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A Spectral Approach to Digitally Restore a Faded Agfacolor Print from 1945

Giorgio Trumpy; Norwegian University of Science and Technology; Gjøvik, Norway
Sreya Chatterjee; University of Applied Sciences; Berlin, Germany

Abstract

The negative-positive chromogenic process, despite being an important milestone in the evolution of color motion picture film technology, exhibits significant fading of its image dyes, leading to the loss of chromatic integrity. A complete spectral approach for the digital restoration of chromogenic film is proposed. A material-based image processing method allows to extract the residual color information associated with the analytical densities, selectively enhance the faded dyes, and finally recreate the original aesthetics by associating the spectral properties of the film stock.

Introduction

One of the most significant challenges in the preservation of cinematographic heritage is the fading of the image dyes, which compromises the original color, commonly resulting in the pink/magenta cast of old films. This is a prevalent problem for chromogenic materials produced between the 1940s and 1980s, whose dyes were often photochemically and thermodynamically unstable. The gravity of this deterioration has been highlighted in the film preservation community since the 1970s [1,11,19].

While chemical treatments have not proven to be adequate for the restoration of faded film, digital image processing has been used over the last decades to numerically reverse the fading. Gschwind and colleagues' research into describing the contribution of the dyes' side absorptions in the image capture, developing the linear bleach model, and conducting accelerated fading tests [7,8] laid the required foundation for the development of a complete spectral approach to digital dye reconstruction. Based on the linear bleach model, Ando et al. proposed a digital restoration method that uses correction matrices to account for the side absorptions, in which the matrix coefficients were determined with target reference colors [3]. Chambah and Besserer, further attempted to remove effect of the side absorptions in the digitization process by testing the effectiveness of correction matrices based on both linear and offset bleach models [5]. These previous methods, however, did not use the spectral densities of the dyes to (I) quantitative determine the contribution of each emulsion layer to the image formation based on the RGB spectral sensitivities of the digital imaging system and (II) compute the supposed color aesthetics of the original film before fading.

A complete digital restoration method

The present paper proposes a new material-based approach that adopts principles of color science and image processing techniques to digitally restore the faded colors and reconstruct a supposed original look of film projection before fading.

The method is based on two main assumptions about chromogenic film stock. **1 -** Considering the film a non-scattering material, the Beer-Lambert law can be considered valid, so the overall spectral density of the film is the sum of the spectral densities of the individual dyes with weights corresponding to their local concentrations. **2 -** The fading of a dye can be modeled as a single multiplication factor that uniformly reduces the spectral densities of the individual emulsion layer containing the fugitive dye. In view of the above assumptions, the absorption spectrum of a film at a certain position (x,y) is derived by the following equation:

$$ABS_{film}^{(x,y)}(\lambda) = \sum_{i \equiv C,M,Y} \left(\frac{1}{F_i} \cdot k_i^{(x,y)} \cdot ABS_i(\lambda) \right) \quad (1)$$

where the absorption spectrum of each emulsion layer is given by the product of $ABS_i(\lambda)$—indicating the dye's characteristic spectral density—the weight k_i—corresponding to the local dye concentration—and the inverse of the factor F_i—a value greater than 1 that expresses the degree of dye fading. The overall film absorption spectrum $ABS_{film}(\lambda)$ is the sum of the absorption spectra of the C, M and Y emulsion layers.

The proposed digital restoration method is the completion of an already published work [17]. The complete procedure that is here presented unfolds in five steps:

1) Image capture - The residual color information present in the film is digitized with a dedicated RGB imaging system that uses narrow spectral sensitivities and captures high bit-depth images. The narrow RGB bands allow to minimize the 'cross-talk' effect due to the dyes' side absorptions, thus capturing images whose correlation with the transmittances of the individual emulsion layers is highest [16]. Low cross-talk means that the R, G and B bands primarily capture the cyan, magenta and yellow layers respectively.

2) Dye purification - Even though the dyes' cross-talk is minimized with narrow RGB bands, the captured images contain a mixed contribution of all three dyes, and this is especially true in case of faded dyes (see for instance the percentages in Fig. 2). Thus, a computational method is necessary to obtain images corresponding to the individual emulsion layers of the film. This image processing method is called "dye purification" and will be described in the following pages.

3) Digital unfading - Once the images corresponding to the transmittances of the individual emulsion layers are calculated, the original film colors are obtained counterbalancing the fading factors F_i (see Eq. 1). The unfading factors to be applied to the absorbance values are determined considering unexposed parts, which were supposedly black before fading. Therefore, the unfading factors are set to render an equalized high density in the unexposed parts for all three dyes.

4) Spectral reconstruction - The restored images contain monochromatic transmittance values that correlate to the weights $k_i^{(x,y)}$ of Eq.1 via a logarithmic relation. To obtain the final aesthetic of the unfaded film, it is necessary to build a spectral cube in which each pixel contains the film transmittance in the full visible range. This is done following the model expressed by Eq. 1, so the values of the restored images weight the characteristic spectral densities of the film dyes according to their local concentrations.

5) Color calculation - By leveraging the psychophysical properties of the human visual system [12], the final aesthetic of the restored film is calculated from the spectral cube considering the illumination condition of film projection.

A faded Agfacolor print

Figure 1. *A film frame of "Panorama No. 4". The fading of the yellow and cyan dyes gives an overall pinkish cast. The dark unexposed area in between the frames turned from black to purple.*

To test this approach, a case study was conducted on an Agfacolor print from 1945. This unique element—a 35 mm combined positive on a cellulose acetate base—was a projection print of the "Panorama No. 4", a cultural film of the Third Reich. The monthly series "Panorama" was produced for neutral foreign territories at the fag end of the Second World War [2], trying to depict a prosperous image of the Reich. The film series was created using the newly introduced three-color subtractive Agfacolor negative-positive process, which was a substantial breakthrough in the development of chromogenic film due to its diffusion-resistant dye components. Agfacolor was deemed an adequate competitor of Technicolor, which was the market leader of professional filmmaking despite the elaborate paraphernalia it necessitated for shooting and processing [9]. Given its straightforwardness in filming, processing and projection [13], Agfacolor was promptly incorporated into the propaganda machinery as a coveted national symbol of technical innovation.

The subdued pastel-like palette of Agfacolor painted a surreal yet familiar world of beauty, prosperity, calm and hope, opposed to the dreary reality of the Second World War. "Panorama No. 4", which was the last of the "Panorama" series, is a discordant juxtaposition of visually mesmerizing imageries of a glassmaking factory, acrobatic feats at a local circus, combined with wartime training and maneuvers, shot using two distinct Agfacolor negative types, Type B and Type G, which were introduced in 1940 for filming respectively in daylight and incandescent light [4].

Nonetheless, the chemical stability of the Agfacolor negative-positive process was limited, and the fading of its fugitive image dyes—yellow and cyan—led in the course of time to a strong magenta coloration.

Archival records indicate that between 1950-1980 new film elements were created from the "Panorama No. 4" print, both positives and negatives [20]. A comparison with these elements illustrates that the dye fading has become progressively stronger in the course of time. Each of these elements documents different stages of this irreversible chemical deterioration, of which the original-most element—the 1945 combined positive print—appears to be the worst affected. However, none of the duplicates can be considered an accurate copy, thus the 1945 original Agfacolor print is the only film element that can be used as source material for the proposed process of digital restoration.

A thorough bibliographical research led to the determination of the optical properties of the dyes used in Agfacolor positives during the time period when "Panorama No. 4" was produced [14]. This finding was pivotal to determine the spectral densities of the 1945 Agfacolor print, which were essential to reconstruct—to the best of our knowledge—the original aesthetics of the faded film.

Image capture

To reconstruct the faded dyes of "Panorama Nr. 4" using the dye purification process, the film element was digitized with a multispectral scanner constituted by a 6-channel LED illumination system and a 16 MP monochrome camera. The sequential capture of each film frame with six narrow-band images allowed the recording of accurate colors to document the current material state (see Fig. 1) [18]. For the digital restoration procedure, however, only three bands were used out of the six: the RGB bands with sensitivity peaks at 415, 530 and 657 nm (reported as dashed lines in Fig. 2).

In view of the fading tests conducted by Gschwind and Frey [8], the fading of chromogenic dyes can be considered a homogeneous reduction of the original dye concentrations and be modeled as a multiplicative factor that attenuates the original spectral densities of the individual dyes (as expressed by Eq. 1). To obtain the maximum spectral densities of the faded film, the spectra found in [14] were processed with fading factors, so the resulting integral film density (the black solid line in the plot of Fig. 2) corresponds to the purple color of the darkest area in between the film frames.

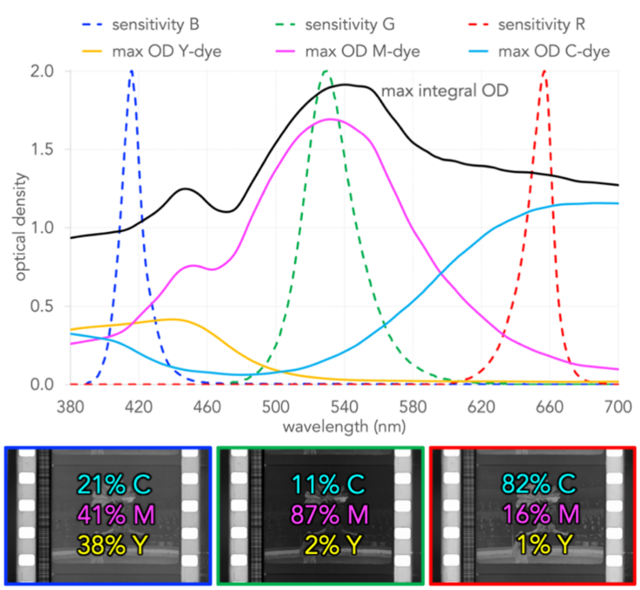

Figure 2. *Top: The normalized spectral sensitivities of the RGB image capture (dashed lines) plotted together with the maximum analytical and integral densities of the faded film stock (solid lines) derived from [14]. Bottom: The calculated percent contribution of each dye to the total film absorbance in the three digital images.*

The resulting spectra reported as solid lines in the plot of Fig. 2 indicate that the yellow dye is highly faded, the cyan dye is partly faded, and the magenta dye is well-preserved. These curves allow to quantitatively determine the contribution of each emulsion layer to the overall absorbance of the film, as this is recorded during the image captures according to the RGB spectral sensitivities (dashed lines). The percentages reported in the bottom of Fig. 2 indicate that the blue is a mix of all three dyes, while the green has primarily magenta with some cyan, and red has cyan with some magenta.

Dye purification

The percentages reported in Fig. 2 allow the development of a dye purification procedure [17]. To initiate the process, a fundamental approximation is required: the image captured with the green LED has the highest percent value and is assumed to be pure magenta. The absorption contribution of the magenta emulsion layer in the image captured with the red LED can now be calculated and subtracted from the image, thus obtaining pure cyan (ignoring the 1% of yellow). Finally, the absorption contributions of the magenta and cyan emulsion layers in the image captured with the blue LED are calculated and subtracted. So, the described procedure provides images that contain the transmittance values of the individual emulsion layers.

Digital unfading

The dye purification process allows to numerically increase the density of the individual emulsion layers in a selective manner. To restore the original colors of the Agfacolor print, the densities of the faded yellow and magenta layers have to be increased. There is no reference that can establish what is the correct density increase. However, it is fair to assume that unexposed parts of the film were neutral black before fading. Therefore, the densities of yellow and magenta were increased to obtain a neutral black for the unexposed areas of the film, and they were finally adjusted to obtain a chromatically balanced image at the end of the process.

Spectral reconstruction

Following the linear model represented by Eq. 1, the original absorption spectra of Agfacolor positive material reported in the historical literature [14] were associated with the restored images to create a hyperspectral cube that represents the optical properties of the film before fading in the whole visible range.

Color calculation

The final aesthetic of the restored film was calculated from the spectral cube performing colorimetric calculations [18] considering the spectral emission of a Xenon arc bulb used in film projections and saving RGB values in the DCI-P3 standard space.

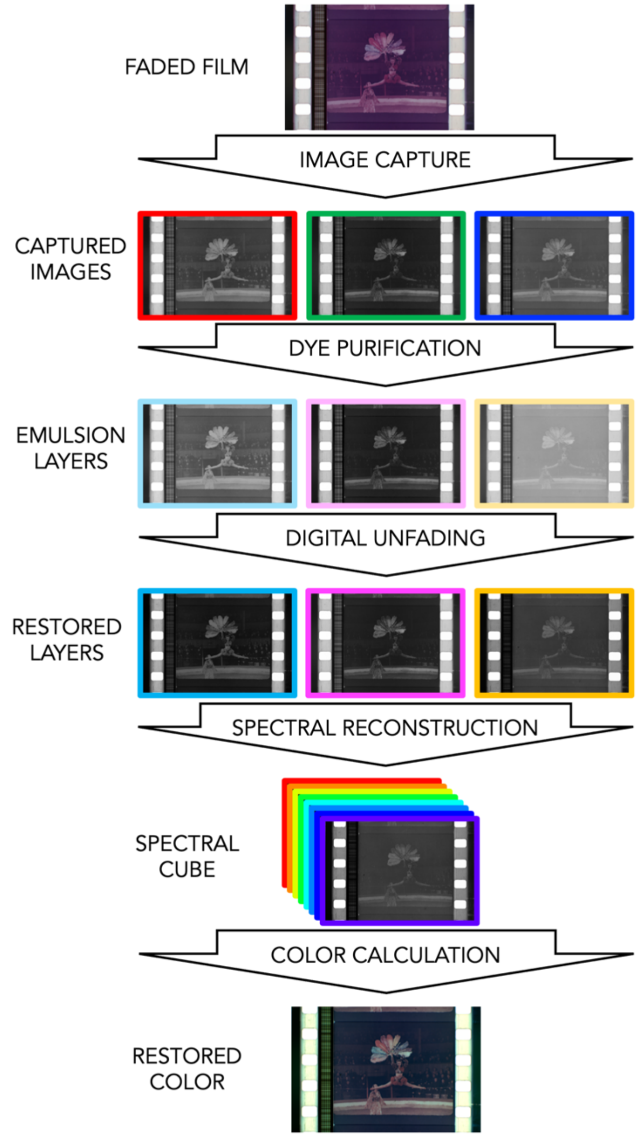

Figure 3. *Diagram depicting the five steps of the proposed spectral approach for the digital restoration of faded chromogenic film.*

Results

The current state of the faded Agfacolor film and the result of the digital restoration process are reported in Fig. 4 for four selected frames of "Panorama Nr. 4".

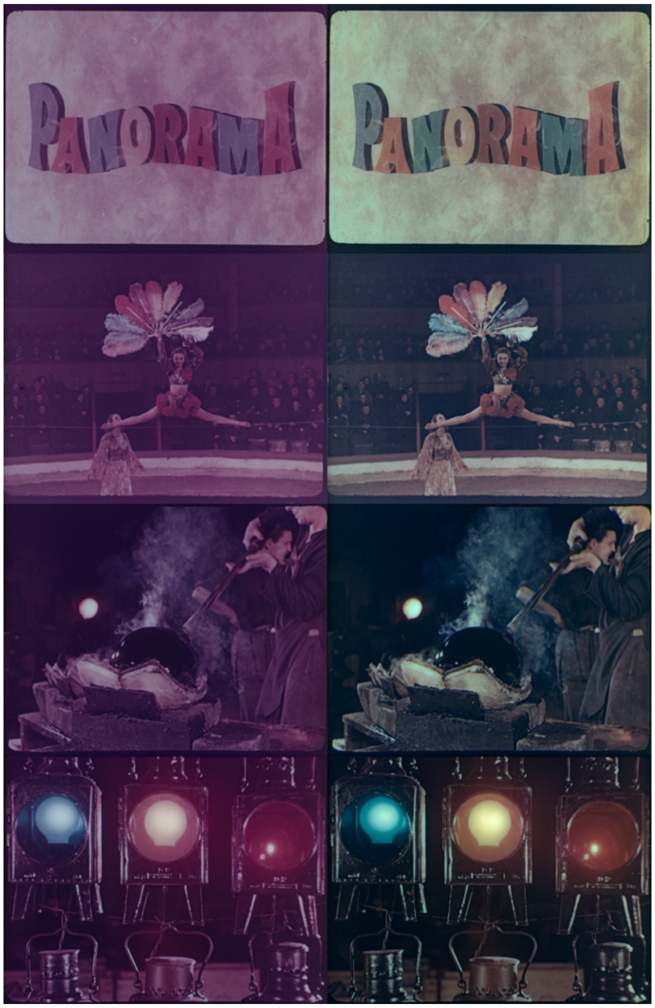

Figure 4. *Left: Four exemplary frames of Panorama Nr. 4 as it looks today. Right: The supposed 1945 original colors resulting from the proposed spectral approach of digital restoration.*

To compare the result of the proposed, material-based, spectral approach with a 'standard' RGB method for digital unfading, the captured images were processed with the "LUTgenerator" algorithm [6]. The specialized image-processing software minimized the color difference with the result of the spectral approach (Fig. 5-left), finding the optimal values for three parametric curves through a multistep minimization process based on the Nelder-Mead simplex algorithm [10], and defining a simple one-dimensional look-up table [15]. The resulting images (Fig. 5-center) have the closest possible colors achievable with RGB curves.

The residual color differences are significant (Fig. 5-right), indicating that, even in the unlikely event in which a color reference of the unfaded film is available, achieving those reference colors at a color grading suite would require complex, laborious operations.

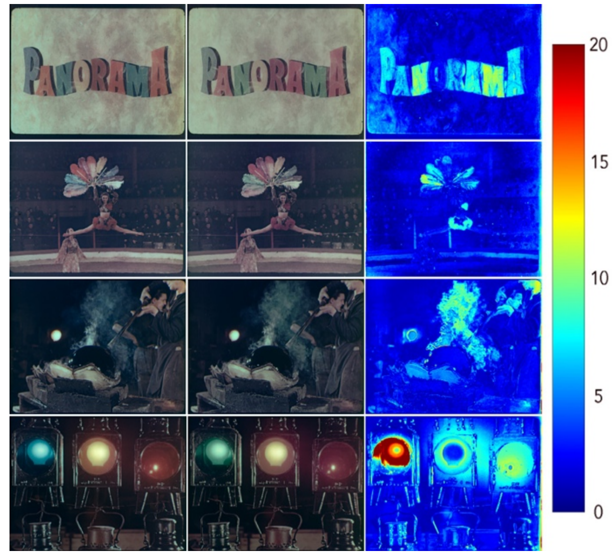

Figure 5. *Left: The results of the proposed spectral approach of digital restoration. Center: The closest possible result achievable processing the RGB capture with a 1D-LUT. Right: Heatmap reporting the colorimetric difference deltaE between the two images.*

Conclusion

The proposed digital restoration method is a material-based, quantitative approach to infer the original optical properties of a faded chromogenic film and reconstruct the supposed appearance during analog theatrical projection. The validity of the five-step method is based on the extraction of the residual color information present in the film with a multispectral image capture. Prior knowledge about the analytical spectral densities of the film allows the development of an image processing technique called "dye purification" that provides images corresponding to the individual emulsion layers. A selective restoration of the faded dyes is thus possible. The following steps of spectral reconstruction and color calculation allow us to finally reconstruct—to the best of our knowledge—the original aesthetics of the faded film.

In the present case study, bibliographical resources supplied the spectral densities of the dyes contained in the investigated Agfacolor material, which were imperative for the successful implementation of the restoration procedure.

The present paper showcased the result of the proposed digital restoration method for a selection of film frames. The frame-by-frame restoration of the full 218-meter long "Panorama Nr. 4" will be soon completed for theatrical digital projection.

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Author Biography

Giorgio Trumpy is member of the Colourlab, Associate Professor at the Norwegian University of Science and Technology, and research scientist at the University of Zurich. His main interests are optics and spectroscopy, colorimetry and image processing, heritage conservation and visual arts.

Sreya Chatterjee holds a BA Degree in Mass Communication, Video Production and Film Studies from Calcutta University, India and a Postgraduate Diploma in Film Editing from Film and Television Institute of India, Pune, India. Currently, she is pursuing a master's degree at the Conservation and Restoration department of University of Applied Sciences, Berlin, Germany with a focus on Audiovisual and Photographic Heritage. Her research interests encompass chemical-analytical investigations into the materiality of film heritage.