our approach to fading simulation is based on multiple data sources and data capturing techniques, that include photogrammetry, hyperspectral imaging and photographic documentation of the museum objects (kimono and Victorian dress). In addition, we acquire the full spatially-varying appearance of mock-ups that imitate the composition of the kimono and Victorian dress, and that were artificially aged to show the unfaded and faded states of the relevant dyes.

Photogrammetry capture for 3D model generation: The Victorian dress and the kimono (see Fig. 2b) were mounted on a mannequin and on a T-bar structure, respectively; they were placed in a photographic studio and lit with continuous halogen lights that remained in the same position throughout the capture process. The lighting was kept soft and non-directional to avoid harsh shadows on object. A Sony Alpha 7 IV hybrid camera alongside a Sony 50mm f1.4 lens was used during capture, ensuring a >60% overlap between images in both x and y direction. The focus was set and not changed throughout the capture process. The software for image processing was Agisoft Metashape Professional.

Hyperspectral imaging. Reflectance imaging spectroscopy (400–1000 nm, 128 bands, 4.5 nm step) was performed with a SOC 710 camera (Surface Optics Corporation), capturing 13 × 17 cm² frames (0.25 mm resolution) at 1.3 m distance. Illumination was provided by two 300W halogen lamps (reflectance) and two 405 nm LED lamps (fluorescence), positioned at 45° relative to the surface.

Reference documentation images: Several digital images of details in the kimono exist in the museum's archive. The earliest dates back to 2006 (front-side), followed by 2019 (front-side), then 2024 when the reverse-side of the inner folds of the kimono, hidden from light exposure, was captured as well. For the Victorian dress, there is a digital image with the reverse-side from 2024.

Mockups and artificial aging: The textile mockups for the kimono and dress (see Figure 3) dyed with natural and synthetic dyes respectively under controlled conditions, allowed for the systematic analytical study of dye stability, degradation mechanisms, and material interactions. In detail, for the kimono mockups, dyed silk was prepared through artisanal dyeing process using a mixture of Miscanthus tinctorius with indigo to obtain a green hue. For the artificial aging process, a halogen lamp and a LED at 5000 K were used simultaneously, with an average irradiance of 4.28 x 10^3 W/cm^2, for a total of 259 hours of light exposure, which corresponds to 2.5 years of museum lighting conditions. colour changes were monitored spectroscopically using colorimetry and reflectance techniques. For the Victorian dress, dyed cotton mordanted mockups were prepared for the turquoise colour. The mockups were hand-dyed using a basic green triarylmethane dye.

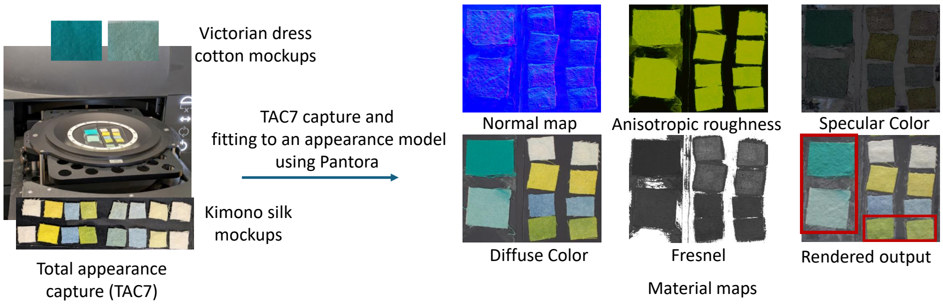

Figure 3: *Appearance capture using TAC7 [KRFS18] and fitting to the appearance model using Pantora [X-R19] were performed on the kimono silk and Victorian dress cotton mockups created by a conservation scientist. The mockups that represent the original colors of the kimono and Victorian dress are marked with red boxes.*

For the artificial aging experiment, a Xenon lamp, filtered by water and UV filters, was employed, with an irradiance of 1.58 x 10^4 W/cm^2 for a total of 203 hours of light exposure. colour changes were monitored spectroscopically with colorimetry and reflectance techniques. While the colour may not exactly match the original garments, the chemical composition of the dyes and substrates is reproduced, enabling a reliable simulation of photodegradation processes. The mockups were monitored under artificial photoaging, providing comparative data to better understand the complex chemistry involved during their fading processes.

Appearance capture. The state of the art in physically based rendering utilizes spatially varying reflectance models, with the primary goal being to acquire spatially varying bidirectional reflectance distribution function (SVBRDF) from real-world samples. We use the Total Appearance Capture (TAC7) [X-R18, KRFS18, MWK17] developed by X-Rite to capture accurate SVBRDF of the mockup samples. The TAC7 is a commercially available scanner designed to capture the appearance of materials. It operates using Pantora software [X-R19], which supports postprocessing and optional editing of the resulting SVBRDFs. The TAC7 consists of a hemispherical array of 29 white LEDs and four monochrome cameras positioned in an arc above a rotating turntable. Five of the LEDs are fitted with colour filter wheels containing 10 filters that span the visible spectrum. To achieve a finely detailed sampling of reflectance lobes, a strip-type light source, referred to as a linear light source, can be rotated in the space above the sample holder. For each material measured, we collect 100 colour images, 348 monochrome point-lit images, and 280 linear light source images [MHRK19]. Additionally, a structured light projector captures low-resolution surface geometry, and transparent materials can be illuminated from below with an LED that passes through a diffusor plate in the sample holder. The TAC7 typically takes 30 minutes for low-gloss anisotropic fabrics [MHRK19]. It detects fluorescence and warns users but does not account for it in measurements, though a mask may identify fluorescent fabric sections.

4. Methodology

Our method allows the 3D digital restoration of heritage clothing by segmenting faded regions within the texture atlas (Figure 1), maintaining a rigid and stationary setup. This texture atlas, also known as the segmentation atlas, is created through 2D parameterization, which maps multiple smaller segments into a single large image while efficiently packing them and assigning UV coordinates for proper alignment and overlap prevention. The generated segmentation atlas is then used for restoring and simulating the colors in the faded regions.

Atlas-based segmentation To generate the segmentation atlas, we employ HSV (Hue, Saturation, Value) color-based segmentation with thresholding to identify and isolate the faded regions within the parameterized texture atlas, as illustrated in Figure 4. For the *i-th* faded region the thresholds are defined as $H_{min}^{(i)} \leq H_{max}^{(i)}$, $S_{min}^{(i)} \leq S_{max}^{(i)}$ and $V_{min}^{(i)} \leq V_{max}^{(i)}$ for hue, saturation and value respectively. The overall condition for segmenting a pixel in the $i-th$ faded segment can be expressed as:

$$(H_{\min}^{(i)} \leq H \leq H_{\max}^{(i)}) \wedge (S_{\min}^{(i)} \leq S \leq S_{\max}^{(i)}) \wedge (V_{\min}^{(i)} \leq V \leq V_{\max}^{(i)}) \quad (1)$$

The 3D construction of the kimono and Victorian dress using photogrammetry provided the texture atlas, which we utilized to generate the segmentation atlas through the aforementioned method. However, CAD data often lacks a texture atlas, which can be created using tools similar to Blender's "Smart UV Project" algorithm [Ble24]. We created a custom shader that utilizes the UV-parameterized segmentation atlas to achieve the desired appearance modeling for the different segments of the heritage clothing.

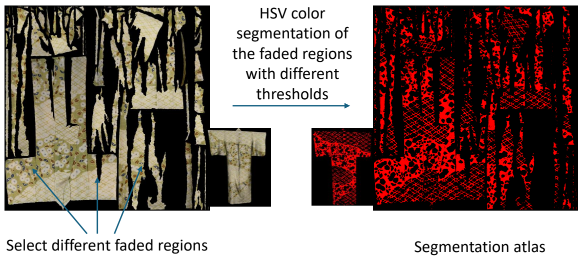

Figure 4: *Segmentation atlas generation by HSV colour segmentation of the faded regions using different thresholds.*

Appearance modeling We captured the appearance of textile mockups (kimono silk and Victorian dress) using the TAC7 device.

After the capture, we extracted the material maps using Pantora [X-R19]. This software fits the appearance capture with a SVBRDF and produces the corresponding material maps, as shown in Figure 3. To the best of our knowledge, the fitting model provided by Pantora is considered state-of-the-art for achieving high-quality material fits. The anisotropic SVBRDF resulting from a TAC7 measurement consists of 13 channels: comprising 3 channels for diffuse color, 3 channels for normal maps, 3 channels for specular color, 3 channels for anisotropic roughness, and 1 channel for Fresnel (see Figure 3) The appearance modeling in the TAC7 is defined by the combination of diffuse and specular terms, as represented by the following equation:

$$f(i,o) = f_d(i,o) + f_s(i,o) \tag{2}$$

where, i denotes the incoming light and o represents the outgoing light at a point on the object's surface. The diffuse term represents Lambertian reflectance behavior as:

$$f_{\text{Lambert}}(i,o) = \frac{\rho_d}{\pi} \tag{3}$$

where, ρ_d represents the diffuse colour map. The specular term can be expressed using microfacet theory, as proposed by Cook-Torrance [CT82], with the specular BRDF modeled as follows:

$$f_s(i,o) = \rho_s \frac{F(i,h)G(i,o,h)D(h)}{4|i \cdot n||o \cdot n|} \tag{4}$$

where $F(i,h)$ is the Fresnel term, $G(i,o,h)$ is the geometric attenuation term, $D(h)$ is the microfacet distribution function, i and o are the incoming and outgoing light directions, respectively, n is the surface normal, and h is the halfway vector between i and o.The Fresnel term is attenuated using Schlick's Fresnel approximation as shown in equation 5.

$$F_{\text{Schlick}}(i,h;F_0) = F_0 + (1-F_0)(1-(i \cdot h))^5 \tag{5}$$

where F_0 is the Fresnel map representing the total hemispherical reflectance of the specular BRDF in the normal direction. The microfacet distribution function ($D(h)$) and geometric attenuation term ($G(i,o,h)$) follows the GGX BRDF model [WMLT07]. The distribution term ($D(h)$) is the Trowbridge-Reitz microfacet distribution and is represented as:

$$D^{TR}(h;\alpha_x,\alpha_y) = \frac{1}{\pi\alpha_x\alpha_y} \frac{1}{\left(\frac{h_x^2}{\alpha_x^2} + \frac{h_y^2}{\alpha_y^2} + h_z^2\right)^2} \tag{6}$$

where α is the anisotropic roughness map.The geometry attenuation term (($G(i,o,h)$) is defined in its separable variant by Smith:

$$G^{\text{Smith}}(i,o,h;\alpha_x,\alpha_y) = G_1(i,h;\alpha_x,\alpha_y) \cdot G_1(o,h;\alpha_x,\alpha_y) \tag{7}$$

The Cook-Torrance reflectance model, along with the Fresnel term, geometric attenuation, and microfacet distribution, is implemented in our custom shader to match the appearance model used by Pantora for fitting the appearance capture.

Fading simulation and spectral unmixing: Our fading simulation methods assume that we have either mockups that imitate the appearance and chemical composition of the dyes in the textiles and that underwent artificial aging, or that we have visual records (reference photographs) that capture the colour of the objects at different moments in time. The series of spectral reflectance measurements of the mockups at all the time steps considered during the accelerated aging experiment can be combined with the appearance modelling explained in the previous section to simulate the colour change in the textiles in a continuous way temporally-wise. By replacing the appearance of the objects with that of the mockups, we are aiming at restoring the original appearance of the object (when using the first temporal measurement) and gradually fading it by covering the full time-span of the accelerated aging. This implies that the mockups fully and completely characterize the appearance of the real objects. However, this is an idealization and it can be further improved by linking the appearance of the mockups with that of the current state of the object. We achieve this by performing spectral unmixing in those details from the textiles scanned with HSI. In particular, we decompose the hyperspectral images into the constituent pure materials (also known as endmembers) of the two textiles. The spectral signatures of the endmembers are taken from the mockups for those materials that were recreated with mockups, and from the hyperspectral image itself for those materials not covered by the mockups. After spectral unmixing, we obtain the abundance of the dyes at each pixel in the hyperspectral images, usually called abundance maps, as shown in Figure 5. Then, to simulate fading, we can recompose the hyperspectral image, by remixing the abundance maps with the aged or unaged spectra of the mockups.

Semantic restoration and web application: The segmentation atlas utilized by the custom shader semantically restores fugitive colors by applying the necessary material assets, fading data, or reference image data. The material maps generated from the TAC7 are combined with the reference image or fading data by replacing the diffuse colour with the corresponding image textures. This approach makes our restoration and fading appearance-aware, allowing for relighting with various light types and colour temperatures. Our application and shaders are implemented in Three.js, which utilizes WebGL for rendering (see Figure 6). The application supports three modes of visualization:

- *Mockup appearance:* The material maps of the mockups (both aged and unaged) can be applied to the fugitive colors for appearance-aware construction.
- *Spectral unmixing:* By combining the accelerated aging data of the mockups with spectral unmixing techniques, a correlation is found between the fading of the mockup and the fading of the objec. This is represented by texture images that show a sequence of fading, and that are applied to the segmented fugitive colors.
- *Reference image data:* Textures from reference documentation images representing the object in the past, can be applied to fugitive colors to visualize restoration.

The application also supports outputting the diffuse colour while ignoring the other material maps. In both the spectral unmixing and reference image data modes, the diffuse colour is replaced with the corresponding image textures, while the remaining material maps are left unchanged to create an appearance-aware rendering.

5. Results and evaluation

To demonstrate the potential of our approach, we present both quantitative and qualitative evaluations, as well as assessments from experts in the field of conservation science.

Figure 5: *Dye abundance maps obtained with spectral unmixing from the hyperspectral images of the details in the Victorian dress (left) and kimono (right). For the Victorian dress, we first define the turquoise endmember with the spectral signature of the corresponding unaged mockup (top row). This is used for fading simulation from present to future. Then, in the bottom row, we extract the signature of the turquoise endmember from the hyperspectral image itself, as this dye is applied purely and unmixed. This is used for attempting to virtually restore the original colour in the dress. The green in the kimono is a mixture of miscanthus and indigo, so we perform the unmixing with the two spectra of the dyes taken from the unaged mockups. Because the detail scanned with HSI contains both green in good condition (top center) and faded green where indigo has severely depleted (left margin), we can simulate both the restoration of the past colors and the present to future discoloration, respectively.*

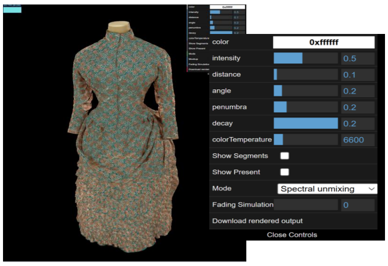

Figure 6: *Our application showing the spectral unmixing mode.*

5.1. Qualitative analysis

We perform qualitative analysis based on the different evidences for restoration of the fugitive colors based on which defined the visualization as described in Section 4 — restoration using appearance capture from mockups, Fading simulation based on spectral unmixing and restoration based on reference images. The qualitative analysis for all three modes has been conducted by a conservation scientist who is an expert in this area of research and analysis.

Mockup appearance: The material maps derived from the TAC7 measurements were applied to evaluate the fugitive colors of both the kimono (Figure 7) and the Victorian dress (Figure 8). This comparison reveals how the aging process has transformed the appearances of both the kimono and the Victorian dress. The unaged (b) and aged (c) mockups of the kimono, assessed under a 6600K light source, illustrate shifts in colour and material characteristics over time. Similarly, the Victorian dress is evaluated, providing a comprehensive understanding of the effects of aging (Figure 8). The colors replicated in the mockup, based on historical dye recipes from the literature, are speculative and do not precisely match the garments' original appearance. However, the chemical formulations of the mockups do enable a robust visual simulation of actual photofading in the fugitive regions of the kimono and dress.

Spectral unmixing: The fading simulation through spectral unmixing demonstrates the progressive change of colour vibrancy (Figure 9) in both the kimono and Victorian dress over time, highlighting the impact of aging on their respective appearances. Fading simulation through spectral unmixing associates any colour change to actual chemical changes permitting a meaningful tracking of the progressive loss of colour directly correlated to the behavior of the original materials. The spectral unmixing approach offers a more analytically accurate method to model the photodegradation and assess dye stability over time in both the kimono and the Victorian dress.

Reference documentation images: The reconstruction of the kimono using reference images (Figure 10) reveals notable changes in colour and detail from 2006 front-side (a) to 2019 front-side (b), illustrating the effects of time on its appearance. Similarly, the reverse side view of the kimono (c) photographed in 2024 show less fading compared to the present day appearance captured in the 3D model (see Figure 7(a)), providing valuable insights into how the colors may have looked like originally. Nevertheless, it seems that the reconstruction based on the reverse side of the kimono falls in-between the 2006 and 2019 reconstructions. This is expected, as although the reverse side was not exposed to light, other non-tracked aging factors (humidity, temperature) probably provoked discoloration in the inner folds of the kimono as well. Similar to the kimono, when we compare the reverse side reconstruction of the Victorian dress (Figure 10 (d)) with its present-day appearance captured in the 3D model in Figure 8 (a), we can see that the former is less faded than the latter. Reconstructing colour changes from time-lapsed photographs allows for retrospective modeling of degradation. It provides important qualitative insights into the temporal evolution of dye fading and the long-term behavior of historic textile materials without providing evidence of environmental implications of any colour alterations. However, an important limitation when using documentation pictures recorded in various years in the past is the ambiguity given by subjective choices in the photography, such as the various view-illumination geometrical setup and the possibly different post-processing operation. In future, we plan to ensure colour consistency throughout the pictures from various sources and years by applying colour management techniques.

Relighting: The estimated material maps allow relighting of the kimono and Victorian dress under various conditions, as shown in Fig. 11 with a warm 3500K light. Our appearance-aware pipeline enables realistic visualizations of these textiles under different lighting scenarios.

5.2. Quantitative analysis

In this section, we assess the impact of applying mockups, fading data, and reference images on fugitive colors by comparing the rendered output of the appearance model using the colorfulness met-

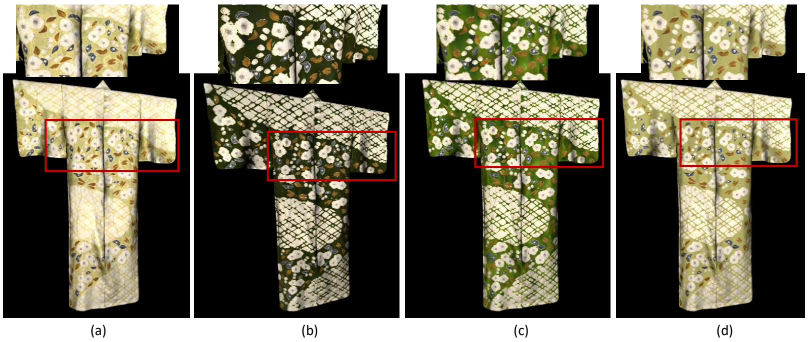

Figure 7: *Comparison of the Kimono's present-day appearance as perceived in the 3D model (a) with simulations using the representative mockups: unaged with reduced exposure (b), unaged as captured with TAC7 (c) and aged (d) as captured with TAC7. Renderings employ a spot-light source with a colour temperature of 6600K.*

Figure 8: *Comparison of the Victorian dress's present-day appearance as perceived in the 3D model (a) with simulations using the representative mockups: unaged (b) and aged (c) as captured with TAC7. Renderings employ a spot-light source with a colour temperature of 6600K.*

ric [HS03]. This metric quantifies the overall colorfulness of natural images based on human visual perception, where a higher value indicates a more colourful image. Colourfulness has been previously used to assess the performance of colorization of black and white images [vGVv21]. Ideally, in simulation of colour change in artworks, colourfulness would increase when we are dealing with colour restoration and it would decrease when we are dealing with future fading. However, it is important to mention that aging might incur more complex colour changes, such as hue shifts and/or darkening, which might give different fluctations in the colourfulness metric.

Table 1 compares the colorfulness metric of two heritage garments, the kimono and Victorian dress, under faded and unfaded conditions after applying appearance capture of mockups using TAC7. Notably, the Victorian dress exhibits a significant increase in colorfulness when restored from its currently faded state, indicating that the virtual restoration manages to retrieve the loss in colour saturation.

Heritage Clothing	Colorfulness Metric	
	Faded mockup	Unfaded mockup
Kimono	16.72	16.79
Victorian dress	16.01	24.41

Table 1: *Restoration from mockup: Comparison of colorfulness after applying appearance capture of mockups using TAC7. Faded and Unfaded represent rendered outputs after the application of aged and unaged mockups.*

Table 2 presents a comparison of the colorfulness metric for the kimono and Victorian dress after applying colour from reference images from the reverse of the kimono, as well as from the years 2006 and 2019. The kimono shows varying colorfulness scores, with a notable peak in 2006 at 11.07, which is expected since it was less faded, while the 2019 score is similar to the reverse reference. In contrast, the Victorian dress's reverse score of 17.25 is slightly more than its faded score (refer Table 1), suggesting that the unfaded mockup version has greater colorfulness than the reverse, although other reference images are unavailable for comparison. The colorfulness metric for the kimono and Victorian dress at

Heritage Clothing	Colorfulness Metric		
	Reverse 2024	Front 2006	Front 2019
Kimono	10.71	11.07	10.28
Victorian dress	17.25	-	-

Table 2: *Restoration from reference images: comparison of colorfulness after applying colour from reference images of the reverse-side of the kimono, 2006 and 2019. We present in addition the colourfulness of the Victorian dress as recolored with the reference image of the reverse side from 2024.*

various stages of simulated fading are shown in Figure 12) show a progress. The steps in x-axis cover a different timespan from case to case, as explained in the main text. Thus, for the Victorian dress simulation based on only mockup (blue curve), step 0 would be the original appearance at time 0, and step 18, fading of the original appearance to the indicated illuminance. The decreasing values of

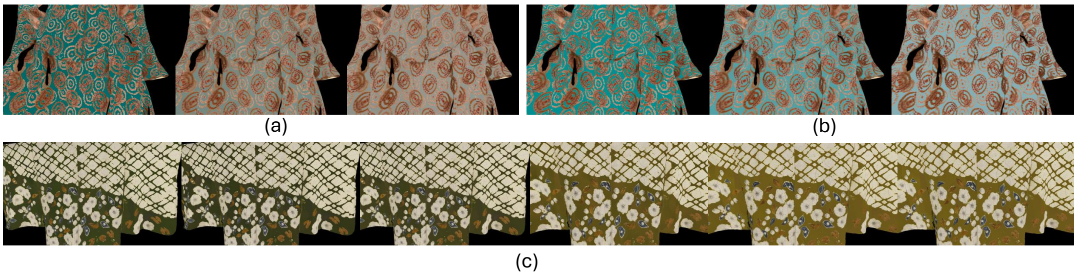

Figure 9: *Top row: fading simulation through for the Victorian dress at various time intervals – hypothesized original color, current colour today and fading expected in the future – (a) considering correlation of the mockups with the actual heritage clothings through spectral unmixing and (b) considering only mockups. Bottom row: fading simulation of the kimono using spectral unmixing (c). The* 1^{st} *picture in the sequence represents the restoration to a good-state green from the inner folds of the kimono, while the* 3^{rd} *image considers 2.5 years of fading from the restoration, assuming controlled display conditions as observed with the mock-ups. Gradually, in areas, the mixture of mischantus and indigo dyes will start to fade,, shifting the hue from green to a brown or "muddy" green, as it is in the present-day (the* 4^{th} *image). Finally the* 6^{th} *picture shows the future green colour, following an expected 2.5 years of display. The* 2^{nd} *and* 5^{th} *images represent speculated intermediate aging steps.*

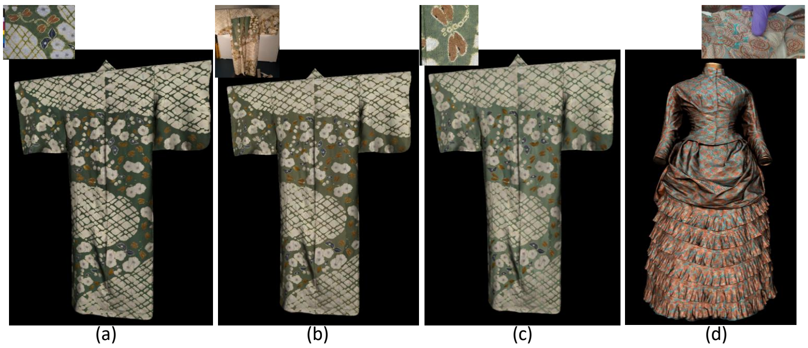

Figure 10: *Reconstruction of the Kimono's past colours using reference documentation images visible in the top corners: (a) from 2006, (b) from the reverse, unexposed to light side of the Kimono, and (c) from 2019 , alongside the Victorian dress (d) from the reverse side, all illuminated under a spotlight with a colour temperature of 6600K.*

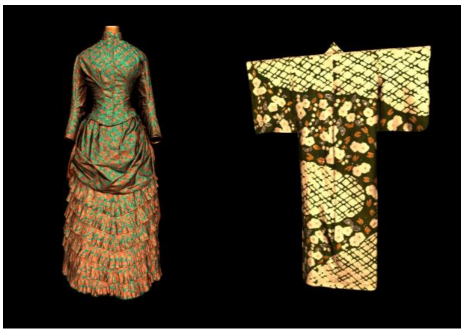

Figure 11: *Relighting of the Kimono and Dress using a spotlight source with a colour temperature of 3500K.*

colourfulness with time are consistent with the fading of the green dye in the Victorian dress. For the spectral unmixing simulation of the Victorian dress (orange curve), step 0 means original appearance at time 0, step 1 present-day appearance, and step 18, the future appearance after under expressed conditions. Also here, we notice a decreasing trend in colourfulness. However, in this case we have a swift jump from the restoration of the past colours (step 0) to present-day (step 1). Then, the transition from present to future (step 18) is significantly more subtle, as the colorfulness values change only marginally. For the kimono simulation with spectral unmixing (green curve), time step 0 corresponds to restoration to a good-state green, time step 10, the previously mentioned restoration plus 2.5 years under current exhibition conditions, time step 11, present-day appearance and time step 18, future appearance after 2.5 years of display. Contrary to the Victorian dress, we have increasing colourfulness values for the kimono between past, present, and future. The green in the kimono is a mixture of two dyes, whereas the turqouise in the Victorian dress is a single dye. For this reason, it is plausible to consider that the aging mechanisms in the kimono are more complex, and involve not only fading, but also hue shifts. More precisely, on fading the kimono, the mixture of michantus and tinctoria takes on an intermediate brown hue before becoming ultimately yellowish. This hue shift can be followed with the visual results in Figure 9.

Heritage Clothing	Avg. Render Time (ms)	Memory Usage (MB)
Kimono	0.21	274
Victorian dress	0.36	585

Table 3: *Average render time and memory usage for heritage clothing colour change simulation.*

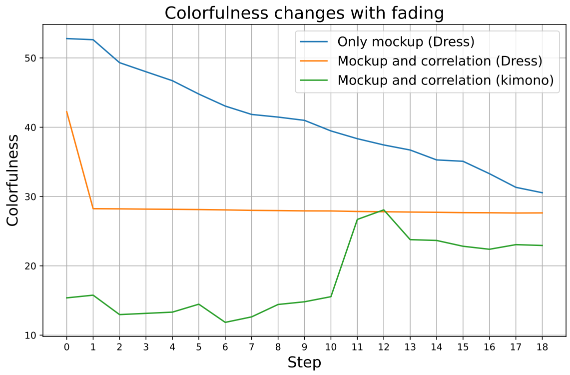

Figure 12: *Plot of the colorfulness metric for the various simulations. Note that the steps in x-axis cover a different timespan from case to case, as explained in the main text.*

We also conduct a performance analysis of the 3D models to demonstrate their efficiency and effectiveness in rendering various heritage clothing items. The average render times and memory usage (see Table 3) for both the kimono and Victorian dress are plausible, making them suitable for use on most modern devices, including smartphones, tablets, and XR devices, which support high frame rates (FPS). This efficiency underscores the potential for real-time applications in various contexts, enhancing user experiences without compromising performance.

6. Conclusion and future Work

This work demonstrates a novel approach for virtually restoring and simulating fading effects in heritage clothing, focusing on two real-world examples: the kimono and the Victorian dress. By modelling the appearance of the textiles and the mockups that recreate their materiality, we manage to characterize the aging behaviour of the fugitive dyes. With the atlas-based segmentation, we manage to apply the colour change simulation over the entire extent of the object's surface, even there where the fugitive dyes have significantly faded. The quantitative and qualitative analyses reveal the effectiveness of the proposed atlas-based segmentation method and the accompanying web-based application. This tool allows experts and lay audiences to visualize and understand the various evidence sources, such as spectral data, mockups, and reference images — providing valuable insights into the restoration process and enhancing the accuracy of colour simulations.

Future work can focus on refining segmentation techniques specifically for the Victorian dress, allowing for a more precise restoration of faded areas with diverse colour variations. The use of more representative mockups, particularly when based on accurately reconstructed dye recipes, is expected to significantly improve the fidelity and overall quality of digital restorations. Exploring learning-based approaches for lightweight material estimation, although not as effective as the traditional devices used, represents an exciting avenue for future research.

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