Linking Inkjet Printing to a Common Digital Source Document

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Minimal differences in a digital source document will drastically change the error diffusion dot pattern of an inkjet print. This study explains and demonstrates this effect and shows how this particular property of the error diffusion screening method can be used to link inkjet-printed documents to a common digital source. The results of the study were applied in a case.

Introduction

This paper will give a short overview of digital halftoning methods that are used by commonly encountered printers in the home and office environment. The impact of minimal changes in the digital source of the printed image on an error diffusion dot pattern is studied with simulations and with an experiment. Finally, the results will be applied to the problem of linking 2 inkjet-printed documents in a case.

Most printers create the illusion of a full-color (or grayscale) image with a very limited number of colors (or just black) at their disposal. They use a large variety of digital halftoning methods (Kang, 1999) to accomplish this, and the particular method chosen depends on the type of printer (Figure 1).

The common principle of digital halftoning or dithering methods is that they trade spatial resolution for the illusion (impression) of continuous tones. These methods can be divided into 2 main categories: (1) threshold array methods and (2) error diffusion methods. For clarity, the discussion of these categories will be limited to grayscale images, but the extension to full-color images is relatively straightforward.

Threshold Array Dithering

The most direct way to convert a continuous-tone image to a halftone image is to threshold it; however, this completely removes the continuous-tone quality of the source image. A much better result can be achieved by threshold array dithering methods. Although implementations vary, the most general way of looking at these methods is to see them as a multiplication with a threshold mask, followed by thresholding. These masks generally consist of a repeating pattern, and their unit cells are carefully chosen to obtain a perceptually pleasing end result. A number of possibilities for these unit cells or "threshold arrays" (Figure 2) include:

(i) noise (the pattern does not repeat itself, and this method is computationally intensive and rarely used);

(ii) a line pattern with a sinusoidal variation in intensity (Figure 1b);

(iii) a 2-dimensional sinusoidal pattern (Figure 1a); and

(iv) a n×n-ordered dither thresholding array (Figure 3).

These halftoning methods are commonly used with laser printers. Methods using patterns like (ii) and (iii) are sometimes referred to as amplitude modulation (AM) techniques, since the frequency of the pattern is fixed but the size or amplitude of its elements varies.

Error Diffusion Halftoning

Error diffusion methods are commonly used with inkjet printers. They are sometimes referred to as frequency modulation (FM) techniques, because in this case the size of the elements (dots) is fixed while their frequency of placement varies.

In error diffusion dithering, the 1st pixel of the image (e.g., in the upper left corner) is approximated by a black or a white pixel. Subsequently, the difference between the original value and the approximation (the error) is diffused to

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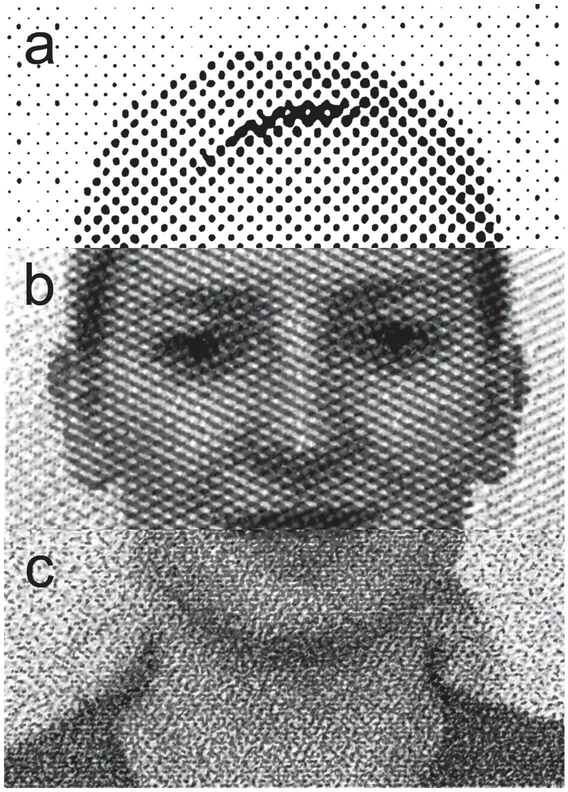

Figure 1. Examples of screens encountered in common printers such as (a) black-and-white laser printer (b) color laser printer, and (c) color inkjet printer.

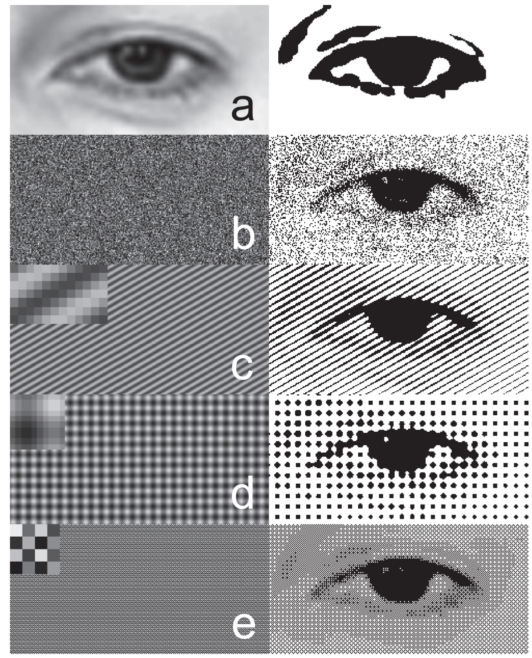

Figure 2. The original image (a) is shown together with a thresholded version. The halftone images on the right below this were generated by multiplication with the mask on the left, followed by thresholding. The masks used were: (b) noise, (c) line mask, (d) sine mask, and (e) ordered dither mask (4×4). The unit cells of the masks (threshold arrays) in (c), (d), and (e) are shown in insets on the left.

neighboring (following) pixels. The whole procedure is repeated for all the pixels in the image. For example, if a pixel is dark gray and approximated by a black pixel, neighboring pixels in the source image will be made brighter by a certain fraction (Figure 4) of the error made in the approximation (to compensate for the error in the subsequent steps of the procedure). This study applies to all variations of the error diffusion method. Variation involving printer manufacturer or printer driver has not been the subject of this study.

Methods

Simulations

Simulations were carried out on digital images, using Adobe® Photoshop® for halftoning of images with different methods. Then minimal changes were introduced to the original images, after which images were once again generated with different dithering methods. Finally, it was shown to which extent the dither patterns were influenced by the introduction of minimal changes in the original image.

Experiment

To verify the results of the simulations, the original image, as well as the image with the modified pixel, was printed on an inkjet printer (HP DeskJet 895C). The error diffusion dot patterns of the different colors of the printed image were separated using color deconvolution (Berger, in press). Color deconvolution is a digital image processing method that does a color space transformation to single out color components of choice.

Results

Simulation

For threshold array dithering, small changes in the original image will usually cause small changes in the resulting image. For error diffusion

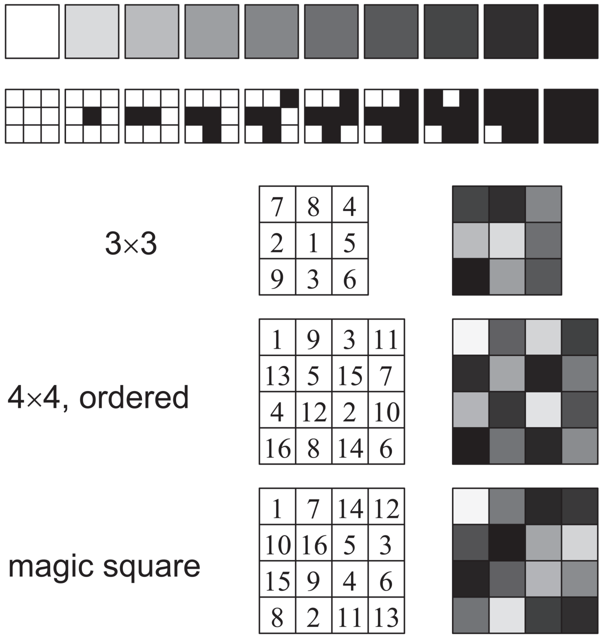

Figure 3. The top part shows how a 3×3 threshold array suggests gray levels by switching pixels on, one by one. The order in which this takes place is shown in numbers as well as gray levels in the matrices in the middle. The latter can be used as the unit cell of the mask to multiply the image with before thresholding. Different sizes and orders can be chosen.

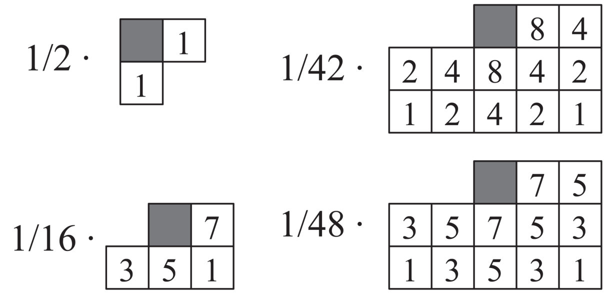

Figure 4. Different schemes for error diffusion, showing how the difference between the intended gray level and its approximation is spread over neighboring pixels for subsequent compensation.

dithering (Figure 5), even a small change in the source image causes drastic changes in the placement of the dots in the dithered image. This is clearly visible in Figure 5d in the pixels that were processed after encountering the changed pixel.

Experiment

No significant differences were observed between multiple prints of the same source image (Figure 6a,b). However, as in the simulation, the dithered version of the slightly modified image (Figure 6c) was found to have a different placement of the dots.

Case Report

In 2 cases, inkjet-printed (forged) money had been found at the scenes of shootings. The purpose of the document examination was to see whether the shootings could have been connected by linking the forged money to the same source. No

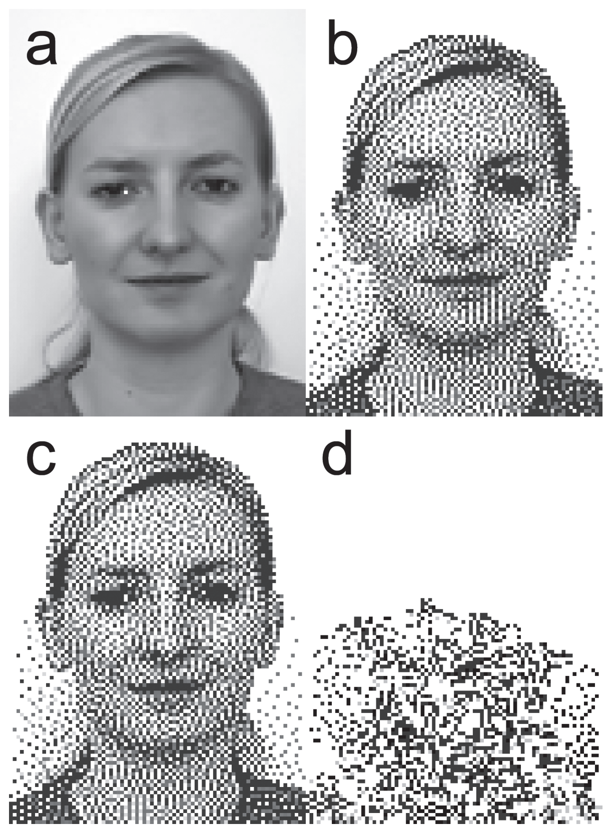

Figure 5. Illustration of the impact of a small change in an image on its error diffusion halftone version: (a) original image with 1 pixel in the eye turned to white, (b) halftoned original image, (c) halftoned modified image, and (d) the difference between (b) and (c).

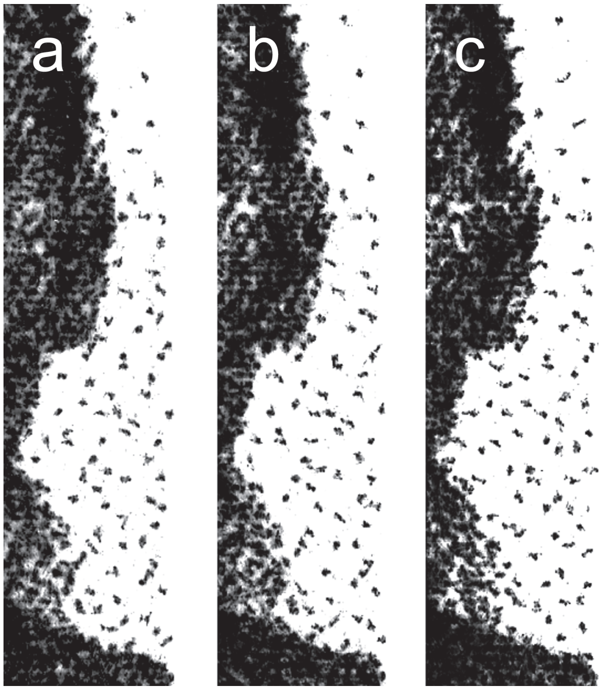

Figure 6. Details of the inkjet-printed versions of the original and modified image: *(a)* and *(b)* show the magenta dots for 2 prints of the original image, *(c)* shows the magenta dots for the printed modified image. As in the simulation, differences are apparent in *(c)* below the ear.

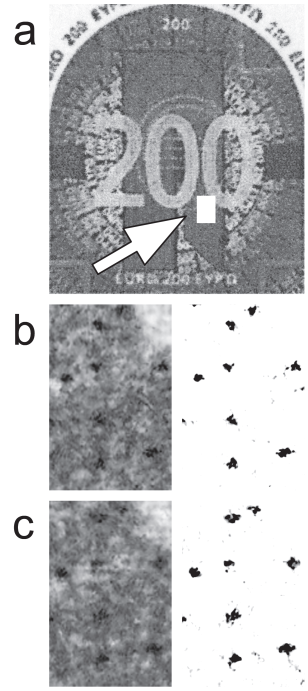

Figure 7. An analysis of a detail (*a*) in the inkjet-printed forgeries showing the same distribution of black dots (*b*)(*c*) in the area analyzed.

marks (from the original or introduced in the scanning of the original) were found that could have helped establish a link between the documents. Applying the results presented in this paper, the details of the dot pattern were studied and found to be the same (Figure 7).

Discussion

Detailed analysis of an error diffusion inkjet dot pattern can link 2 prints to a common source, since 2 images with a minimal difference (i.e., 1 pixel) will generate a significantly different dot pattern. However, when a different dot pattern is found, the images may very well still have a common digital source document. For example, an identical image in a different word-processing document may result in a different dot pattern even when the printing software and hardware are identical.

In addition, one should always be aware that new versions of dithering methods are constantly being invented and introduced. Among these is the use of very large (256×256) "blue noise" stochastic dithering masks, with output that could be misidentified as error diffusion halftoning. Another example is a variation of error diffusion where the fractions of the error that will be diffused are randomized, thus producing a different dot pattern with every print.

References

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