Style Transfer in Advanced Film Digitization and Rendering Workflows

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Abstract

This paper introduces *Multi-sourced Aesthetic Transfer* (MAT), a crucial feature in advanced film digitization and rendering workflows. It is essential when integrating various film elements—whether negatives or positives—and matching their differing material characteristics to produce an aesthetically coherent result.

In typical professional filmmaking of the analog era, the camera negative and exhibition prints represent the two material endpoints of the production process. The camera negative holds the original information from a film's primary shooting, preserving the full dynamic range of captured scenes and superior sharpness. Moreover, as negatives were generally stored safely and were never subjected to the wear and tear of projector use, they are typically more complete and remain in better condition. Exhibition prints, by contrast, serve as a better color reference, reflecting adjustments made during color timing for aesthetic or narrative reasons. However, it is important to note that exhibition prints often can vary due to differences in the film stock or processing technique. Additionally, if a print has faded over time, digital restoration may be required to recover its original appearance. When both a camera negative and a reference projection print are available, *Multi-sourced Aesthetic Transfer* (MAT) becomes invaluable. It allows for the integration of the structural integrity of the camera negative with the refined color palette of the projection print.

The combination of the camera element—negative or reversal—with exhibition prints is just one application of MAT. Other "non-final" elements, such as interpositives or internegatives can be the input source for MAT. This tool is also applicable to other film element sets, such as black-and-white color separations used in two-color and three-color processes, most notably in Technicolor's dye-transfer system. These processes often use arbitrary and idiosyncratic color components for printing and produce image textures distinct from the graininess of the black-and-white separations.

By integrating disparate film elements, MAT preserves the complete spectrum of color and spatial details, ideally captured through multispectral scanning. This enables digital recreations of a film's appearance as it would have been experienced in analog cinema. Through this process, MAT ensures that digital renderings retain both the aesthetic integrity and historical authenticity of original screenings.

Keywords: film scanning, multispectral imaging, style transfer, film aesthetics, film restoration.

Introduction

In discussing the surviving prints of a film, Paolo Cherchi Usai (1994) observed that "film is a multiple object".[1] This inherent multiplicity encompasses all the accessible elements that can contribute to the digitization and restoration of a film. Consequently, critical questions arise: which element should serve as the primary source material for scanning? Which should be used as the color reference? Furthermore, the so-called philological reconstruction of a film often requires restorers to combine various source materials into a final digital version, striving to include all available sequences from the film's original première. These questions have been central to debates in restoration ethics and practices for decades (Read and Meyer, 2000; Venturini, 2006) and have gained even greater importance with the advent of digital technologies (Catanese, 2013; Fossati, 2009).

These general observations highlight two key requirements that are addressed in this paper. *1) Accurate Digital Translation of the Color Reference Element*: Ensuring that the selected color reference element is translated into the digital domain with a physically accurate method is critical. This process requires high-quality imaging of its film frames combined with scientifically rigorous visual rendering. Ideally, a multispectral scanning approach is used, sampling the visible spectrum at evenly spaced intervals. The resulting images must exhibit sufficient spatial resolution, high bit depth, and an excellent signal-to-noise ratio. These high-quality spectral images are then processed to produce color-accurate images using standardized color matching functions (CIE, 2015) and the spectral power distribution of historical film projectors. *2) Precise Color Transfer to Source Material Scans*: Accurate transfer of these color values from the reference to scans of the optimal source material is essential. The source material should be selected based on its aesthetic integrity, its physical and mechanical condition, superior resolution, and the presence of a wider range of scene luminance levels—qualities typically found in earlier-generation film materials.

Source Materials for Scanning (MAT input)

While original camera negatives are often the best source materials for scanning due to their dynamic range and oftentimes pristine condition—not only are they not exposed to the wear and tear of film production, but they are often also more color-fast than prints—they do not contain the color adjustments and alterations made in post-production and color grading for aesthetic and narrative purposes. Therefore, for various reasons, different reference materials are required for the most convincing result that meets the core requirements of restoration ethics.

Understanding a film's history as an artwork, its aesthetic qualities, and the production and post-production technologies used is crucial, as different historical color processes are rooted in distinct technical and conceptual foundations. Therefore, selecting the right scanning materials requires not only knowledge of a film's specific history and context but also a thorough understanding of the color technologies applied. Chromogenic multilayer films that have become the standard for color film production in the mid-1950s were conceptualized with a comprehensive workflow consisting of a specialized film stock for shooting, adapted development and processing steps in the lab and a printing process on a positive film stock that was adjusted to these material requirements. Its foundation relies mostly on sophisticated chemistry to establish a working connection between the sensitization of the silver halides, the colored couplers of the correction mask (if present), and the image-forming dyes embedded in the layers of the film emulsion.

[1] "The 'original' version of a film is a multiple object fragmented into a number of different entities equal to the number of surviving copies." (Cherchi Usai 1994: 84)

Earlier processes, such as the many two-color technologies and the three-strip dye-transfer Technicolor No. IV, were built on much more arbitrary connections between the recording stocks—black and white separations captured through color filters—and the result in the dye-transfer exhibition print. This arbitrary assignment of printing dyes to the representation of spectral characteristics in the taking stocks not only yielded highly idiosyncratic color renditions—for instance the typical Technicolor look—but, as we will show, it is also much more challenging for the transfer of color information present in exhibition prints onto scans of the black-and-white color separations.

Our study shows how modeling the relationship between the various film elements can change depending on the case at hand and the collection of film elements included in the process.

Reference Element for Aesthetic Appearance (MAT reference)

When correcting colors in film digitization, the ideal reference is an exhibition print, as it faithfully represents the visual presentation originally intended for audiences. To apply Multi-sourced Aesthetic Transfer (MAT) effectively, it is not necessary to scan the entire reference film element. Instead, it is sufficient to scan a selection of representative frames. These frames must encompass a diverse range of colors, adequately reflecting the overall color palette of their respective shots. Given that the chosen reference film element may be fragmentary, it is crucial to ensure that representative frames are available for each shot. Capturing these frames with high color accuracy is essential, and this can be achieved through appropriate color management workflows using standardized reference color targets or, ideally, by employing multispectral imaging techniques (Trumpy *et al.*, 2021).

Multi-sourced Aesthetic Transfer

Multi-sourced Aesthetic Transfer (MAT) employs an input image and a reference image to automatically generate look-up tables (LUT) that minimize the color difference between the processed input and the reference image. Leveraging LUT processing—a standard technique in video editing—MAT effectively harmonizes diverse film elements by aligning their differing material characteristics, producing an aesthetically cohesive result. An overview of the MAT workflow is presented in Table 1.

Overview of Multi-sourced Aesthetic Transfer Workflow	
1	Investigate and select pairs of matching scene frames from input and reference sources.
2	Use high-quality imaging systems with superior optics, advanced electronics, and robust software to scan and render the selected images. Ensure the input image has sufficient spatial resolution, while prioritizing high color accuracy for the reference image.
3	Crop images to remove the perforation area, focusing exclusively on the image region.
4	Perform image registration to precisely align the input and reference images, ensuring pixel-to-pixel correspondence of their features.

5	Generate a 1D LUT to minimize the color difference between the input image, processed via the look-up table, and the reference image.
6	If needed, create a 3D LUT to further reduce any residual differences.
7	Apply the generated look-up tables in color grading software to the input video file or image sequence, ensuring they are selectively applied to the specific shot corresponding to the representative frame.
8	Repeat steps 2 through 7 for each shot, using the input and reference images corresponding to the representative frame for that specific shot.

Table 1 - Workflow for Multi-sourced Aesthetic Transfer

When the input image is from a negative film element, step 5 includes a negative-to-positive conversion, followed by optimization to minimize the color difference with the reference. These transformations are combined in a single 1D LUT. For certain film sources, such as the Technicolor case study, a 1D LUT alone may not provide a satisfactory result, requiring the use of a 3D LUT (step 6) for a better match. The following case studies illustrate how the presented technology functions in practice.

Case study #1: ROTE OHREN FETZEN DURCH ASCHE, AUT 1991
Internegative to exhibition print (both chromogenic)

The film ROTE OHREN FETZEN DURCH ASCHE (English title FLAMING EARS) presents a typical example of how Multi-sourced Aesthetic Transfer (MAT) can adjust an input image to match the color aesthetic of a reference image using a one-dimensional look-up table (1D LUT). This experimental Austrian science-fiction punk film was directed by Ursula Pürrer, Dietmar Schipek, and Ashley Hans Scheirl (1991). It was originally shot on chromogenic Super-8 reversal, from which a blown up 16 mm internegative film was created. From the internegative, Atlantik-Film in Hamburg produced the prints for exhibition purposes. The Super-8 camera material was unfortunately lost. The negatives, cut into A and B rolls, were digitized using a *Kinetta* scanner equipped with an RGBW LED illumination chip and a *Lumenera* Lt16059H color camera. Reference frames from the original 16 mm print were selected from various scenes and captured using a prototype 25-band multispectral scanner developed as part of the "VeCoScan" research project (ERC Proof-of-Concept 812583). Accurate color renderings of these reference frames were calculated from the 25-band data, following the methodology outlined in a previous publication (Sec. 3 in Trumpy *et al.*, 2021). These rendered images served as the reference for MAT, while the input consisted of the corresponding frames from the scanned internegative.

MAT streamlined the color grading process, eliminating the subjectivity inherent in manual adjustments. The process employed a two-step workflow:

1. **Inversion to Positive (neg2pos)**: The negative input image was converted into a positive image with an adaptive, content-aware process (Diecke *et al.*, 2020).
2. **Color Optimization (pos2ref)**: A 1D LUT was optimized to minimize residual colorimetric differences between the processed positive image and the reference.

The look-up tables generated in steps (1) and (2) were then combined into a single 1D LUT for application. The resulting combined 1D LUT is compatible with standard color grading software, enabling efficient and consistent rendering of the restored film. In this specific case, the restoration achieved a remarkable visual alignment between the scanned internegative and the reference frames from the exhibition print, as illustrated in Figure 1. While director Ursula Pürrer expressed great satisfaction with the results, she requested subtle refinements to ensure the final version fully adhered to her creative intent.

Case study #2: LEA AUS DEM SÜDEN, GDR 1963
Camera Negative to Exhibition Print (both chromogenic)

Another compelling application of Multi-sourced Aesthetic Transfer (MAT) is the restoration of LEA AUS DEM SÜDEN, a short musical film shot in 1963 by Deutsche Film AG (DEFA), directed by Gottfried Kolditz and photographed by Erich Gusko. This film highlights the use of Agfacolor, a widely employed color process in German cinema of the era. Compared to FLAMING EARS, this case presented a greater challenge, as the materials used in the MAT workflow spanned three generations of duplication. The original camera negative, preserved in excellent condition, served as the input material for MAT. For the reference, an exhibition print—produced through three successive duplication steps from the camera negative—was selected to represent the intended color aesthetic. Despite the generational differences, MAT effectively created a unified 1D LUT, offering a streamlined workflow that revitalized the film's vibrant aesthetic while maintaining its historical authenticity. As shown in Figure 1, MAT's application to LEA AUS DEM SÜDEN demonstrates its ability to digitally emulate multiple photo-chemical film copying processes with a 1D LUT and successfully reconstruct the original Agfacolor palette. However, due to the extended duplication chain, some residual color differences remain more pronounced compared to the FLAMING EARS case.

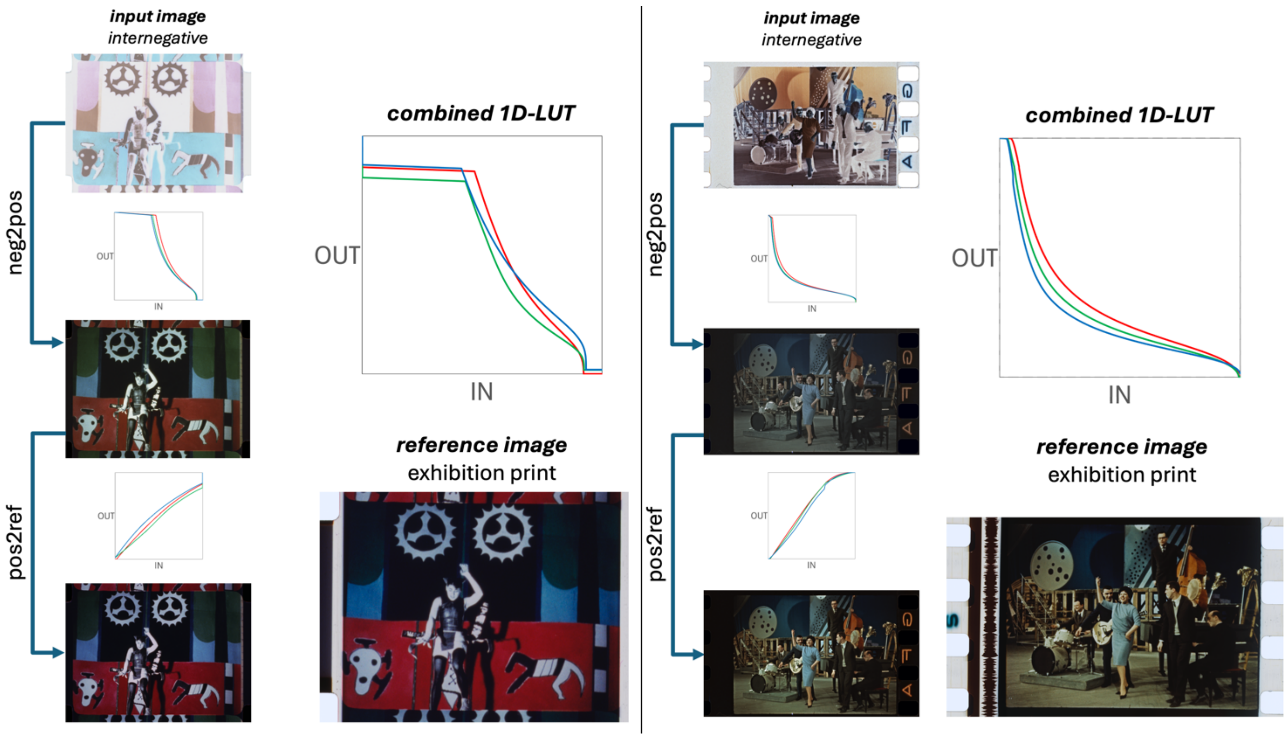

Figure 1 – MAT applied to ROTE OHREN FETZEN DURCH ASCHE (left) and LEA AUS DEM SÜDEN (right). In both cases, the result of pos2ref (bottom-left image in each part) well matches in color the reference image at its right.

Case study #3: HEIDI UND PETER, CH 1955
Black-and-white Separations to Technicolor Dye-transfer Print

In the 1950s, Technicolor transitioned from its cumbersome three-strip camera system to using chromogenic Eastmancolor negatives for filming. From these negatives, three black-and-white separations were created to produce the printing matrices for Technicolor's distinctive dye-transfer prints. HEIDI UND PETER, the first Swiss feature film shot in Technicolor, was based on Johanna Spyri's famous novel and produced by Lazar Wechsler / Praesens-Film, directed by Franz Schnyder. The film's chromogenic negative, the black-and-white separations, and three dye-transfer prints are preserved in the holdings of Swiss television SRF at the Cinémathèque suisse. These prints exhibit noticeable color variations, which are characteristic of Technicolor prints. The "German print" has cooler, more neutral hues, while the "French print" and the "SRF 2003" print display warmer tones.

In a previous research project (DIASTOR, Swiss Commission for Technology and Innovation), we were granted access to these film elements and documented them using a color-managed workflow based on a DSLR camera. For this case, the input is the color image obtained by merging the black-and-white separations for the cyan, magenta and yellow primaries into the R, G and B channels respectively. The reference used was one of the prints. Following the procedure described in previous case studies (neg2pos and pos2ref), the transformation found was condensed into a single 1D LUT. Despite the optimization process, the residual mismatch between the resulting positive image and the reference remained unacceptable. To address this, an additional 3D LUT was applied to map the colors of the 1D LUT-processed input to match the reference colors of the print. While a 1D LUT maps each dimension independently of the others, transforming input RGB values into corresponding output RGB values, a 3D LUT adjusts the mapping by considering the interdependencies between all three color dimensions. The 3D LUT is constructed from pixel data of both the input and reference images. Its size increases exponentially with the number of RGB table entries per dimension. Each output RGB value is calculated through standard triangular interpolation, using the input RGB and surrounding or intersecting RGB entries in the table. This approach ensures the interpolated output RGB values align closely with the reference data.

The earlier registration of the frame pairs provides sample correspondence between the input colors and the reference colors. These sample pairs of input colors and reference colors are assigned to one or more sets. When a 3D-LUT input RGB address used for triangular interpolation has no unique contributing RGB reference values, the nearest RGB input and reference values are used; when this occurs, these input reference RGB pairs contribute to more than one set. Each input RGB table entry is associated with a set of one or more input reference RGB pairs. A color difference metric is used to find a fit to map each pixel pair set from its input values to its 3D LUT interpolated output reference values. The CIE76 color difference is faster to compute than more recent color difference metrics, and it was therefore adopted. Optional adjustments local to specific input RGB neighborhoods to the color difference function weights can improve the calculation of table entries for colors with low luma or high chroma extent. Data quality and the amount of data of the sample pairs of input colors and reference colors will impact the quality of the 3D LUT.

For this case study, two different shots of HEIDI UND PETER were selected. The two Technicolor shots are shown in Figure 2; each shot (*a* on the left and *b* on the right) has four sub images. From the lower left clockwise, these sub images show the input negative, the result from applying the combined 1D LUT described in the previous case studies #1 and #2, the result from the following application of the 3D LUT, and the reference exhibition print.

a *b*

Fig. 2 – Two test cases of HEIDI UND PETER (*a* and *b*) – for each case, bottom left represents the input; top left is the result of the combined 1D LUT; top right is output after applying 3D LUT; bottom right is reference positive.

Closing Remarks

The multi-sourced aesthetic transfer (MAT) case studies presented here illustrate how modeling the relationship between various film elements can vary significantly depending on the specific context and the combination of film elements involved. MAT harmonizes the differing material characteristics of these elements to achieve an aesthetically coherent result, even in complex transformations. An example is the Technicolor process, where the arbitrary connections between black-and-white separations and the dye-transfer print necessitate the use of 3D LUTs. The effectiveness of the MAT approach is evident when comparing the output to reference frames, as shown in Figure 1 (bottom) for the *ROTE OHREN FETZEN DURCH ASCHE* and *LEA AUS DEM SÜDEN* case studies, and in Figures 2a and 2b (right) for the *HEIDI UND PETER* case study.

Multispectral film scanning enhances film digitization by measuring the transmittance values of the film across each spectral band within the selected set. The possibility to select specific spectral bands for the visual rendering enables better digitization results tailored to the purpose of the digitization. This ensures either the physically accurate reproduction of color values (with the full set of spectral bands), ideal for well-preserved projection prints, or the enhancement of color information (with narrow RGB bands), which is particularly useful for negatives or films that have faded.

The combined use of MAT and multispectral film scanning, creating look-up tables from digital files generated through multispectral captures, provides a robust framework for producing aesthetically coherent results. This approach preserves both the aesthetic integrity and historical authenticity of the original screenings, ensuring a faithful representation of the cinematic experience.

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