LIGHT SOURCE CRITERIA FOR DIGITIZING COLOR FILMS

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***Abstract*— The poor stability of film dyes and the decline of film photography require the development of digitization techniques designed to acquire the full amount of color information carried by photographic film. The spectral characteristics of the light source used during the image acquisition extremely influence the quality of the final digital reproduction of color films; this paper thoroughly discusses the criteria to be adopted to properly choose the light source. A method is described to infer the analytical densities of a color film from a set of measurements of the integral density; this provides the necessary spectroscopic information for the choice of the light source. The experimental part reports the analysis of two photographic samples from archival material: a Technicolor and an Agfacolor from the 1940s. The experiments highlighted the peculiar spectroscopic characteristics of the analyzed samples. The attention was drawn on the historical aesthetics of color film and the ethical issues related to its preservation.**

Keywords—Motion Picture digitization; Spectroscopic Analysis; Preservation of Cultural Heritage; Multi-spectral Imaging

I. INTRODUCTION

The basic step in subtractive color photography is the formation of cyan, magenta, and yellow dye-images, which modulate the long, medium and short visible wavelengths respectively[1]. In modern subtractive processes of film photography the three images are taken simultaneously on three emulsion layers coated one on top of the other (*tri-pack*). During emulsion manufacturing, the three layers are made sensible to different regions of the visible electromagnetic range (*sensitization*). After the exposure in camera, in each emulsion layer the developing process produces a dye; the quantity of produced dye is dependent on the spectral composition of the light to which the emulsion was exposed and on the sensitivity of the layer. In the end of the process, a dye concentration triad characterizes each point of the film.

In the case of negative film, the creation of the final color image requires additional processes (e.g. the chromogenic color print, or the digital scan followed by image processing); on the other hand, in a reversal film a final version of the color image is directly formed on the film itself.

[1] For sake of simplicity, we will not take the correction masking into account.

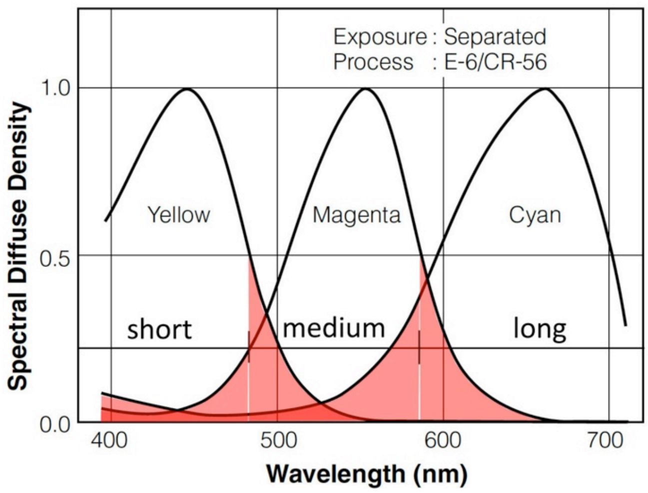

Fig. 1. Spectral densities of Fujichrome Velvia 50 Professional [RVP50] scaled to one [1]; the side absorptions are highlighted in red

In theory maximum visual efficiency is achieved with dyes having either total or zero spectral transmittances (ideal *block dyes*). Beside their pertinent spectral absorption region real dyes have smooth transitions and partly absorb in the other regions (Fig. 1); these are called *side absorptions* [2]. Every photographic company tuned its own processes, adopting different sensitizers and image-forming dyes, and developing different corrective methods (e.g. *masking*); the majority of practical sensitizers are *cyanine* and *merocyanine*, while the image-forming dyes generally belong to the families of the *indoanilines* and the *azomethines*. The recipes chosen by different companies determined the deviations from an exact colorimetric reproduction, which defined the typical 'look' of the products. For example, early *Agfa* products generally had a pastel brown-green look; very special are the yellows and reds of *Kodachrome*; *Fujichrome Velvia* is known for its rich, emerald greens [3].

The poor stability of the dyes and the decline of film photography make digitization of the photographic heritage a research topic of great interest. Thus, the development of effective digitization techniques for photographic film is fundamental, guaranteeing the future fruition of its visual content and, in case of *dye fading*, allowing its digital restoration [4].

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Fig. 2. Digital reproduction of a frame of "Heidi": result of the appearance-purpose (top-left half) and of the information-purpose (bottom-right half)

II. IMAGE ACQUISITION: APPEARANCE VS. INFORMATION

The creation of a digital reproduction of a color film by means of a RGB imaging device (camera or scanner) entails the two stages of *image acquisition* and *image processing*; the validity of the procedure adopted for the first of these stages extremely influences the quality of the final reproduction. The determination of the most valid acquisition procedure requires clarifying the purpose of the reproduction: [I] we want to reproduce the visual appearance of the transparency (we will refer to this approach with the term *appearance-purpose*), or [II] we want to migrate in digital form the color information carried by the film (*information-purpose*). If we follow the appearance-purpose, we aim to reproduce the color of the film in transmission, which results from the light absorption carried out by the tri-pack considered as a whole. This approach is suitable in case of unfaded positives, to be directly projected on screen or watched in a slide viewer; in fact, by adopting accurate procedure of color management, it is possible to re-create digitally the distinctive chromatic characteristics of the film brand. On the other hand, the colors of an intermediate image (e.g. *negative* or *interpositive*) do not correspond to the intended final colors; in this case, rather than accurately reproducing the appearance of the film transparency, it is more convenient to follow the information-purpose, i.e. retrieving the dye concentration triads. This approach considers the film as an information storage system; the absorption spectra of the dyes are not relevant: only their concentration is important.

The colors of films affected by dye fading can be restored by digital image processing [4]; to this aim, it is fundamental to acquire the most possible remaining color information of the film, and therefore, it is convenient to follow the information-purpose. In case a RGB imaging device is used with the appearance-purpose, a white light with a homogeneous spectrum (e.g. halogen source) is the suitable source. The following section (sec. III) describes the characteristics of the suitable light source and the procedure to fulfill the image acquisition of a color film with the information-purpose. The difference between the visual results of the digitization with the two different purposes is illustrated in Fig. 2.

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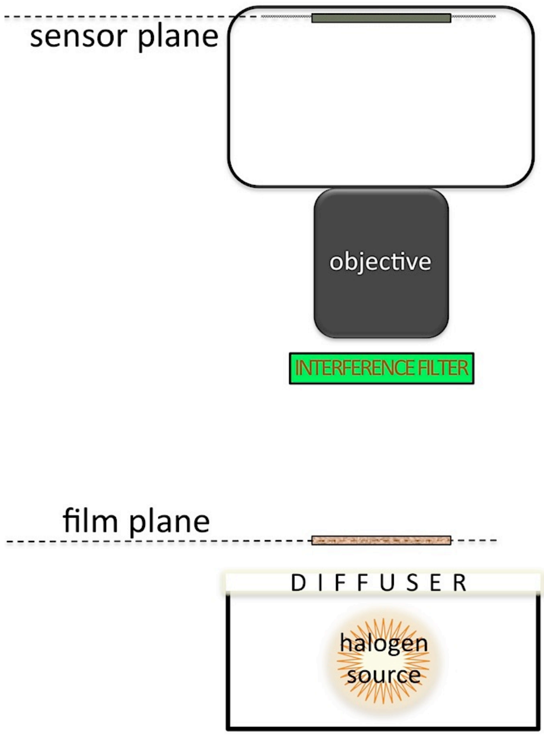

Fig. 3. Setup for image acquisition of a photographic film with DSLR camera, diffuse light source and interference filters

III. EXTRACTION OF COLOR INFORMATION

To image a color film retrieving the full amount of color information, the ideal light consists of three monochromatic sources. Their wavelengths have to maximize the absorbance variance of the component dyes, while minimizing the influence of the side absorptions (we will indicate these monochromatic lights with *source-Y*, *source-M*, *source-C*); in this way the correlation between the images of the color bands (i.e. the R, G and B channels of the image file) is lowered and an expanded color information is produced. The best method for this purpose is a multi-spectral approach that consists in acquiring three monochromatic images separately, using only one source for each channel (image-B with source-Y, image-G with source-M, and image-R with source-C); these images are then merged in the final RGB image [5].

Some film scanners available on the market adopt three LEDs in an effort to increase the acquired color information (e.g. ARRISCAN). Another method is to filter the emission of a single source. In the setup depicted in Fig. 3, a diffuse halogen source illuminates a photographic film, and a DSLR camera acquires the image filtered by an interference filter[2]. The acquired image[3] is the transmittance map of the tri-pack corresponding to the band selected by the interference filter.

[2] Cameras with a color filter array (CFA) are designed to directly acquire color information; this kind of imaging device is not ideal for a multispectral purpose; however, their combination with interference filters can be a cheap and decent solution for a portable multispectral imaging system.
[3] We refer to monochromatic raw images, opportunely normalized referring to total and zero transmittances.

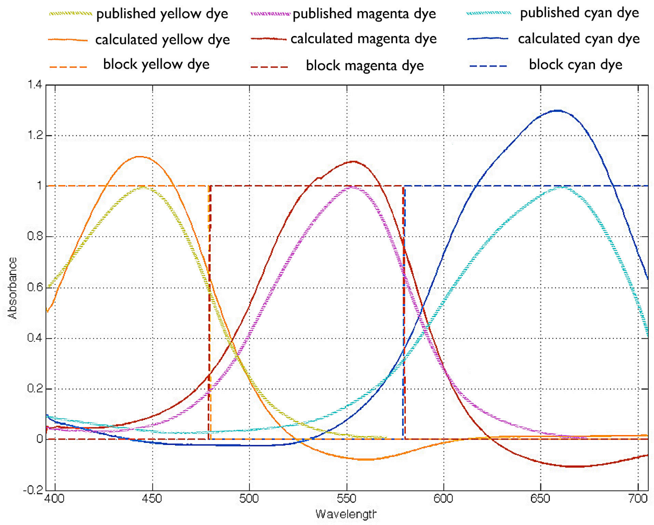

Fig. 4. Fujichrome Provia 400X [RXP]: the published analytical densities [7], the analytical densities estimated with the PCA/block method, and the block dyes

By using three interference filters, whose transmission wavelengths correspond to the absorption peaks of the dyes (~440nm, ~550nm, ~665nm in the example of Fig. 1), the three transmittance maps are primarily ascribable to the variation of concentration of one single dye. If there were no side absorptions, these transmittance maps would contain the complete color information carried by the film.

In view of all this, the knowledge of the spectral position of the peaks of absorbance allows optimizing the image acquisition for the specific film to be reproduced, selecting the best wavelengths for source-Y, source-M and source-C. For materials of recent production, the manufacturers often supply datasheets containing also a plot of the spectral densities of the dyes as opposed to older materials, for which no technical information is present. The following section describes a method to estimate the spectral densities for these latter cases; this allows tweaking the wavelengths of the light sources and, in doing so, optimizing the digitization procedure.

IV. Estimation of the Analytical Densities

Spectroscopic transmission measurements have to be carried out to estimate the optical densities of the individual dyes of a film (*analytical densities*). It has to be considered that it is rather impossible to find points of the film where only one dye was formed; therefore, a transmittance measurement (*integral density*) always blends together the absorptions of all the three dyes. Reference [6] provides a procedure to infer the analytical densities from a set of measurements of the integral density. The analysis of a film consists in measuring the integral density of a comprehensive set of saturated colors and applying a Principal Component Analysis (PCA) on the spectra measured[4]; a prominent difference is generally found between the third and fourth eigenvalue, consistently with the number of independently variable components (i.e. the three dyes).

The real absorbance spectra of the constituent dyes might be estimated by finding the proper linear combination of the three *eigen-spectra* with the highest eigenvalues; in [6] the author suggests narrowing the range of possible linear combinations of the eigen-spectra by supposing reasonable assumptions (e.g. spectral absorptions and concentrations of the dyes are always non-negative). We propose to achieve an approximation of the spectra of the dyes by performing a minimization with a linear least-squares method to the ideal block dyes (to which every set of dyes refers). This procedure (in the following referred as “*PCA/block*”) allows reaching a unique solution for every film treated.

The PCA/block method has been first tested on a modern film, whose analytical densities were supplied by the vendor. A Fujichrome Provia 400X [RXP] was exposed to a colorful scene and developed with the E-6 process. After that a set of points of the film was selected with the aim to create a comprehensive set of saturated colors. A double-beam spectrophotometer with a 1 nm spectral resolution (SHIMADZU UV-1800) was used to measure the transmittance of the twenty-four selected points, including an area of circa 1 mm^2. The PCA/block method was carried out on the dataset and the three analytical densities were estimated. The result reported in Fig. 4 shows an excellent match between the calculated and the published spectra. The absorption peaks identified are circa 442nm, 544nm, and 658nm (Fig. 4).

V. Experimental Results

This section reports the analysis of two photographic samples from archival material: a Technicolor (subs. a) and an Agfacolor (subs. b) from the 1940s.

a. Samson and Delilah

A spectroscopic analysis was conducted on a 35mm Technicolor dye-transfer trailer of the motion picture “Samson and Delilah”, directed by Cecil B. De Milles in 1949. A colorful set of twenty-four points has been selected from different frames of the film reel, and spectroscopic measurements were carried out with the SHIMADZU UV-1800. The spectra were processed with the PCA/block method (sec. IV) and three eigen-spectra were obtained (Fig. 5). The eigen-spectra show distinctive absorption profiles: the cyan exhibits two peaks (660 nm and 720 nm), the magenta displays an absorption peak (540 nm) with a shoulder (575 nm), while the eigen-spectrum corresponding to the yellow dye shows a single peak (460 nm).

These distinctive eigen-spectra profiles with multiple absorption peaks represent an interesting case to challenge digitization using the information-purpose approach. This requires choosing a single wavelength for each of the three light sources. To identify the best set of wavelengths to be used for the digitization of “Samson and Delilah”, multi-spectral imaging was conducted on one frame of the motion picture.

[4] Considering the absorbance values of the various wavelengths as attributes of each observed point of the photograph

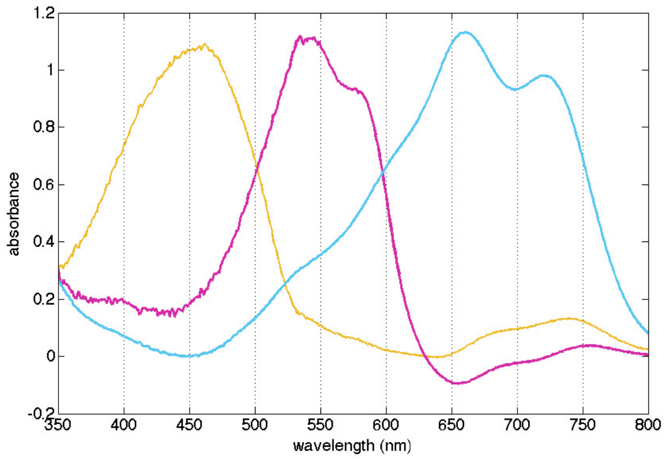

Fig. 5. Eigen-spectra obtained with the PCA/block method from the Technicolor print of "Samson and Delilah"

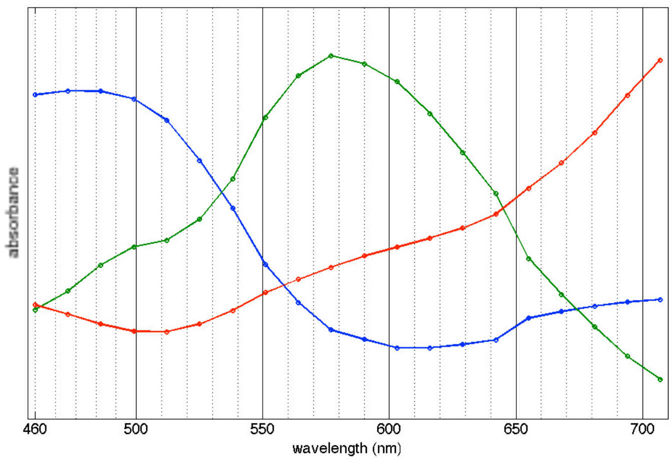

Fig. 6. Eigen-spectra obtained from the motion picture "Opfergang" shot on Agfacolor

The images were acquired with a portable system (cfr. Fig. 3) constituted by a halogen light, a variable interference filter (VERIL *Schott* linear variable) and a DSLR camera (Canon EOS 5D). Five monochromatic images of the selected frame have been acquired at the absorption peaks of the dyes[5] (Fig. 5): *Y* (460 nm), *M1* (540 nm), *M2* (575nm), *C1* (660 nm) and *C2* (720 nm). Additionally a 'normal' RGB image has been acquired without filtering the halogen lamp, exploiting the color filter array (CFA) of the CMOS. The five spectral images can be combined to create four different RGB images[6], choosing either the main or the secondary absorption value for the cyan and magenta dyes: Y-M1-C1, Y-M1-C2, Y-M2-C1, Y-M2-C2.

If the noise effect is opportunely addressed by spatial downsampling and temporal averaging, the decorrelation level between the images of the three RGB channels is considered a good indicator of the wealth of colors that the image contains [5]. The correlation matrices of the four multi-spectral combinations and of the single capture with the CFA are reported in Table I.

TABLE I. CORRELATION BETWEEN CHANNELS

Combination Y-M1-C1

Y	1		
M1	0.984	1	
C1	0.852	0.842	1
	Y	***M1***	***C1***

Combination Y-M1-C2

Y	1		
M1	0.984	1	
C2	0.815	0.805	1
	Y	***M1***	***C2***

Combination Y-M2-C1

Y	1		
M2	0.945	1	
C1	0.852	0.944	1
	Y	***M2***	***C1***

Combination Y-M2-C2

Y	1		
M2	0.945	1	
C2	0.815	0.895	1
	Y	***M2***	***C2***

Simultaneous R-G-B

B	1		
G	0.981	1	
R	0.940	0.977	1
	B	***G***	***R***

[5] The Full Width at Half Maximum was circa 10 nm

[6] We refer here to the simple case of direct transformation represented by a diagonal matrix

First of all, Table 1 provides a numerical assessment of the increased color information obtained with the multi-spectral approach; in fact, the values of 'Simultaneous R-G-B' are all well above 0.9, indicating low decorrelation. Choosing M2 lowers the correlation between magenta and yellow (0.942 with M2, in respect to 0.984 with M1). Still, the overall correlation is lowest by choosing of the spectrally distant M1 and C2.

In light of this experiment, the best wavelengths to be used for the digitization of "Samson and Delilah" are 460, 540 and 720 nm.

b. Opfergang

Another spectroscopic analysis was conducted on a camera negative conserved at the Friedrich-Wilhelm-Murnau-Stiftung in Wiesbaden (D). The movie "Opfergang", directed by Veit Harlan in 1944, was among the first movies shot on the new chromogenic Agfacolor film.

For this analysis we adopted the above described multi-spectral imaging portable system. A specific frame has been selected for its particular abundance of saturated colors with different hues; twenty images of this frame were acquired every 13 nm between 460 and 707 nm. Linearly translating the sensor data (*raw*), and including in the images the film perforation (100% transmittance) and a completely opaque area (0% transmittance), it has been possible to calculate the film absorbance for each pixel. These absorbance spectra were processed with the PCA/block method (sec. IV) and three eigen-spectra were obtained (Fig. 6); their absorbance peaks are around 480 nm (yellow), 580 nm (magenta) and over 700 nm (cyan).

The three absorbance peaks found in "Opfergang" are located at considerably longer wavelengths when compared with the typical absorbance spectra of AGFA films of recent production. A color reproduction of this Agfacolor camera negative was created with the multi-spectral approach, combining three different spectral images acquired at 473, 577, and 707nm; the resulting image has been "digitally printed" in Photoshop (inversion and gamma curves).

Fig. 7. Digital reproduction of a frame of "Opfergang" (Agfacolor - V. Harlan - 1944): reproduction of the nitrate print with appearance-purpose (top-left half) and reproduction of the camera negative with information-purpose (bottom-right half). Copyright: Murnau Foundation, Wiesbaden

The Filmmuseum Dusseldorf conserves a nitrate positive film for projection that was printed from the analyzed camera negative; this film print was imaged with the appearance purpose (sec. II), using the halogen light without interference filter and following accurate color management procedures through the usage of an IT 8.7/1 target for Agfa.

We created two digital images of the same film frame:

- The reproduction of the positive film with appearance-purpose
- The reproduction of the camera negative with information-purpose, "digitally printed" with image processing

Fig. 7 shows the two images with their very different appearances; the colors of the digitally printed camera negative (bottom-right half) are extremely more saturated, and many color nuances that are here distinguishable cannot be perceived in the image displayed in the opposite side (top-left half).

VI. Conclusion

This paper highlights the extreme importance of properly designing the light sources of a film scanning system. In light of this study, the development of a new generation of scanning systems is envisioned; the possibility to tweak the emissions of three monochromatic light sources will make these systems able to excellently migrate in digital form the color information of each specific film scanned.

The experiment conducted on the Technicolor dye-transfer trailer identified the optimal set of wavelengths that retrieve the maximum amount of color information. These three wavelengths do not match with the main absorption peaks of the three dyes.

The visual comparison between the resulting images of the experiment on the Agfacolor (see Fig. 7) poses an interesting dilemma: the 'information-purpose' image contains more color information and has pleasant colorful appearance; however, the 'appearance-purpose' image is probably closer to the historical appearance that the motion picture had in the 1940s.

A fundamental principle of Conservation of Cultural Heritage suggests that an artwork has to be transferred to future generations in its complete integrity, with conscious respect of its historical aesthetics. For motion pictures there is oftentimes a multitude of sources —negative and different positives. Therefore, the recreation of a film's appearance requires an extensive research on the film's aesthetics, the various material instances, completed by consultation of written sources from the period of the film's production. In the case of early Agfacolor, the company itself published a series on their technical inventions [8].

We think that the proper approach is to carry out the acquisition retrieving the largest amount of color information, entrusting to image processing the task to render the final appearance, which has to rely on a thorough colorimetric and aesthetic analysis of all available historical sources.

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