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Contact-screen pulse-width encoding of a polychromatic image on a single piece of black-and-white film

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Abstract

Theory and experiment of the encoding of a color image via contact screen pulse-width modulation on a single piece of high contrast black-and-white (B&W) film and the reconstruction of the image in color from the film in a white-light image processing system are described. The three primary colored components of a color image are sequentially and separately encoded on a high contrast B&W film. During the encoding process, the original image, filtered by a primary filter, is contact-printed through a one-dimensional contact screen onto the high contrast film. The three colored components are encoded with the line cells of the screen oriented at three different and properly separated angles. After encoding and development, the B&W film may be placed at the input plane of a white-light image processor and an image can then be reconstructed in color by appropriate filtering through three primary colors at the Fourier plane of the processor.

I. Introduction

Beginning with the paper by Ives[1] in 1906, numerous schemes[2~5] have been reported for the reconstruction of polychromatic images from their corresponding encoded B&W transparencies. In the Ives scheme, a slide viewer is used to produce color images by spectral diffraction instead of absorption. Gratings either of different spatial frequencies or azimuthal orientations are used to modulate the three primary colors. And a spatial filter with three suitable apertures were placed at the spatial frequency plane to pass three primary colors (red, green, and blue) through so that a color image can be produced at the output plane. However, due to limitations of the geometrical shape of the aperture, certain marginal resolution was lost in this method; also, the color reproduced was dependent upon the size of the aperture and the spectral band of the light source. Later, Mueller[2] described a similar color image retrieval technique that uses a tricolor grid screen for image encoding. In decoding and image retrieval three quasi-monochromatic bands of light source are utilized. The technique offers an advantage of a single encoding step, but it also suffers from a drawback that a set of cross-product spectra in the spatial frequency plane occurs. Only by careful control of the photographic and spatial-filtering processes in his method can the linear superposition be achieved, and the cross-product representing cross-talk be eliminated.

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Nevertheless, the color reproduced still depends on the size of the limiting apertures and the spectral bands of the quasi-monochromatic light source used.

Recently Yu and his colleagues[3] adopted a similar but strictly white-light technique for color film archival storage and faded color restoration. Instead of using limiting apertures for color retrieval, broad spatial color filters are used to prevent marginal resolution loss.

In all the reported techniques, there is a common requirement. The development of the encoded film must be controlled very carefully to achieve a combined film gamma of minus two, so that linear encoding can be assured and serious cross-talk[4] can be avoided. The accurate control of the photographic development process usually takes a tedious two-film process and is not very easy to achieve. Besides, the two-film process usually adds noise and loses fidelity due to possible poor contact during the two exposures. As a result resolution may be reduced.

More recently, for the storage and retrieval of many different images on one film, Rogers and Sehdev[5] used a pulse-width modulation technique instead of the pulse-amplitude modulation methods as described above. Contact screens with one-dimensional (or line) cell patterns are used instead of Ronchi gratings in achieving the pulse-width modulation. The modulated images were recorded on a high-contrast film. The technique has the advantage of being quite insensitive to any minute variations in the photographic development process. However the cross-talk problem still can not be totally eliminated.

The purpose of this paper is to describe the theory and experiment of the encoding of a color image via contact-screen pulse-width modulation on a single piece of B&W transparency and the reconstruction of the image in color from the encoded film in a white-light image processing system. The encoding part of our technique is similar to that of Rogers and Sehdev and other halftone techniques reported previously, however, our goal and the reconstruction process are different.

II. Theoretical Discussion

We assume that the polychromatic intensity transmittance function at a given point (x, y) in the plane of a color transparency may be written as[2]:

$$T(x, y, \lambda)=C_r(\lambda)T_r(x, y)+C_g(\lambda)T_g(x, y)+C_b(\lambda)T_b(x, y), \tag{1}$$

where $C_r(\lambda)$, $C_g(\lambda)$, and $C_b(\lambda)$ are the spectrai transmittances of the red, green, and blue primary color filters, and $T_r(x, y)$ $T_g(x, y)$, and $T_b(x, y)$ are the transmittances of the corresponding primary color components of the image at (x, y).

In the encoding process, as shown in Fig. 1, an original color transparency is sequentially filtered through one of the three primary color filters red, green, and blue. Each filtered image is then contact-printed through a one-dimensional contact-screen at a corresponding angle θ (where θ equals θ_r for red, θ_g for green, and θ_b for blue) onto a high-contrast (ideally with infinite gamma) B&W film. The type of the high-contrast recording film can either be positive or negative. The developed film becomes the encoded transparency which, depending on the type of film used, may either be a positive with a transmittance of $t_p(x, y)$ or a negative with a transmittance of $t_n(x, y)$. It contains three halftone[7~8] images with amplitude (or intensity) transmittances $h_r(x, y)$, $h_g(x, y)$, and $h_b(x, y)$ corresponding to $T_r(x, y)$, $T_g(x, y)$, and $T_b(x, y)$. If the gamma of the film is assumed to be infinite, the encoded transparency will be binary in transmittance; i. e. either 0 or 1. The binary image is a pulse-width modulated version of the original through the one- dimensional contact-screen process. The amplitude (or intensity since the image is binary) transmittance of the image $t_p(x, y)$ can then be written as follows:

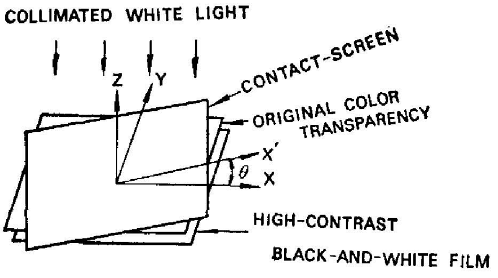

Fig. 1 The encoding process

$$\begin{aligned} t_p(x, y) = 1 - t_n(x, y) = & h_r(x, y) + h_g(x, y) + h_b(x, y) \\ & - h_r(x, y)h_g(x, y) - h_r(x, y)h_b(x, y) \\ & - h_g(x, y)h_b(x, y) + h_r(x, y)h_g(x, y)h_b(x, y), \end{aligned} \tag{2}$$

where the last four terms in the above equation represent cross-talk components (see the Appendix).

In general, the transmittance of a halftone line image of any one image component may also be written[5] as:

$$h(x, y) = \sum_{n=-\infty}^{\infty} \frac{1}{n\pi} \sin[n\pi\, w(x, y)]\, e^{jn\omega_0(x\cos\theta + y\sin\theta)}, \tag{3}$$

where $\omega_0 = 2\pi/P$, P is the period of the contact-screen, and $w(x, y)$ is the normalized width of a transparent line defined as the actual width of the line divided by the screen period P. The angle θ represents the orientation of the halftone lines. The normalized width $w(x, y)$ is a function determined by the original image transmittance $T(x, y)$, transmittance profile of the contact-screen cell, the film characteristics, and the photographic development process. In the present theory, $w(x, y)$ can not be clearly specified since the contact-screen cell transmittance is kept in its general from.

To illustrate the principle of the encoding process in a special case, we assume that the encoding angles are chosen[6] as $\theta_r = 0°$, $\theta_g = 90°$, and $\theta_b = 210°$. Then h_r, h_g, and h_b can be written as follows:

$$h_r(x, y) = \sum_{l=-\infty}^{\infty} \frac{1}{l\pi} \sin[l\pi\, \mathrm{R}(x, y)]\, e^{jl\omega_0 x},$$

$$h_g(x, y) = \sum_{m=-\infty}^{\infty} \frac{1}{m\pi} \sin[m\pi\, \mathrm{G}(x, y)]\, e^{jm\omega_0 y}, \tag{4}$$

$$h_b(x, y) = \sum_{n=-\infty}^{\infty} \frac{1}{n\pi} \sin[n\pi B(x, y)] e^{jn\omega_0(-\sqrt{3}x/2-y/2)}.$$

By substituting Eq. (4) into Eq. (2) we have

$$\begin{aligned} t_p(x, y) &= 1-t_n(x, y) = [R+G+B-RG-RB-GB+RGB] \\ &+ [(1-G-B+GB)\cdot\frac{1}{\pi}\sin(\pi R)]e^{j\omega_0 x} + \left[(1-R-B+RB)\cdot\frac{1}{\pi}\sin(\pi G)\right]e^{j\omega_0 y} \\ &+ \left[(1-R-G+RG)\cdot\frac{1}{\pi}\sin(\pi B)\right]e^{j\omega_0(-\sqrt{3}x/2-y/2)} + \cdots \text{higher order terms.} \end{aligned} \tag{5}$$

For simplicity, the "(x, y)" associated with R, G, and B are omitted in the above equation. In Eq. (5), the Fourier transform of the first term represents the zero-order spectrum and the next three are the first-order terms.

In the decoding or image reconstruction process, the previously encoded transparency is placed at the input plane of a white-light image processor as shown in Fig. 2. At the Fourier plane, the three first-order spectra in Eq. (5) are filtered respectively with three primary color filters having intensity transmittances of $C_r(\lambda)$, $C_g(\lambda)$, and $C_b(\lambda)$. Consequently at the output plane of the processor a color image is formed. The intensity transmittance of the color image may be written as:

$$\begin{aligned} \overline{T}(x', y', \lambda) &= C_r(\lambda)|t_r(x', y')|^2 + C_g(\lambda)|t_g(x', y')|^2 + C_b(\lambda)|t_b(x', y')|^2 \\ &= C_r(\lambda)[(1-G-B+GB)\cdot\sin(\pi R)]^2/\pi^2 \\ &+ C_g(\lambda)[(1-R-B+RB)\sin(\pi G)]^2/\pi^2 \\ &+ C_b(\lambda)[(1-R-G+RG)\sin(\pi B)]^2/\pi^2 \\ &= C_r(\lambda)\overline{T}_r(x', y') + C_g(\lambda)\overline{T}_g x', y') + C_b(\lambda)\overline{T}_b(x', y'), \end{aligned} \tag{6}$$

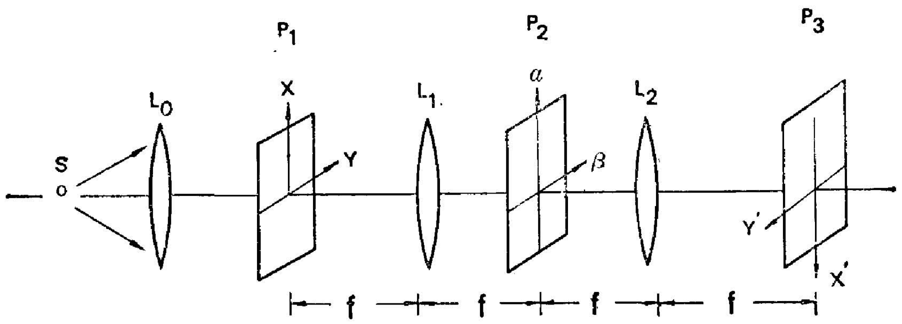

Fig. 2 A white-light image processing system. S—White-light source; P_1—Input plane; L_1 and L_2—Fourier transform lenses; P_2—Fourier plane; and P_3—Output plane

where t'_r, t'_g and t'_b are the second, third, and fourth terms of Eq. (5) respectively and $\overline{T}_r$, $\overline{T}_g$, and T_b are the reconstructed color components. Since $\sin(a) = \sin[(1-a)]$ for $0 \leqslant a \leqslant 1$, one can see from Eq. (6) that if any or all of the normalized widths R, G, and B exceeds 0.5, contrast reversal would occur. To avoid contrast reversal, we should make R, G, and B less than 0.5. But in order to minimize cross-talk, they should be reduced to about 0.3. However, by comparing Eq. (6) with Eq. (1) and as analyzed below, one can find that a high fidelity color image restoration is extremely difficult if not impossible to achieve. However, it also can be found that even though a complete recovery of the original image cannot be obtained, a fairly satisfactory color image resembling the original can be reconstructed if the cross-talk terms can be minimized or their effects compensated.

The condition for high-fidelity color image reconstruction is that all the color components are linearly reproduced so that the original color balance and tone change can be maintained. This condition can be analytically described by the following equations.

$$\frac{\overline{T}_r}{T_r}=\frac{\overline{T}_g}{T_g}=\frac{\overline{T}_b}{T_b}=c, \tag{7}$$

where c is a constant. Or, equivalently,

$$\frac{[(1-G-B+GB)\cdot\sin(\pi R)]^2}{T_r}=\frac{[(1-R-B+RB)\cdot\sin(\pi G)]^2}{T_g}$$
$$=\frac{[(1-R-G+RG)\cdot\sin(\pi B)]^2}{T_b}=c\pi^2. \tag{8}$$

Unfortunately, to require Eq. (8) be satisfied for all (R, G, B) is very difficult if not impossible.

There are two ways to obtain a reasonably good color image reconstruction. The simplest one[5] is to keep R, G, and B in Eq. (8) less than 0.1 and so that Eq. (8) is approximately satisfied. The disadvantage of this method is that the brightness of the image becomes too low and light efficiency becomes too small. A strong illuminating light source is needed for the display of the color image. Another way to reduce cross-talk and to satisfy Eq. (8) is through a masking process[9]. Normally, the color correction masking process is used in color printing for the correction of the unwanted absorptions due to the impurities in the cyan, mangata, and yellow inks. If the masking process is not used in making the color separation negatives, the unwanted absorptions caused by ink impurity may degrade color balance and tone change. The result is similar but simpler to that caused by the cross-talk effect in the present case. With the masking process, each halftone negative is determined not only by its own color component but also by the other two color components so that a desired correction can be made.

By applying the masking process to the encoding process each normalized width can be increased in proportion to the other two color components. The increased width can partially cancel the cross-talk effect which tends to decrease each color component, so that a more faithful reproduction of the original image can be obtained. The disadvantage of using this method is that the photographic process is quite complicated and very good alignment between mask and the original is required; besides, a desired correction is hard to achieve due to the cross-talk effect is not linear.

III. Experimental Demonstration

An experiment has been done to demonstrate the feasibility of the technique. In both of the encoding and decoding process, the three primary color filters used are the Kodak Wratten gelatin filters No. 29 (red), No. 61 (green), and No. 47 (blue). The high-contrast encoding film is a Kodak B&W sheet film No. 2568; a gamma of about six of the film is obtained when it is developed at 68°F for 2.5 minutes in a Kodalith developer. A one-dimensional contact-screen with triangular shaped cell transmittance profile of discrete stepped transmittance is used[10]. The screen frequency is 150 lines per inch. A microphotograph of the screen cell is shown in Fig. 3. Unfortunately, the dynamic range of the Polaroid type 107 B&W instant film is not wide enough to record the shape of the cell pattern completely and therefore the low transmittance parts of the cell are not recorded. When the encoded film is placed at the object plane of the white-light image processor as shown in Fig. 2 and three primary color filters are properly positioned with respect to the first order spectra at the Fourier plane, a color image can be reconstructed at the output plane. The original color image, the encoded B&W transparency, and the reconstructed color image are shown in Fig. 4. (See also the insert of colour-7, 8, 9).

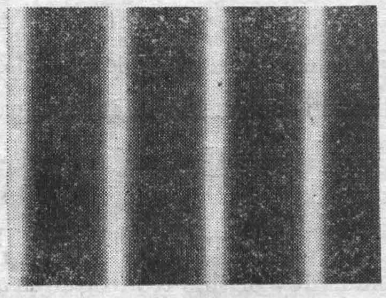

Fig. 3 A microphotograph of the contact-screen used for the encoding process

It should be mentioned that the one-dimensional contact screen used in the experiment is not the most suitable one because the base of the triangular-shaped cell pattern spans over the full width of the cell and hence very high threshold must be used during the encoding process so that the maximum normalized halftone line width of the encoded B&W film is limited to about 0.3. The high threshold of the film will produce a narrow dynamic range in the reconstructed image as the number of steps of the gray scale is reduced. The ideal contact screen for this experiment has a cell pattern like the one shown in Fig. 3. With an ideal contact screen, a high-contrast film with a very low threshold can be used for encoding. Since the base of the triangular shaped cell pattern is about 30 percent of the total cell period, a wide dynamic range of the image can be reconstructed.

It can be seen in Fig. 4 that the thin lines and small characters in the image are not well reconstructed. This is because they are spatially "undersampled". The fact that the frequency of the 1-D screen is about 6 lines/mm which means that the highest reconstructable frequency component in the image is less than 3 cycles per mm. Only for those sharp lines and small characters with lines wider than 1 mm and their highest frequency component not greater than 3 cycles per mm, a faithful reconstruction can be expected.

IV. Conclusion

We have presented the theory and experimental demonstration of color image storage on a single piece of B&W film and the image reconstruction from the encoded film in a white-light image processing system. As compared to the grating amplitude modulation technique, the contact-screen pulse-width modulation technique can simplify the photographic process and save recording films. The technique, similar to the grating modulation technique, is still not free from the cross-talk problem. The brightness efficiency of this technique is aboutt 60 percent of that of the grating techniques since the maximum line width is 0.3 instead of 0.5 which is the line width of a Ronchi grating.

How to optimize the design of a screen for color storage with different color ranges of the primary colors needs further investigations.

Appendix: Calculation of the cross-talk terms

We assume that two binary images h_1 and h_2 as shown in Fig. 5(*a*) are sequentially exposed to a high-contrast positive film. The developed transparency h_{12} should also be an image of binary form as shown in Fig. 5(*b*). From the figure, it can be seen that the portion of h_{12} is opaque if the corresponding overlapping portions of h_1 and h_2 are both opaque, otherwise, it is transparent. This relation is equivalent to the logic "OR" operation. The relationship between h_{12} and h_1 and h_2 may therefore be written as:

$$h_{12}=h_1\ (\mathrm{OR})\ h_2=h_1-h_1\cdot h_2. \tag{9}$$

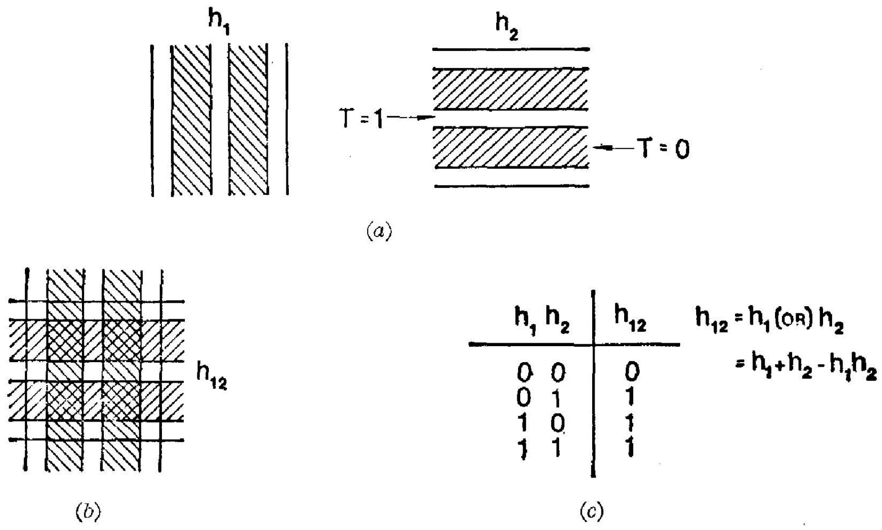

Fig. 5.

(*a*) Binary images h_1 and h_2; (*b*) Combined binary image h_{12};
(*c*) Transmittance functions of h_1, h_2 and h_{12}

Equation (9) can then be easily extended to the case of three binary images h_1, h_2, and h_3. The resultant binary images h_{123} can be considered as a combination of h_{12} and h_3:

$$h_{123}=h_3(\mathrm{OR})h_{12}=h_3+h_{12}-h_3\cdot h_{12}=h_3+(h_1+h_2-h_1\cdot h_2)-h_3\cdot(h_1+h_2-h_1\cdot h_2)$$
$$=h_1+h_2+h_3-h_1\cdot h_2-h_1\cdot h_3-h_2\cdot h_3+h_1\cdot h_2\cdot h_3.$$

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在单张黑白感光片上多色图像的密着网屏脉冲宽度编码

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提　　要

本文描述了以密着网屏脉冲宽度在单张高反差黑白感光板上的调制作彩色图像的编码和在白光图像处理器中再现成彩色图像的理论和实验。本技术的编码部分与 Rogers, Sehdev 及其它半色调屏法相似，但是，我们的目的和再现过程与他们的不同。