Restoration of Movie Films by Digital Image Processing

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In this paper we will present our work on the restoration of old, degraded and damaged motion picture films (black/white and colour) using digital image processing carried out at our lab over the last few years (1-10). Movies are based on photography, which is rather unstable compared to other cultural objects. Since photography and motion pictures play an important role in modern life as documentation, memory, information carriers, artistic medium etc., photographic material represents an important cultural value. It is important to find methods to reconstruct already damaged material and to preserve this heritage in a digital form which will allow long term storage.

In the case of motion pictures several factors limit their permanence: The dyes of colour movies bleach with time, the fine-distributed silver particles of b/w movies oxidise and hence discolour, the film base itself (cellulose acetate / nitrate) degrades and shrinks, and finally mechanical wear and abrasion produces dust and scratches.

Digital restoration of motion picture films requires correct digitizing in the sense of measuring physical properties (i.e. optical densities) instead of mimicking visual colour perception. This and the need for delicate handling of aged films and the prohibitively high price of commercially available scanners forced the development of a simple yet good quality film scanning device. The scanning principle and the imaging aspects specific to digital colour restoration are discussed below.

FADED AND DISCOLOURED MOTION PICTURE FILMS

Restoration of faded colour materials by the use of chemicals is impossible because the bleaching of dyes is an irreversible process. The stability of dyes in chromogenic colour films is low; the lifetime of colour material is in the order of years to decades. Incorrect processing or environmental influences such as light, chemical agents, heat, humidity and storage, affect images by bleaching the dyes or producing stain. Storage at low temperatures is the only possibility to keep colour photographs over a long period.

It is therefore attempted to reconstruct faded colour photographs and films by digital image processing. The digital method is quick, cheap, and does not affect the original. In addition, the restoration of movies ideally requires an automatic procedure in order to keep the human interaction and cost as low as possible. Moreover it is a very universal method.

THE DIGITAL RECONSTRUCTION PROCESS

To carry out a colour reconstruction, we must be familiar with the fading processes. From a chemical perspective, fading is a function of the changes of individual dyes. If it is possible to quantify the spectral variations of the dyes through fading tests, reconstruction becomes simple:

A. Produce coloured test patches (grey and colour wedges) on film material.
B. Determine the relationship OD(faded) = f[OD(unfaded)], by measuring the optical density (OD) of the patches before and after fading.
C. Digitise the faded film.
D. Apply the inverse of the relationship to recalculate the original densities of the colourants.
E. Output the restored digital images, i.e., with a film recorder on colour film or transfer them to video.

But as usual, reality is more complicated than a laboratory setting. In most cases, the only available information is the deteriorated material itself, and nothing is known about the film type or the fading and storage conditions. In addition, most film sequences do not contain any known reference colours. In principle it is therefore not possible to determine the reconstruction parameters automatically. This means that:

- The reconstruction has to be carried out interactively under the visual control and judgement of a human operator for at least a few frames of the film. These reconstruction parameters are then applied to the whole film, assuming that the film consists of the same material and that the fading was homogeneous.

- In order for the colours of the images to be restored and not merely retouched according to subjective taste, the reconstruction process must obey the laws of fading. Accelerated fading tests of different chromogenic materials have been developed and executed to obtain a mathematical model for the fading process. The model should be as simple as possible while covering as many fading behaviours as possible.

The model developed to describe the fading for nearly all chromogenic materials under different conditions is defined by the following linear equation:

$$\begin{vmatrix} Y' \\ M' \\ C' \end{vmatrix} = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{33} & a_{32} & a_{33} \end{vmatrix} \bullet \begin{vmatrix} Y \\ M \\ C \end{vmatrix} + \begin{vmatrix} a_{14} \\ a_{24} \\ a_{34} \end{vmatrix}$$

Y', M', C' = optical density of the faded dyes
Y, M, C = original optical density of the dyes (Yellow, Magenta, Cyan)

The equation takes different effects into account. Normally, the dyes fade proportionally to their original density, which also means proportionally to their concentration (a_{11}, a_{22}, a_{33}). Fading may cause transformation of faded or other colourless substances into coloured artifacts as well. This is referred to as staining. The additional coefficients a_{14} - a_{34} describe an increase or decrease of base density. The base density coefficients are positive when white elements in the images are affected by stain. In the case of light fading, when fading is often not proportional but subtractive, the coefficients are negative. The amount of light fading of each layer depends also on the density of the neighbouring layers, as they act as filters (a_{12}, a_{13}, a_{21}, a_{23}, a_{31}, a_{32}).

The operator processes the image on the computer following the fading model until the correction is satisfactory. Since it is difficult to estimate the coefficients of the linear fading equation directly, the user may work with more familiar visual and photographic parameters such as contrast, brightness, colour cast, and saturation. The program converts these parameters to coefficients of the fading equation. Once the correction is satisfactory, the final coefficients of the fading equation are used to transform the input image.

COLOUR REPRODUCTION ASPECTS FOR SCANNING

During the scanning process channel separation must be executed with narrow-band interference filters (i.e. 450, 550 and 650 nm; half width ≈ 20 nm) to achieve accurate spectral resolution and to ensure correct colour reproduction. As mentioned above, the reconstruction process requires accurate information on the concentration of the dyes. This information can be deduced by applying the Beer-Lambert law stating that the optical density is proportional to concentration. However, the law is valid only for monochromatic light. Ordinary colour scanners are equipped with broad-band colour separation filters and the Beer-Lambert law does not hold good. The aim of most commercial colour scanners is to measure colour and not colourants, i.e., pixel values represent colourimetric data. The spectral sensitivities of the three scanner filters have to be broad to fit the colourimetric tristimulus curves. Figure 1 shows an example of the spectral sensitivity curves of a commercial CCD camera equipped with broad-band filters. Through a suitable linear combination of the sensor signals, the CIE 1931 tristimulus values can be fitted from the spectral sensitivities S_{blue}, S_{green}, and S_{red}.

The spectral half widths of these CCD filters are very broad compared to the absorption band of today's photographic dyes, and the maximum red sensitivity at ≈ 590 nm is much too short compared to the absorption maximum of the cyan dye at ≈ 640 nm.

The determination of analytical densities with such broad-band filters is not possible. As shown in Figure 1, the black bars represent the optical densities for the sum of all three dyes (=grey) as measured with this device. They represent the printing densities. The hatched bars equal the printing densities of each dye in its pure state.

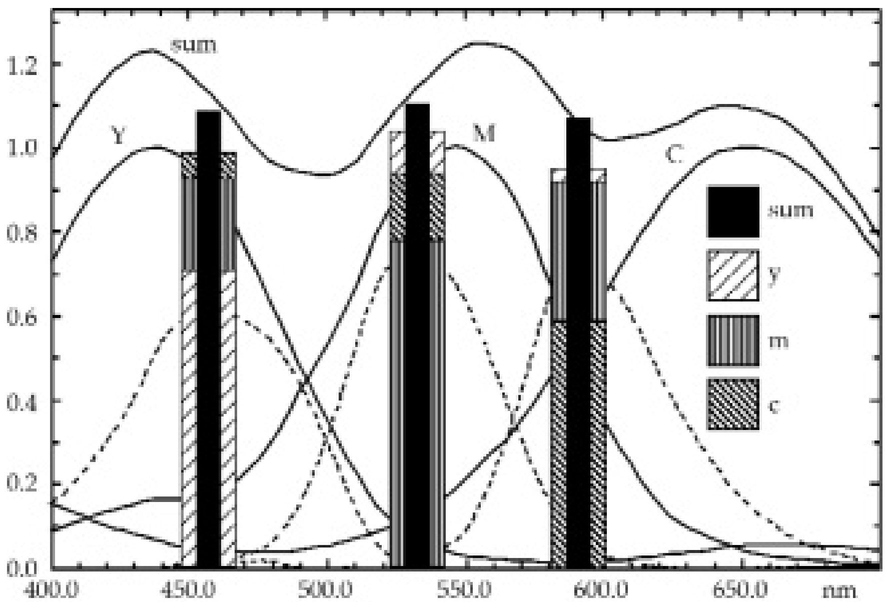

Figure 1. Spectral sensitivity curves Sb, Sg, Sr of a commercial CCD camera (solid lines), and the absorption curves of todays photographic dyes (dashed lines). The bars represent the printing densities as seen by the CCD for the individual dyes (hatched bars) and the integral sum (black bars).

Two points must be noted:

- The sum of the printing densities of the dyes in their pure states (total length of the hatched bars) is less than the printing density (length of the black bars) of the sum of the three dyes. This is a direct result of the broad spectral sensitivities of the scanner. In consequence, analytical densities can only be estimated roughly. With narrow-band sensitivities, this inaccuracy does not exist, because the Beer-Lambert law is fulfilled. For the commercial CCD camera shown in Figure 1, these sensitivities can be obtained by placing narrow-band interference filters in front of the light source.
- The sensitivity of the red colourimetric sensor falls in between the absorption maxima of the magenta and cyan dyes. Consequently, the measured optical density in the red does not originate primarily from the cyan absorption, but is caused up to half by the side-absorption of the magenta dye. This is especially problematic for colour materials where the cyan dye has faded the most. In this case, the red sensor of a colourimetric camera detects more or less only the magenta side-absorption, and a correct reconstruction is no longer possible.

REMOVAL OF SCRATCHES, DUST AND OTHER DEFECTS

Film material, be it b/w or colour film, is often severely degraded by mechanical defects such as scratches, dust, fingerprints etc. Moreover the colour restoration process generally enhances the effect of these defects so that the visual appearance of the movie may be severely degraded. Therefore we propose a processing scheme which eliminates or at least reduces the effect of these defects. Because of the large data volume presented by movies, an automatic method is a necessity, so we use of computer vision methods for the recognition of the image defects. The main problem in this regard is to find algorithms which are able to separate image structures into two distinct classes: image features and image defects.

A movie picture scene can be considered as a temporal-spatial data set, where image defects are characterised by certain properties. Dust particles typically can be found on one frame only and will therefore present a strong discontinuity on the temporal axis. The boundaries of dust particles have step-like profiles. However, intrinsic movements of objects within a scene, or general movements (pans) also result in local discontinuities on the temporal axis. These discontinuities can be distinguished from image defects by a motion analysis carried out on nearby material.

Consequently, for each frame the prominent image features have to be detected and described according to the above properties. Once an image feature has been recognised as a defect, an interpolation using both the spatial and temporal domain is performed to fill in the missing information.

Removal of scratches

Scratches, which mostly result from the mechanical stress during projection of a movie film, consist of long, vertical lines (with a typical line-like profile). Typically a scratch is visible at the same location on several subsequent frames, and is extended from the bottom to the top of each image frame. This characteristic is exploited by our algorithm: in each frame, the one-dimensional function given by the sum of the pixel values of each column of pixels is analysed. If at the given position there is a local extreme in the sums of the upper 1/4, lower 1/4 and over the whole frame it has a line-like profile and continues in the previous and succeeding frame at the same absolute position, it is assumed that this local extreme is the product of a scratch and an appropriate interpolation is applied. This algorithm can be implemented very efficiently, and works well on a wide variety of movie scenes.

Removal of spots, dust, and fingerprints (temporal discontinuities)

The removal of spots is much more difficult than the removal of scratches, since there are no such simple rules to distinguish spots from real image features as in the case of scratches. A spot cannot be identified without understanding the image contents within one frame alone. However, it is possible to compare a frame with the preceding and succeeding frames. Since the time between two frames is small, in general two successive frames will be quite similar on a global scale. On a smaller scale, the differences due to camera movements and intrinsic object movements can be quite noticeable. Both types of movements have to be considered by the restoration algorithm. The procedure to find spots involves 3 consecutive frames $f(x,y,t)$, $f(x,y,t-Dt)$ and $f(x,y,t+Dt)$. The following steps describe the algorithm:

- The frames f(x,y,t-Dt) and f(x,y,t+Dt) are shifted with respect to the frame f(x,y,t) to compensate for camera pans. The shift is calculated using cross-correlation on NxN pixel neighbourhoods near the border of the sobel-filtered frames. N is about 5% of the image size. Only results with a high cross-correlation value are taken into account for calculating the shift values. The result are two frames f'(x,y,t-dt) and f'(x,y,t+dt) which correspond optimally with f(x,y,t) with respect to pan movements.
- The differences $D_1(x,y)$ = f'(x,y,t-Dt) - f(x,y,t) and $D_2(x,y)$=f'(x,y,t+Dt) - f(x,y,t) are multiplied: D(x,y) = SQRT([$D_1(x,y)$*$D_2(x,y)$]+), where the operator []+ indicates clipping for positive values. If the images f(x,y,t) have a spot at (i,k), the differences $D_1(i,k)$ and $D_2(i,k)$ will have the same sign, and the product will be positive. Differences resulting from intrinsic object movements may have different signatures and will therefore be eliminated by the clipping.
- For each pixel, the local variance is calculated for f'(x,y,t-Dt), f(x,y,d+Dt). The local variance is used for adaptive thresholding of the difference image D(x,y) resulting in a binary image M(x,y). It is obvious that a spot within a region of small variance (e.g., cloudless sky) is much more noticeable than the same spot within a region of high variance (e.g., top of a tree).
- After adaptive thresholding, the candidates for spots are identified by a connected component labelling. Each spot is characterised by its size, centre of gravity etc.
- For each spot, a detailed motion analysis by calculating the cross-correlations between f'(x,y,t-Dt) and f(x,y,t), f'(x,y,t+Dt) and f(x,y,t) as well as f'(x,y,t-Dt) and f'(x,y,t+Dt) is performed. If there is no evidence for the spot being the result of a intrinsic object movement, the spot is considered as being an image defect and the interpolation of the pixel values between f'(x,y,t-Dt) and f'(x,y,t+Dt) is filled in.

The algorithm is very robust, since most threshold levels are determined adaptively to the image contents. This allows to fix the parameters and to process different scenes with the same parameters. This allows to use this restoration method off line without interference of a human operator. A first example is shown in Figure 2.

Figure 2. Example of digital restoration: removal of scratches and dust. The illustration on the left shows an original frame (from a 16mm movie film). The illustration on the right shows the image after the application of the dust and scratch removal algorithm described above.

A NEW APPROACH TO MOTION-PICTURE SCANNING

Photographic materials are inherently unstable in terms of archiving requirements (colour fading, mechanical damages etc.). Photographs, the cultural and historical memory of the century, fade within just 5 to 50 years. Digitizing helps to keep these documents from vanishing in two ways: 1) by capturing the "status quo" on digital media, thus saving the still existing information content of the further decaying original, and 2) by making the image available for restoration by digital means[3]. Digitizing and colour restoration methods respecting the chemical properties and fading behaviour have been developed for and successfully applied to photographic stills in earlier projects. Our current work focuses on motion picture films suffering from the same problems.

CONTINUOUS SCANNING

The main idea is to digitize the complete film-strip in its full width and length. This results in a digital representation of the complete film strip as opposed to the sequence of frames provided by conventional film scanners (which ignore the rest of the film strip area). Given enough resolution this data can be called a "digital facsimile" of the film-strip. The film is transported continuously through a scan slit in front of a linear CCD-array with appropriate optics. This allows for simple and inexpensive mechanics not synchronized to the position of frames on the film. The complex tasks of conventionally used film transports operating in a frame by frame (stop and go) fashion are delegated to the software.

TRANSPORT AND CAMERA

The need for delicately handling old films with their numerous differences in size, perforation, frame size etc. called for a transport system independent of these characteristics. Sprockets normally advancing the film by engaging with its perforation were thus not applicable. The film is continuously transported by gently pressing it onto the drive axle by means of small rubber wheels. Only the edge of the film is used for this purpose to protect the sensitive frame area from mechanical stress.

A high speed tri-linear colour CCD (CL-G1 2098 of Dalsa) providing 3 digital outputs corresponding to the red, green and blue segments in combination with a Nikkor lens (105mm) is used (Fig. 3). Each line consists of 2098 pixels, thus the scanner is providing 2K resolution with a depth of 8 bits (linear) per channel in its current version. The three segments have a physical displacement of 112 mm to each other. Using the same resolution for horizontal and vertical dimensions this results in a displacement of 8 pixels in the data streams of two adjacent colour channels (given a film width of 35mm at 2K and a pixel size of 14 mm on the CCD). The camera accepts a maximal pixel clock rate of 10 MHz which resulting in a maximal data rate of 30 MBytes/s. The bottleneck in the current scanner prototype is the disk storage system (commonly available AV hard disk drives) reaching a sustained rate of 6 MBytes/s. Camera control (exposure, frame rate) as well as acquisition are accomplished by a PCI-board developed in-house. The PCI-board has further the ability to pre-process the data on the fly. Algorithms can be implemented in a Field Programmable Gate Array (FPGA) to correct for nonlinearities of the scanning process (Fig. 4).

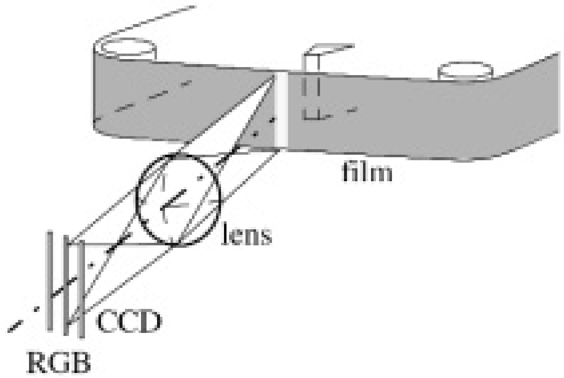

Figure 3. Optical setup.

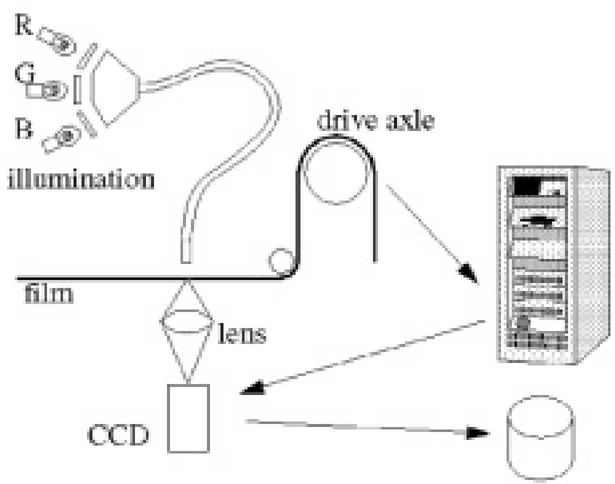

Figure 4. Scanner control and data acquisition

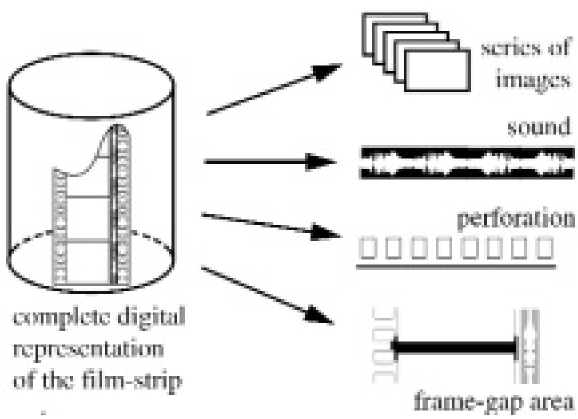

Figure 5. Examples of information to be extracted from the digital representation of the film

ILLUMINATION

A separate cabinet contains the illumination system. The light is guided to the scan slit by means of a fibre optic cross transverse changer (circular to rectangular). This setup yields several advantages. Besides an exact positioning of the illumination behind the scan slit the optical fibres keep heat radiation of the light source from the film. Furthermore, the illumination cabinet is not subject to any size constraints imposed by the rest of the setup. It can consist of sophisticated light sources and filtering.
To correctly carry out a colour restoration it is important to measure physical properties of the photographic material as opposed to the goal of conventional scanners (desktop or film) which are adapted to human colour perception. They use filters with broad spectral transmission characteristics aligned with the maxima of the eyes spectral sensitivity curves. The separate illumination cabinet provides a way to mix light of three narrow-band sources, positioned at the maxima of the absorption bands of the three colour dyes (e.g. 450, 550, 650 nm) of the photographic material[1,2,4]. Three 150W halogen bulbs combined with according interference filters will be used for this purpose.

CALIBRATION

The output of the scanner is expected to be a digital facsimile (being calibrated raw data) of the film strip. Thus the resulting data stream must be completely free of any scanner characteristics. Calibration tasks must be targeted to: 1) CCD characteristics, 2) scattered light, 3) illumination non-homogeneities, 4) displacements of the CCD segments, 5) spectral crosstalk (caused by broadband sensitivities (filters) of the CCD segments) and 6) film movement perpendicular to the scanning direction (film guidance).
1), 2) and 3) can be treated combined by offsetting and multiplying with previously determined per pixel values. Also, the kind of crosstalk mentioned (5 above) can be factored in beforehand and be corrected by means of a matrix multiplication after matching the shifted colour channels (caused by 4)). 6) has to be handled by simple image processing, taking the edge of the film as a reference.

Parts (if not all) of these calibration steps can be implemented on the PCI-board itself and will be applied on the fly while scanning. Considering the huge data amount resulting from scanning a motion picture film - a 2 hour 35mm movie scanned at 2K and 8 bit yields 1.3 Tera-Bytes (10 Tera-Bytes if scanned at a high quality of 4K, 16 bit!), so any processing that can be done on the fly saves a substantial amount of time later.

Such a device shows a simple mechanical setup, because none of the peculiarities of the motion picture film such as pitch of perforation, frame size and displacement etc. are handled by hardware. These tasks are delegated to the software side. While operating on the digital facsimile (ca. 2000 by 0.2 billion pixels!) as it is produced during the scanning process, one job of the software is the extraction of a sequence of images (Fig. 7) which will result in the digital motion picture film when shown at the correct frame rate . We plan to provide a database like interface to the digital Facsimile based on such algorithms (Fig. 5). Queries for soundtrack (as a very long image), sections of the perforation and other various aspects of the digital facsimile can be satisfied in this way.

At an underlying software level there have to be functions for administering and providing the access to the huge image of the scanned film strip. At this early stage of processing the data stream is still unstructured. As a first simple access method a sliding window metaphor has been implemented. A chosen interval of the film strip at a variable position is presented to the higher level algorithms as a standard image data structure. The position of the interval can be incremented or decremented along the length of the digital facsimile during the processing as needed (Fig. 6).

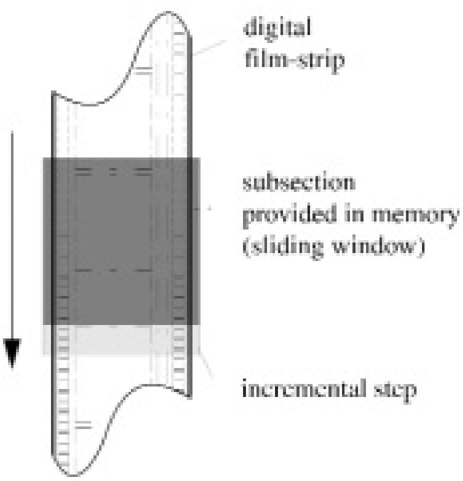

Figure 6. Sliding window protocol.

Figure 7. Iimage part extracted from scan sample.

CONCLUSIONS

The scanner is able to deliver digitized film data of reasonable quality to be used for our restoration research. The possibility of obtaining a digital facsimile of a film in full width and length had hitherto been non-existent. This concept is especially interesting for archivists due to the completeness of the data. Essential characteristics of the original (such as perforation, type of sound track, frame size and position etc.) are preserved. This scanning concept will be a means for producing a digital documentation reflecting all optical properties of the original, even including shrinkage or other forms of damage. Quality comparable to that of commercial scanners (4K, 10bit log) can be easily achieved by connecting a different camera.

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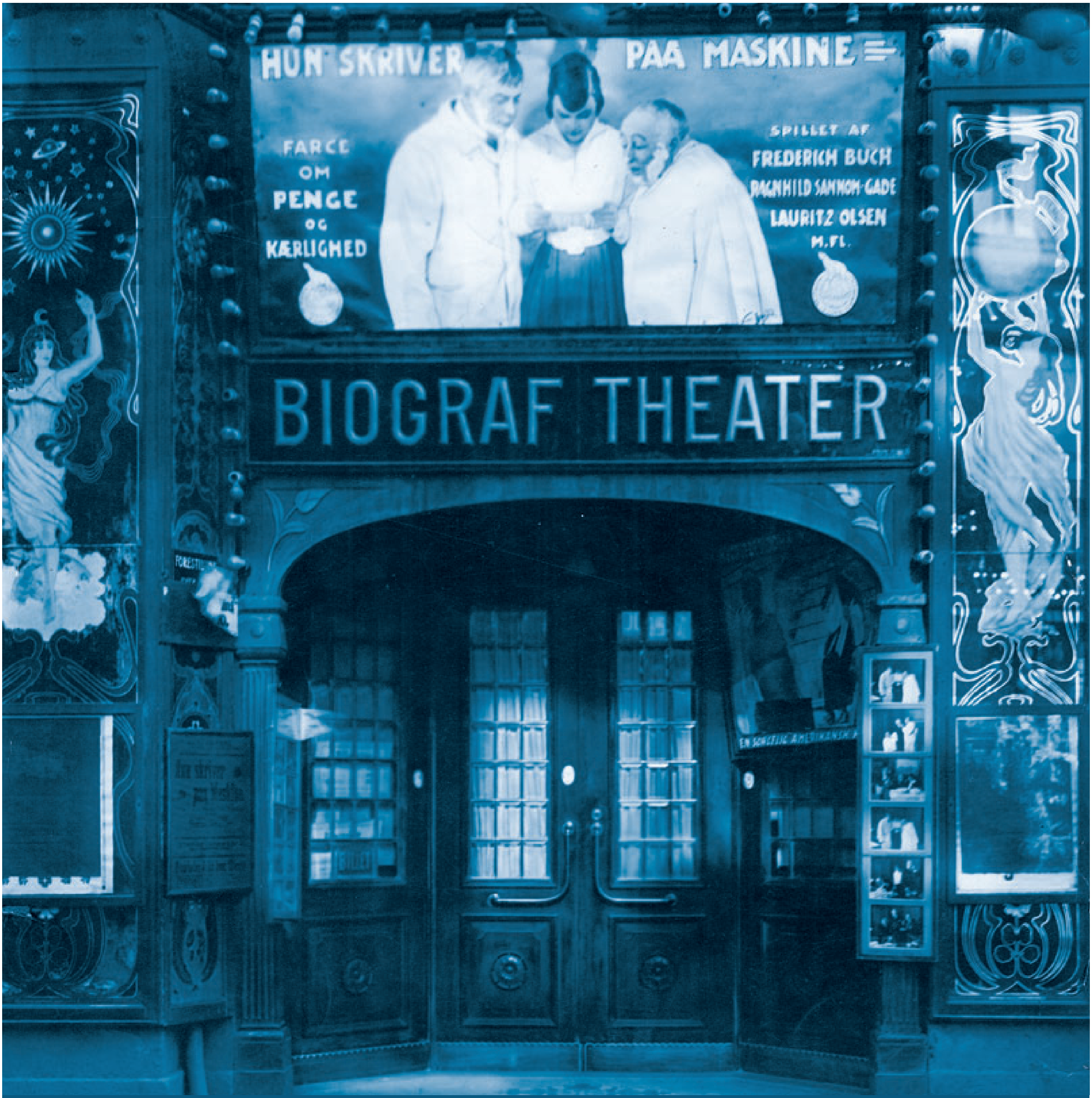
NOTES

1. R. Gschwind and F. Frey: "Electronic imaging, a tool for the reconstruction of faded colour photographs", *J. of Imaging Science and Technology*, 38(6), p. 520, 1994
2. Frey and R. Gschwind: "Mathematical bleaching models for photographic three-colour materials", *J. of Imaging Science and technology*, 38(6), p. 513, 1994
3. R. Gschwind, L. Rosenthaler, F. Frey: "The use of Digital Imaging for the Preservation of Collections of Photographs and Motion Pictures"; Paper delivered at the 11th Triennial Meeting of the International Council of Museums Commitee on Conservation (ICOM-CC), Edinburgh, 1996, vol II, 580-585.
4. L. Rosenthaler, R. Gschwind: "Restoration of old Movie Films by Digital Image Processing"; Proceedings of the European Workshop on Image Analysis and Coding for TV, HDTV and Multimedia Applications (HAMLET Race 2110 Workshop), February 27-28th 1996, Rennes
5. L. Rosenthaler, R. Gschwind, A. Günzl, A. Wittmann: "Restoration of old Movie Films by Digital Image Procesing"; Proceedings of the 3rd Intl. Conference COMMUNICATING BY IMAGE AND MULTIMEDIA (IMAGE'COM 96 Workshop), May 20-22nd 1996, Bordeaux, France 1996, vol II, 580-585
   A. Wittmann, W. Graff, T. Goessi, L. Rosenthaler, ,A. Gunzinger, R. Gschwind, "Neues Digitalisierungskonzept für digitale Filmrestauration und –Archivierung", *Fernseh- und Kino-Technik 51. Jahrgang*, (11/1997) 821-825
6. R. Gschwind, L. Rosenthaler, A. Wittmann, W. Graff and A. Gunzinger: "Restoration of old movie films by digital image processing", *in Care of Photographic, Moving Image & Sound Collections Conference* 1998,York (GB), July 1998, Susie Clark editor, p150-155, ISBN 0 9533229 1 2
7. W. Graff, A. Wittmann, L. Rosenthaler, A. Gunzinger and R. Gschwind: "A New Approach to Motion Picture Scanning", in: *ICPS'98* (The International Committee on the Science of Photgraphy), International Congres on Imaging Science, Antwerp, 7-11 Sept. 1998,Vol 2, p. 235-238.
8. W. Graff, A. Wittmann, L. Rosenthaler, A. Gunzinger and R. Gschwind: "New Scanning Approach to Motion Picture Digitizing", in: *Electronic Imaging: Processing, Printing and Publishing in Colour*, Jan Bares, Editor, Proceedings of SPIE Vol. 3409, p. 196-303 (1998)
9. W. Graff, A. Wittmann, L. Rosenthaler, A. Gunzinger and R. Gschwind: "A New Approach to Motion Picture Scanning", in: *ICPS'98* (The International Committee on the Science of Photography), International Congres on Imaging Science, Antwerp, 7-11 Sept. 1998,Vol 2, p. 235-238
10. L. Rosenthaler and R. Gschwind: "Restoration of movie films by digitale image processing", IEE Seminar "Digital restoration of film and video archives" 01/049, 16.1.2001, London, p. 6/1-677, UK ISSN 0963-3308 - Reference No: 2000/110 (The Institution of Electrical Engineers, Michael Farady House, Six Hills Way, Stevenage Herts SG1 2AY, Breat Britain)



PRESENTATION