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Color Separation in Forensic Image Processing

ABSTRACT: In forensic image processing, it is often important to be able to separate a feature from an interfering background or foreground, or to demonstrate colors within an image to be different from each other. In this study, a color deconvolution algorithm that could accomplish this task is described, and it is applied to color separation problems in document and fingerprint examination. Subtle color differences (sometimes invisible to the naked eye) are found to be sufficient, which is demonstrated successfully for several cases where color differences were shown to exist, or where colors were removed from the foreground or background. The software is available for free in the form of an Adobe® Photoshop®-compatible plug-in.

KEYWORDS: forensic science, document examination, image processing, color separation, color deconvolution, ink analysis, ink discrimination

There are a number of situations in which the colors (and color differences) in an image are important to the forensic examiner. We will consider the following three cases:

(a) It is suspected that changes and additions have been made to existing handwriting or printing; can a color difference be found?
(b) Handwritten entries have been obliterated or masked with a similar but not identical ink; can the original entries be made legible?
(c) A fingerprint has been made visible, but the background of the substrate makes it difficult to interpret; can the background be suppressed?

There are several techniques available to tackle these problems in a nondestructive way, like IR/visible/UV luminescence and reflectance, or with destructive methods such as thin-layer chromatography, high-performance liquid chromatography, and capillary electrophoresis (for an overview see, e.g., Ref. (1)). Depending on the optical properties of the materials involved, optical methods can work very well, or not at all.

This study aims to develop an image-processing tool that can give good results quickly, even when traditional nondestructive techniques fail. As computers and scanners are widely available it is also a low cost method. In previous papers, Adobe® Photoshop® (Adobe Systems Inc., San Jose, CA) was used for similar problems with varying recipes (2–4) depending on the combination of colors in the image. Color-transformation algorithms preparing images for segmentation have been proposed as well (5). The color deconvolution (6) algorithm described in this paper offers a more straightforward and widely applicable tool for distinguishing or removing color components. The user only needs to identify the desired, undesired, and background colors by simply clicking on them after which the algorithm is applied.

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Methods

Digital images are usually stored in a format where the color for every pixel (picture element) is given in RGB color space.

Every color in RGB space is defined as

$$\vec{c} \equiv \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} \equiv \begin{pmatrix} r \\ g \\ b \end{pmatrix}$$

where r, g, and b are the red, green, and blue components, respectively. Figure 1*b* shows what we obtain when we plot the colors of the image in Fig. 1*a* in a three-dimensional histogram in RGB color space.

New unit vectors can be chosen to describe every point in this three-dimensional space, based on the chosen points P, U, and D, where P refers to the *paper* (background) color, U to the *undesired* color, and D to the *desired* color. Choosing point P as the new origin we define the new unit vectors:

$$\vec{u} \equiv \overrightarrow{PU},\ \vec{d} \equiv \overrightarrow{PD},\ \text{and } \vec{n} \equiv \vec{u} \times \vec{d} \tag{1}$$

Using these unit vectors we can express any color $\vec{c}$ in its undesired (u), desired (d), and n-component (where $\vec{n}$ is a unit vector normal to $\vec{u}$ and $\vec{d}$):

$$\vec{c} = u \cdot \vec{u} + d \cdot \vec{d} + n \cdot \vec{n} + \vec{p} \tag{2}$$

with $\vec{p} \equiv \overrightarrow{OP}$. Solving this equation gives aforementioned components.

Removing the undesired component thus results in the corrected color:

$$\vec{c}\,' = d \cdot \vec{d} + n \cdot \vec{n} + \vec{p} \tag{3}$$

Mathematica® (Wolfram Research Inc., Champaign, IL) was used to solve Equation (2) and get a working prototype of the software. Solving Equation (2) with symbols rather than numbers leads to a very long formula for calculating the corrected color $\vec{c}\,'$ from the original color $\vec{c}$ and the chosen vectors $\vec{u}$, $\vec{d}$ and $\vec{p}$, which can be

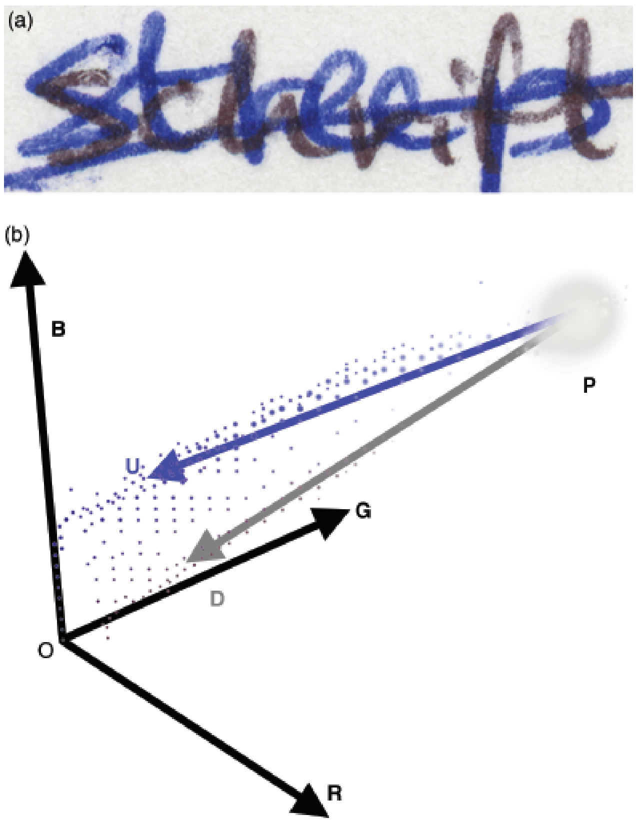

FIG. 1—*(a) A test image of overlapping handwriting in clearly discernable colors (desired: black; undesired: blue). (b) Three-dimensional histogram of the RGB components of every pixel in the image of a. Note the large spherical cluster for the color of the paper and the two elongated clusters representing both inks with the colors for overlapping inks laying in between.* $\overrightarrow{PU}$ *and* $\overrightarrow{PD}$ *are alternative unit vectors based on handpicked colors of the paper background and both inks (desired and undesired).*

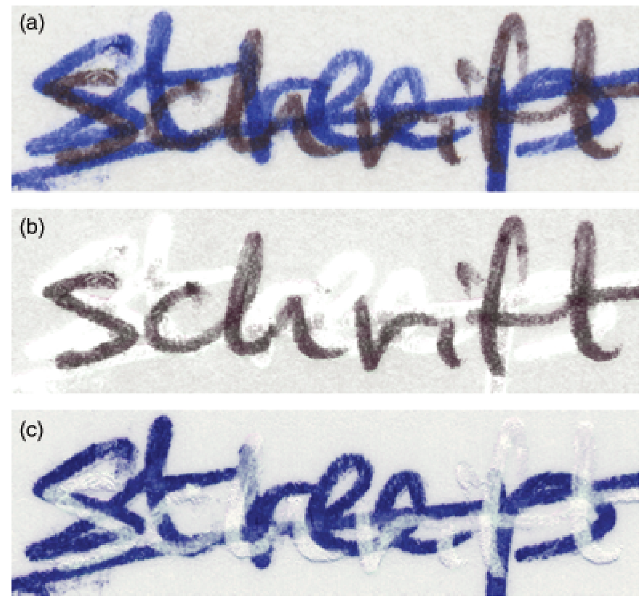

FIG. 2—*(a) Original test image. (b) Resulting image after removing the undesired component. (c) Resulting image after removing the desired component.*

simplified to the following:

$$\vec{c}\,' = \frac{\mathbf{M}\vec{c} + (d_3n_2p_1 - d_2n_3p_1 - d_3n_1p_2 + d_1n_3p_2 + d_2n_1p_3 - d_1n_2p_3)\vec{u}}{(d_3n_2u_1 - d_2n_3u_1 - d_3n_1u_2 + d_1n_3u_2 + d_2n_1u_3 - d_1n_2u_3)} \tag{4}$$

with

$$\vec{n} = \begin{pmatrix} d_3p_2 - d_2p_3 - d_3u_2 + p_3u_2 + d_2u_3 - p_2u_3 \\ d_1p_3 - d_3p_1 + d_3u_1 - p_3u_1 - d_1u_3 + p_1u_3 \\ d_2b_1 - d_1b_2 - d_2u_1 + b_2u_1 + d_1u_2 - b_1u_2 \end{pmatrix}$$

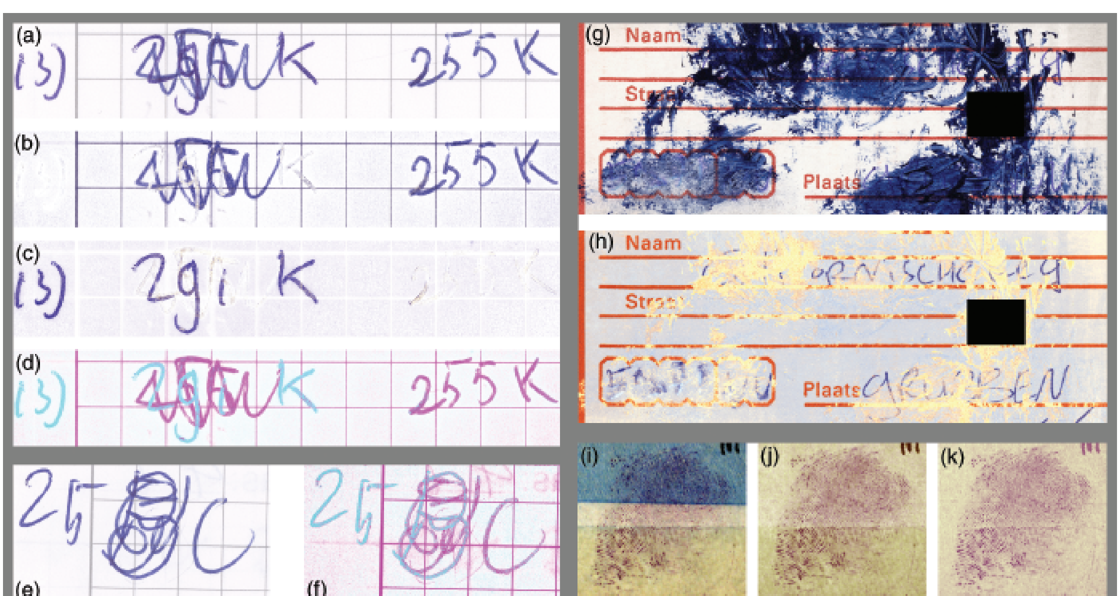

FIG. 3—*Examples from casework. (a–d) Questioned document, additions, original handwriting, and component split, respectively. (e–f) Questioned document and component split. The color difference is close to a minimum for differentiation. (g–h) Address label rendered unreadable and color deconvolution result. Note how even the lower left, which had been treated by destructive methods by another examiner, becomes visible in white. (i–k) Fingerprint on the inside of an envelope, made visible by treatment with ninhydrin; first, deconvolution to remove blue background print; second, subsequent deconvolution to remove yellowish color of the envelope glue.*

and

$$\mathbf{M} = \begin{bmatrix} d_2n_1u_3 - d_1n_2u_3 - d_3n_1u_2 + d_1n_3u_2 & (d_3n_1 - d_1n_3)u_1 & (d_1n_2 - d_2n_1)u_1 \\ (d_2n_3 - d_3n_2)u_2 & d_2n_1u_3 - d_1n_2u_3 + d_3n_2u_1 - d_2n_3u_1 & (d_1n_2 - d_2n_1)u_2 \\ (d_2n_3 - d_3n_2)u_3 & (d_3n_1 - d_1n_3)u_3 & d_3n_2u_1 - d_2n_3u_1 - d_3n_1u_2 + d_1n_3u_2 \end{bmatrix}$$

These expressions were used for an implementation of the algorithm in the form of an Adobe® Photoshop®-compatible plug-in, which is available for free (7). This plug-in also works with other programs supporting PhotoShop® plug-ins, among which are some freeware graphic viewers (7). *P*, *U*, and *D* are defined by simply clicking in the image to sample the corresponding colors (with adjustable sample size) after which the algorithm can be applied in preview. Parameters can be saved and loaded, and if the chosen parameters give a satisfying result in preview the algorithm can be applied to the original image. Optionally the *u* or *d* component can be visualized in a grayscale image with white as a background. Figure 2 shows the image from Fig. 1*a* together with the results of removing the undesired and desired components, respectively.

We can also use *u* and *d* directly as RGB components, and thus obtain an image in which the undesired components are red, the desired components are green, and the background is black (optionally inverting it to cyan, magenta, and white). This can be very helpful in demonstrating subtle color differences.

Results

Making Subtle Color Differences Obvious

Figure 3*a* shows an image from a fraud case in which it was suspected that corrections had been made with a possibly different ballpoint ink. The colors of the handwriting on the left and right as well as the background color were sampled, and the values were used for color deconvolution. Figure 3*b–d* shows the results of removing the desired component, removing the undesired component, and plotting the desired and undesired component as cyan and magenta, respectively. Figure 3*e* is from a different document in the same case, but in this instance, other optical methods (IR/visible/UV luminescence and reflectance) gave inconclusive results. Although color differences are very small, it is still possible to distinguish the inks used for original handwriting (in cyan) and corrections (in magenta).

Removing an Obscuring Ink from Handwriting in a Similar Color

Figure 3*g* shows an example from a case in which an attempt was made to make an address label unreadable. Color deconvolution improves clarity drastically: most of the original handwriting has been recovered, except for a few parts where the covering ink layer was too thick to show any of the underlying color (see Fig. 3*h*). Note how even the part in the lower left, which had been treated by destructive methods by another examiner, becomes visible in white.

Suppressing the Background in a Fingerprint Image

Figure 3*i* shows a fingerprint on the inside of an envelope flap. Color deconvolution was successfully applied twice to first remove the background print (Fig. 3*j*) and then the color of the envelope glue (Fig. 3*k*).

Discussion

Color deconvolution gives excellent results in some cases even when traditional optical techniques give inconclusive results, making it a complementary technique. As the required hardware is already present in forensic labs (or even a home office) it is also a cheap method. Because it only involves a computational effort and minimal user input the method is very fast, and only the digital image of the evidence is required, not the physical evidence itself. Unlike some other image processing algorithms, color deconvolution applies the same calculation to every pixel in the image (no area selection or influence of neighboring pixels is involved). This means that two pixels that were the same before processing will still be the same after processing, and that the whole procedure is easily documented by simply storing the nine numbers that define *U*, *P*, and *D*.

This tool can help forensic scientists in improving clarity of images and determining and demonstrating color differences in images, with the following limitations:

(i) When the ink is not transparent or mixing *at all* there is of course no hope for image analysis methods alone to separate overlaying colors, but seemingly hopeless cases can sometimes still give good results.
(ii) The quality of the image is important: an image obtained with a high-quality scanner will likely give much better results than a digital photo with poor exposure (although even then spatial averaging might help).
(iii) When color differences are extremely small *P*, *U*, and *D* might have to be sampled in different parts of the image to see which parameters give the best results in the preview. Obviously, one cannot conclude two inks are identical when no difference can be demonstrated.

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