HIGH CONTRAST STOCHASTIC SCREEN WATERMARKS FOR COLOR HALFTONE PRINTS

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ABSTRACT

Embedded watermarks in printed halftone images, which can subsequently be detected using an visual aid or using a watermark detection algorithm on a scan of the image, are of interest in wide range of applications. For black and white halftone printing using stochastic screens, digital watermarks that are embedded as correlations in the halftone screen have been previously proposed. Here we present a novel extension of these watermarks to color that produces a high contrast watermark by using the colorant separations coherently with a single watermarked stochastic screen and performing detection coherently across the color separations. Compared with independent watermarking of the halftone separations, the resulting watermark offers significantly higher contrast in the detected image.

Index Terms— color halftones, halftone watermarks, stochastic screens, visual watermarks

1. INTRODUCTION

Conventional paper watermarks are visual patterns embedded in the substrate of a sheet of paper by creating variations in thickness when manufacturing the paper. The technology of paper watermarks is amazingly long-lived, having been in use since the late thirteenth century[1], and utilized to this day for authenticating and preventing counterfeiting of currency and other high value documents.

In recent years, with similar motivations, halftone-based watermarks have been proposed for watermarking of printed images. These watermarks are commonly embedded as correlations in the halftone patterns which are revealed either by overlaying a suitable decoder on the printed image document, or by using a software decoder on a (high-resolution) scan of the print, which overlays one region of the scan on another to achieve the same effect as the overlay of a decoder. Halftone correlation watermarks were first introduced by Knox [2] for monochrome, i.e. black and white, images printed with stochastic halftone screens. These designs were improved upon in [3] to obtain better contrast for the recovered watermark patterns. Applications to adaptive dispersed dot halftoning techniques [4, 5, 6] and to clustered dot screens have been subsequently developed [7, 8]. Most of this work addresses black and white halftones with the notable exception of [4] which also applies to error diffusion based color halftones and [9], which extends the clustered-dot continuous phase modulated halftones [8] to color printing. Color versions of stochastic screen based halftone watermarks have received limited attention [10].

This paper proposes a novel stochastic screen watermark for color halftone prints, which offers an advantage over [10] by offering higher contrast for the detected watermark pattern. By using "successive filling" for the color separations with a screen designed with an embedded watermark, the different separations work together in producing the watermark, producing a detected watermark pattern with high contrast. The method offers a significant improvement in watermark contrast over the previous color watermarking method described in [10]. We note that the work reported here is covered by patent [11].

The paper is organized as follows. Section 2 reviews monochrome stochastic screen watermarks, providing foundation for our proposed high contrast color stochastic screen watermark, which is described in Section 3. Experimental results demonstrating the performance of the proposed watermark and comparing against the prior work in [10] are presented in Section 4. Section 5 concludes the paper.

2. MONOCHROME STOCHASTIC SCREEN WATERMARKS

Halftoning is typically used for rendering pictorial images and graphics on bi-level output devices, such as printers and e-ink displays. We focus exclusively on the printing application of halftoning, where the halftoning is usually performed just prior to printing.

Screening is a common technique used for halftoning, which operates by comparing a *continuous tone* image $I(m,n),\ 0 \leq m \leq M, 0 \leq n \leq N$, pixel-by-pixel, against a periodically-tiled *halftone threshold array* $T(i,j), 0 \leq i \leq H, 0 \leq j \leq W$, producing a bi-level halftone image $I_h(\cdot) \in \{0,1\}^{M\times N}$, mathematically specified by

$$I_h(m,n) = \begin{cases} 1 & \text{if } I(m,n) \leq T\left([m]_H, [n]_W\right), \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

for all $0 \leq m \leq M,\ 0 \leq n \leq N$,, where $[a]_b$ denotes the remainder obtained upon dividing the nonnegative integer a by the positive integer b. Among the different methods that can be used for halftoning [12], screening is often preferred because it is extremely computationally efficient, requiring only one comparison per pixel. As a notational short-hand, we will denote the computation of the halftone image by I_h thresholding with the screen $T(\cdot)$, as $I_h \leftarrow \mathscr{T}(I,T)$.

When the halftone image $I_h(m,n)$ is printed, pixels with a value of 1 are rendered black with the printer colorant and pixels with values of 0 remain white. The pixels that are in a minority, for instance, black pixels in regions where fewer than half the pixels are black, are referred to as the *minority pixels*. Depending on the printer technology and application requirements, screens may be designed to produce either clustered dot halftones, where the minority pixels occur clustered together, or dispersed dot halftones, where the minority pixels tend to be dispersed [12]. Stochastic screens, in particular, are dispersed dot halftone screens. For pleasing visual appearance, stochastic screens are designed to ensure that the minority pixels at

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This work was conducted while G. Sharma was at Xerox Corporation.

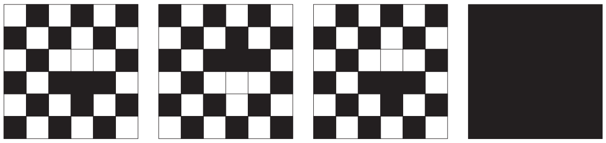
1	172	24	232	80	168
228	88	154	104	208	40
32	200	56	36	8	252
219	116	240	137	188	16
65	160	103	209	72	138
202	125	172	96	248	40

(a) Screen 1

254	83	231	23	175	87
27	167	101	151	47	215
223	55	119	219	247	3
36	139	15	118	67	239
190	95	152	46	183	117
53	130	83	159	7	215

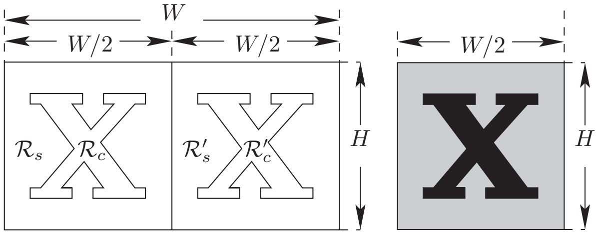
(b) Screen 2

Fig. 1. A pair of conjugate halftone screen functions.



(a) H1 (b) H2 (c) H1 ⊕ H1 (d) H1 ⊕ H2

Fig. 2. Output halftones for images screened with the pair of conjugate halftone screen functions of Fig. 1 and their overlays.



(a) Screen Constraints (b) Detector Output

Fig. 3. Watermarked stochastic screen design: a) Constraints for watermark pattern embedding, b) Watermark detector output.

any given gray level are evenly distributed. This ensures that the error introduced in the halftoning process is (largely) distributed at high spatial frequencies and therefore less visible [12].

In [13] the use of conjugate halftone screens for watermarking of monochrome was proposed. Halftone screen threshold functions $T_1(\cdot)$ and $T_2(\cdot)$ are said to be in a conjugate relation with each other if

$$T_1(i,j) = 255 - T_2(i,j)$$

for all corresponding pixels (i,j). A sample pair of conjugate halftone screens are shown in Fig 1. Note that the sum of two values in any pair of corresponding pixels shown in Fig 1 is 255[1].

If an input with a constant level 128 is halftoned by the conjugate screens shown in Fig 1, the result will be a "conjugate" pair of binary patterns as shown in Fig. 2 (a) and (b). An overlay of any of these patterns with itself, yields exactly the same binary pattern, as shown in Fig. 2 (c) for the pattern in Fig. 2 (a). On the other hand, an overlay of the two binary patterns as shown in Fig. 2 (a) and (b) yields a completely black pattern as shown in Fig. 2 (d).

Figure 3 illustrates one way in which a watermarked stochastic screen is obtained using the concept of conjugate screens. The $H \times W$ spatial extent (in pixels) of the stochastic halftone screen is partitioned vertically into two halves as shown in Fig. 3 (a)[2] The region for each half is further partitioned into two pairs of congruent regions: regions $\mathcal{R}_s$ and $\mathcal{R}'_s$ where the screen thresholds for corresponding pixels are constrained to be the same (s) and regions $\mathcal{R}_c$ and $\mathcal{R}'_c$, corresponding to the insides of the "X" in each half, where conjugacy (c) constraints are imposed on the halftone screen thresholds. A watermarked stochastic screen is then obtained, by designing the thresholds for overall $H \times W$ stochastic screen to maximize, under the constraints already indicated, a merit function that characterizes how evenly minority pixels are distributed across the range of gray scales. Details of the merit function and the optimization methodology can be found in [14]. The watermark is detected in monochrome images generated using the watermarked stochastic screen, by scanning the halftoned image from the print and overlaying, upon the scanned image, a version of the scanned image translated by a distance corresponding to $(W/2)$ pixels in the halftone. Observe that if a contone image with a constant value of 128 is halftoned using the watermarked stochastic screen, we can readily see that the use of the watermark detector on the resulting halftone yields the output shown in Fig. 3 (b), regions where the screens are conjugate appear black, whereas regions where the screens are same maintain half black and half white pixels, resulting in a mid-gray appearance at typical viewing distances. Typical printed images will not exactly match the idealized scenario of Fig. 3 (b) but will nonetheless render the embedded watermark visible as a dark pattern corresponding to the shape of the region $\mathcal{R}_c$ (the "X" in Fig. 3 (b)). Note that the design has the advantage that the detection process is self-referencing. In actual practice, the tiling periodicity can also be estimated from the scan, though local adaptation of the shift may be necessary to compensate for local geometric distortion introduced in the printing process [14].

3. PROPOSED COLOR HALFTONE WATERMARK

Suppose $T(i,j), 0 \leq i \leq H, 0 \leq j \leq W$ is a well-designed watermarked stochastic screen threshold function for monochrome halftoning, obtained using the method outlined in Section 2. The threshold function simultaneously meets two requirements of:

1. *Halftone Image Quality:* At any gray-level, the colorant pixel distribution obtained by thresholding with $T(\cdot)$ has evenly distributed minority pixels.
2. *Watermark Detectability:* In the two horizontal half-tiles obtained by splitting $T(\cdot)$, the thresholds in the congruent regions $\mathcal{R}_s$ and $\mathcal{R}'_s$ are identical and in the congruent regions $\mathcal{R}_c$ and $\mathcal{R}'_c$ are conjugate.

To design our color stochastic screen watermark, we use a (single) watermarked stochastic screen to halftone the four cyan (C), magenta (M), yellow (Y), and black (K), separations of a color image, while maintaining the aforementioned two requirements. To motivate our development, we consider a useful alternative conceptual representation of a stochastic screen threshold function. We represent the halftone dot as a collection $\{\mathscr{S}_t\}_{t=1}^{255}$ of sets of pixel locations, where $\mathscr{S}_t$ is the set of pixel locations that are first turned on at a threshold value of t. From (1), we see that

$$\mathscr{S}_t = \{(i,j) | 0 \leq i \leq H, 0 \leq j \leq W, T(i,j) = t\}\,. \qquad (2)$$

It follows that the sets $\{\mathscr{S}_t\}_{t=1}^{255}$ form a partition of the HW pixel positions in the halftone threshold array T. Equivalently, any such partitioning represents a halftone array. Fig. 4 depicts this representation by using a linear array of thresholds arranged in increasing

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[1] Eight bit images are assumed throughout, generalizations to other bit depths are straightforward.

[2] W is assumed to be even. Horizontal partitioning can be used equally readily.

order from left to right, going from 1 through 255, where the entry t in the array represents the corresponding set $\mathscr{S}_t$. When halftoning an image, a pixel is turned on if the image value at that pixel exceeds the threshold. We assume that the dot is linear, i.e. when a constant image with value V is halftoned, the fraction of the pixels turned on in the output is $V/255$ (or the nearest obtainable approximation) for all values of V between 0 and 255. Thus as V is increased starting from 0, *we progressively fill in the pixel locations in the linear array in Fig. 4* proceeding from left to right upto (and including) V. For our description of the proposed method, we focus our attention on thresholds less than 128, i.e. in the region where the colorant pixels are a minority. Symmetry arguments allow for the argument to be extended to regions with white minority pixels.

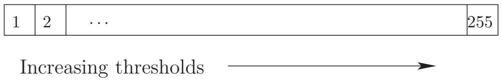

Fig. 4. Threshold-indexed representation of halftone threshold array.

The optimized design of $T(\cdot)$ ensures that filling in the thresholds in the array in Fig. 4, proceeding from left to right with colorant dots provides an even distribution of dots. The human eye is much more sensitive to high frequency variations in luminance than to variations in chrominance, i.e. compared with the luminance contrast sensitivity, the eye's chroma contrast sensitivity falls off very rapidly with increasing spatial frequency. We can exploit this characteristic of the eye, for halftoning the C, M, Y, and K, colorants typically used in printing using a single halftone threshold array $T(\cdot)$. Specifically, consider a spatially constant region over which the values of the C, M, Y, and K separations are constant. In order to obtain a more uniform luminance distribution, it is desirable to have the dots for the different separations well-dispersed with minimal overlap between separations. Furthermore, because the screen is designed to have optimal frequency response when the lower levels are filled first, it is desirable to have the final printed colorant dots distributed over the thresholds in Fig. 4 such that the lowest threshold regions, with the best frequency response characteristics, are occupied by pixels corresponding to the darkest colorant combinations. Accordingly, we halftone the separations sequentially in the order corresponding to *decreasing luminance modulation*, i.e. proceeding from the color separation whose dots cause the largest variation in luminance to the separation whose dots cause the next largest variation in luminance, and so on. Typically this order is K, M, C, Y and this will be assumed for our following description. For each colorant, the number of pixel positions to be printed is determined by the digital value, as is desirable, and these pixels are placed in the lowest unoccupied thresholds or, in the situation where there are no unoccupied thresholds, the thresholds already occupied with the lightest colorant combinations. We refer to this technique, which can also be applied to color halftoning independently of the watermarking application considered here [15], as *successive filling halftoning*. Figures 5 illustrate successive filling for a couple of situations, one in which no overlap is necessary between the pixels with different colorants and the other in which overlap is required because the sum of requested colorant pixels exceeds 100%. Other situations corresponding to different colorant combinations can be similarly obtained using our representation of the halftone threshold function as a linear array of increasing thresholds indexing corresponding pixel locations. The successive-filling characteristic can be implemented by suitably biasing each colorant separations digital value, using the contone and halftone values of previous separations, and then halftoning each separation using the same basic stochastic screen. Algorithm 1, outlines this process.

(a) No overlap (b) Overlap

Fig. 5. Examples illustrating successive filling.

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input : CMYK contone separations $i_C(m,n)$, $i_M(m,n)$,
        $i_Y(m,n)$, $i_K(m,n)$
begin
    Threshold K separation $b_K \leftarrow \mathscr{T}(i_K, T)$;
    // Binary halfones take values in
       $\{0, 255\}$ in this description
    Calculate K separation halftone error map
    $e_K(m,n) = i_K(m,n) - b_K(m,n)$ ;
    Calculate modified M separation
    $i'_M(m,n) = i_M(m,n) + e_K(m,n)$ ;
    Threshold modified M separation $b_M \leftarrow \mathscr{T}(i'_M, T)$;
    Calculate M separation halftone error map
    $e_M(m,n) = i_M(m,n) - b_M(m,n)$;
    Calculate modified C separation;
    $i'_C(m,n) = i_C(m,n) + e_K(m,n) + e_M(m,n)$;
    If $((b_M(m,n) = 0) and (b_K(m,n) = 255)$ then
    $i'_C(m,n) = i'_C(m,n) + \min(e_K(m,n), -e_M(m,n))$;
    else if $((b_M(m,n) = 0) and (b_K(m,n) = 255)$ then
    $i'_C(m,n) = i'_C(m,n) - min(e_M(m,n), -e_K(m,n))$;
    Threshold modified C separation $b_C \leftarrow \mathscr{T}(i'_C, T)$;
    Calculate C separation halftone error map
    $e_C(m,n) = i_C(m,n) - b_C(m,n)$;
    Calculate Modified Yellow separation $i'_Y(m,n)$;
    // Details omitted.
    Threshold modified C separation $b_Y \leftarrow \mathscr{T}(i'_Y, T)$;
end
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Algorithm 1: Algorithm for halftoning a C, M, Y, K color image using a single (watermarked) stochastic screen $T(\cdot)$.

For watermark detection, we note that with the successive-filling *if we made all the colorants black, then the watermark detection should be performed identically to the black and white watermarking scenario described in Section 2.* In a scanned red, green, blue channel image, because the cyan, magenta, and yellow channel are complementary to the red, green and blue, scanning channels, and because black absorbs in all three of the red, green, and blue channels, we can virtually render all the colorants black by converting the scanned three channel image $\{I_j(m,n)\}_{j=R,G,B}$, into a single channel (grayscale image)

$$I_g(m,n) = \min_{R,G,B} I_j(m,n). \tag{3}$$

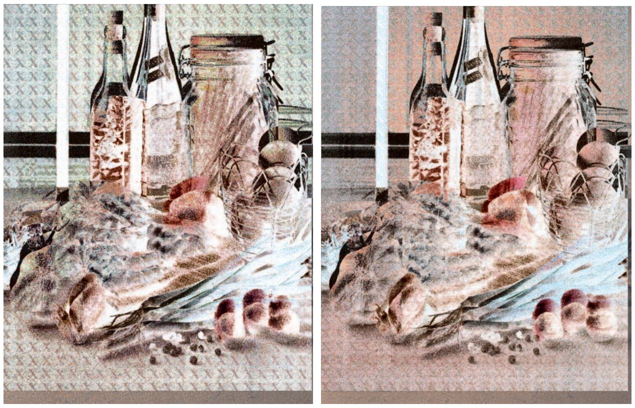
Once this conversion is completed the watermark detection can proceed as in the black and white case, outlined in Section 2. The use of the single halftone screen with successive filling for halftoning along with the above process for virtually converting all the colorants to black in the scanned representation, ensures that the dots of all the different colorants coherently contribute to the detected watermark pattern and produce a high contrast.

Note that the methodology by which we are exploiting a single screen for halftoning of multiple separations assumes good registration between the printing colorant (C, M, Y, and K) separations, both for maintaining image quality with successive filling and for improved contrast for the detected watermark. This assumption is valid in most inkjet printers, where the nozzles for printing of the C, M, Y, and K colorants are located on a single print-head ensuring that accurate alignment is maintained between the printed colorant separations on paper.

4. RESULTS

The proposed high contrast stochastic screen color watermarking technique was experimentally evaluated and compared against the alternative color contrast method of [10] which is referred to here as the dot-on-dot scheme. Halftones generated with both techniques were printed on a Xerox Phaser 850 (solid-ink) printer at 300 dpi resolution. The printed images were scanned using a UMAX Powerlook desktop scanner at 300 dpi resolution and the watermark detection algorithm was employed on the scanned images[3].

Figures 6 (a) and (b) show the result of watermark detection for the image watermarked with the proposed algorithm and with the alternative method of [10], respectively. Note that in Fig. 6 (b) the watermark is extremely faint and visible only in certain regions, whereas in Fig. 6 (b) for the proposed method, the watermark “X” pattern is clearly visible over most smooth regions of the image. From the figures, it is clear that the proposed successive filling color watermark offers a very significant improvement in detectability in comparison to existing methods. To obtain a numerical measure of the improvement, the ratio of the contrast between the watermark pattern region and the background was also computed; the contrast for the proposed scheme was found to be 3.8 times higher, consistent with the visual results in Figs. 6


(a) Proposed

(b) Dot-on-Dot

Fig. 6. Watermark detection result with: a) proposed method, b) color contrast technique of [10]

A comparison of the visual quality of the printed halftoned images shows that the halftone image obtained with the proposed technique appears smoother with less visible halftone textures as compared with the image produced using the color contrast technique of [10]. Thus the proposed method also meets our design objective of maintaining the visual quality of the printed image in the process of halftoning the multiple separations with the single halftone screen. Given that these are printed images, these cannot be directly included here. The visual quality can also be demonstrated by looking at low-pass filtered and down sampled of the scanned halftone images, where the low pass filtering serves as an approximation to the visually perceived images. Space limitations, however, do not allow for the inclusion of these images here.

Though results have only been presented for one image, the technique performs well across a variety of image content, subject of course to the normal limitations of halftone correlation watermarks; extremely light and dark regions do not offer adequate watermark contrast.

5. CONCLUSION

The method proposed in this paper is an effective technique for the insertion of visual watermark patterns in printed color halftone images. By using the color separations coherently with a single watermarked halftone screen, the color halftone watermarking technique proposed in this paper produces a printed halftone image, which, upon suitable detection from a scan of the halftone print, yields a high contrast watermark pattern. The method offers a significant improvement over prior methods proposed for stochastic screens.

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[3] As we see subsequently, scan resolution matched with the printer resolution suffices for detection. Higher scan resolution can be utilized for detection, though at the cost of increased computation and memory for dealing with the larger images.