Clustered-Dot Color Halftone Watermarks

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Abstract

Spatial frequency separability is proposed as an attractive exploit for obtaining color halftone watermarking methods from monochrome clustered-dot halftone watermarking techniques. Detection of watermarks embedded in individual halftone channels is typically confounded by the cross-coupling between colorant halftone separations and scan RGB channels caused by the so-called "unwanted absorptions". This problem is resolved in the proposed framework by utilizing spatial filtering in order to obtain estimates of individual separation halftones that are suitable for watermark detection. The effectiveness of this methodology is experimentally demonstrated by utilizing continuous phase modulation for per-separation watermark embedding. The embedded watermark patterns in the halftone separations can be clearly detected from scans using the proposed spatial separability exploit. Continuous phase modulation based per-channel embedding with detection following spatial-filtering based separation thus provides an effective watermarking method for clustered-dot color halftones.

1 Introduction

Digital watermarks have recently emerged as an important enabling technology for security and forensics applications for multimedia [1–4] and for hardcopy [5, Chap. 5] [6]. In the hardcopy domain these techniques provide functionality that mimics or extends the capabilities of conventional paper watermarks that have been extensively utilized since their introduction in the late thirteenth century [7].

Since the majority of hardcopy reproduction relies on the halftone printing, methods that embed the watermark in the halftone structure comprise one of the primary categories of hardcopy digital watermarks. These methods allow printed images to carry watermark data in the form of changes in the halftones, which are normally imperceptible but can be distinguished by appropriate detection methods. Considerable work has been done in this area [8–16]. One limitation of most existing techniques in this category is that they are designed primarily for black and white printing and are not directly applicable to printed color images.

In this paper, we focus on the problem of watermark embedding and detection in clustered-dot color halftones. By considering the spectral characteristics of the colorants along with the spatial (frequency) behavior of their halftones, we demonstrate a framework[1] that allows extension of black and white halftone watermarking methods to color on a per-channel basis. With clustered-dot color halftones, per-channel embedding can be readily performed, as in the monochrome case. The extraction of these watermarks; however, poses a challenge because "unwanted absorptions" of the constituent colorants cause coupling between the different colorant halftones in the scanned RGB channels. Specifically, in our work, we exploit the fact that, when suitably designed, the halftones for different colorants can be separated in 2-D spatial frequency despite the coupling caused by the unwanted absorptions. Thus, even though the spectral interactions couple the halftone separations in the scans, by utilizing the differences in the spatial frequencies, we can obtain estimates of the individual separations. These estimates, though not perfect (due to moiré), do allow for a detection of the embedded watermarks on a per-channel basis. We exploit this methodology to extend, to color images, our previous work on embedding watermarks in monochrome images via continuous phase modulation [18].

[1]Dot-on-dot watermarking [17] may be viewed as an alternate, though rather restrictive, framework for extending black and white watermarking methods to color.

2 Clustered-Dot Color Halftone Watermarking

Due to their stability and predictability clustered-dot halftoning [17] is the predominant halftoning method for the xerographic and lithographic printer families. Clustered-dot halftones are also known as *amplitude modulated* halftones in the sense that different shades of gray are reproduced by varying the size of halftone spots (clusters of individual printer dots), whose frequency is constant over the halftone image. Color printing is accomplished with clustered-dot halftones by using multiple colorant separations, typically correspond to Cyan (C), Magenta (M), Yellow (Y), and Black (K) colorants. These separations are halftoned and printed in overlay to generate the color halftone. For simplicity in this description we consider the scenario of 3-colorant CMY printing.

In this case, the overall watermark embedding and extraction scheme can be represented as shown in Fig. 1. The watermark w_i for the i^{th} separation, where i is one of C, M, or Y, is embedded in the halftone separation $I_i^h(x,y)$ during the halftoning stage. The color halftone image $I_{C,M,Y}^h(x,y)$ is obtained by printing the constituent separations in overlay. Scans of the printed image are obtained using a conventional RGB scanner. Ideally, one would like each of the scanner channels to capture only the halftone information in one of the colorant separations, which would then allow for visual detection of the watermark. However, due to the "unwanted absorptions" in the colorants, this is not true in practice (see Fig. 2 later in this paper for an illustrative example). We therefore rely on the spatial characteristics of the halftones to provide a solution to this problem. If the halftone frequencies are suitably chosen, spatial filtering can be utilized to filter each of the R, G, and B scanned channels to provide estimates of the complementary C, M, and Y colorant channels, respectively. The spatial filtering process (described in greater detail in Sec. 4) thus "cleans" out unwanted halftone structures from each of the scanner channels. Thus, for example, spatial frequencies corresponding to C and Y

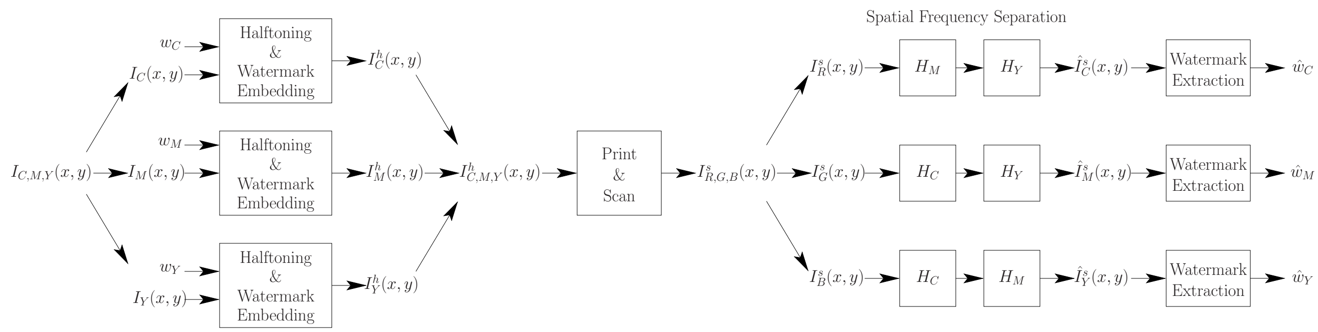


Figure 1. *Overview of clustered-dot color halftone watermark embedding by exploiting spatial frequency separation principle.*

halftone structures are filtered out to estimate M halftone separation from the G channel of the scanned RGB image (see Fig. 4 for an example). Once a (clean) estimate $\hat{I}_i^s(x,y)$ is obtained for the i^{th} colorant channel, the monochrome watermark detection method can be applied to the separation in order to recover (an estimate of) the corresponding watermark w_i.

Having described the overall framework in an abstract setting, we next demonstrate a specific and concrete instantiation based on continuous phase modulation for monochrome watermark embedding [18]. In this specific instantiation, the watermarks w_i can be thought of as visual patterns represented as "low-frequency (in comparison with the halftone frequency) images." Large font text rendered as a bi-level image is one example of such visual patterns.

3 Watermark Embedding by Continuous Phase Modulation (CPM)

Embedding of watermark patterns by varying the halftone phase has been proposed in multiple ways and for several different applications [10, 13, 15, 18]. Here we utilize the method in [18] which alters the halftone phase through a modulation of the phase of an underlying analytic *threshold function*. This method has the benefit that the watermark pattern may be decided upon dynamically just prior to halftoning, as opposed to some of the alternate embedding strategies where the pattern must be incorporated in the design of the halftone thresholds and is therefore static. For completeness, we briefly summarize the embedding process here in our specific context of color halftoning.

The halftone for the i^{th} separation, $I_i^h(x,y)$ is assumed to be obtained by comparing the contone image values $I_i(x,y)$ against a periodic halftone threshold function $T_i(x,y)$. Specifically

$$I_i^h(x,y) = \begin{cases} 1 & \text{if } I_i(x,y) > T_i(x,y), \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

where x and y represent the spatial coordinates along the horizontal and vertical directions, respectively. In order to describe our watermark embedding technique, we use a modified version of the analytic description proposed by Pellar [19, 20]. We assume that the C, M, and Y separations have halftone frequencies of f^C, f^M, and f^Y lpi, and are oriented along angles θ^C, θ^M, and θ^Y, respectively[2] and the corresponding threshold function for the i^{th} separation is

$$T_i(x,y) = \cos\left(2\pi \frac{f^i}{\sqrt{2}} x'\right) \cos\left(2\pi \frac{f^i}{\sqrt{2}} y'\right), \tag{2}$$

where

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\left(\phi^i - \frac{\pi}{4}\right) & -\sin\left(\phi^i - \frac{\pi}{4}\right) \\ \sin\left(\phi^i - \frac{\pi}{4}\right) & \cos\left(\phi^i - \frac{\pi}{4}\right) \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}. \tag{3}$$

A watermark pattern is embedded in the halftone by modulating the phase of one of the cosine function arguments by incorporating a spatially varying phase function $\Psi_i(x,y)$ such that phase variations are allowed along the respective halftone frequency direction. The modified version of the halftone threshold function is given by

$$T_i(x,y) = \cos\left(2\pi \frac{f^i}{\sqrt{2}} x' + \Psi_i(x,y)\right) \cos\left(2\pi \frac{f^i}{\sqrt{2}} y'\right). \tag{4}$$

Discontinuities in the phase term Ψ_i may produce visible artifacts in the halftone separation. Continuity and smoothness of this term need to be ensured to prevent these artifacts. We therefore refer to the technique as continuous phase modulation (CPM). A visual watermark pattern such as a bi-level text image serves as the watermark based on which the phase modulation term Ψ_i for the i^{th} halftone separation is determined. Typically, the bi-level watermark is smoothed using a spatial blur to ensure continuity of the phase and the resulting values are normalized between $(0, \pi]$ to introduce a phase change of π radians between the two levels of the watermarked image, which results in maximal contrast for the detected watermark pattern [18].

4 Watermark Detection Exploiting Spatial Frequency Separability

Per-channel watermark detection can be attempted on the R, G, B color channels of the scanned image. However, as we pointed out earlier, unwanted absorptions of the constituent colorants cause couplings between the different colorant halftones in the scanned RGB image. Figure 2 shows an enlarged view of a region from the G channel of the scanned RGB image $I_{R,G,B}^s(x,y)$, which we use in our experiments to test our framework. In the scanned image, it is apparent that the not only is the halftone structure of the desired M channel visible, but due to the fact that the C and Y separations also have absorption in the green scanner channel band, we can also see the undesirable halftone structure for these separations in the G channel. This interference can be also observed in

[2]This description assumes orthogonal halftones, where the matrix of frequency vectors for each halftone separation is composed of two orthogonal vectors of equal length. More general descriptions are possible [21].

the frequency domain. Figure 3 shows enlarged view of the log-magnitude Fourier spectrum of the G channel image around low frequency regions. It can be observed that the Fourier spectrum exhibits not only the frequency vectors of the M separation, but also the frequency vectors of C and Y separations, and moiré frequencies. We exploit the fact that, when suitably designed, these frequencies appear at distant locations in the frequency domain and unwanted frequency components can be cleaned out by spatial filtering.

Figure 2. *Enlarged view of a region from the scanned G channel image $I^s_G(x,y)$ showing the coupling between the halftone structures from M separation and C and Y separations.*

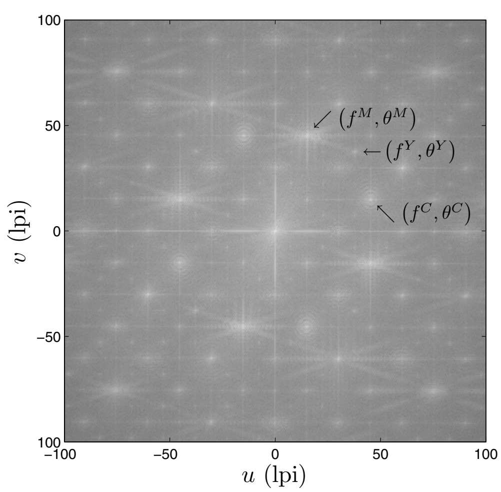


Figure 3. *Enlarged view of the $\log$-magnitude Fourier spectrum of $I^s_G(x,y)$. For illustration purposes, the frequencies of the constituent halftone separations are indicated by arrow and text labels.*

Specifically, an estimate of the i^{th} halftone separation can be obtained by

$$\hat{I}^s_i(x,y) = \mathscr{F}^{-1}\left(\mathscr{F}\left\{I^s_{i'}(x,y)\right\}\prod_{\substack{j=C,M,Y\\ j\neq i}} H_j(u,v)\right), \qquad (5)$$

where $\mathscr{F}$ denotes the (spatial) Fourier transform operation, i' is scanner channel that is the complement/inverse of the i^{th} colorant, $H_j(u,v)$ is a narrow band-reject filter for the i^{th} separation, and u and v represent the frequency coordinates along the horizontal and vertical directions, respectively. This process of spatial filtering may be efficiently implemented by utilizing the 2-D Discrete Fourier Transform (DFT). Our experimental results indicate that eliminating frequency content of the unwanted halftone separations around a certain neighborhood (typically a few lpi) of fundamental screen frequencies and their second-order harmonics provides a useful estimate of the respective halftone separation.

We demonstrate this in Fig. 4, which shows the same region as in Fig. 2 after cleaning out the inference from C and Y halftones using the aforementioned spatial filtering process. The halftone structure of the M separation can be observed much more clearly in Fig. 4 in comparison with Fig. 2. In this "zoomed-in view", the phase modulation can also be clearly seen in the Fig. 4.

Figure 4. *Enlarged view of the region shown in Fig. 2 after cleaning out the frequencies corresponding to C and Y halftone screens.*

Monochrome watermark detection methods can then be applied to the estimated (clean) halftone separations. For CPM watermarking, a useful technique to retrieve the digitally embedded watermark pattern from the printed halftone image $I^h_i(x,y)$ is to overlay a constant gray-level non-modulated halftone image, having same halftone frequency and orientation with the i^{th} halftone separation, printed on a transparency. In addition to experimental validation of this "demodulation method" [10, 13, 18], it has also been analytically demonstrated that the visible pattern after this overlay resembles the embedded watermark pattern, which allows visual detection [15]. This operation can be digitally simulated for the individual estimated halftone separations to extract the watermark patterns.

5 Experimental Results

Our experimental setup utilized an electrophotographic CMYK color printer with an addressability of 600×600 dpi. Digital rotated clustered-dot CMY halftone screens with angular orientations close to the conventional $15^\circ, 75^\circ$, and 45° rotated clustered-dot halftones were utilized for our experiments. The frequency vector representation of these screens is shown in Fig. 5. In each of the C, M, and Y colorant channels a watermark pattern was embedded via the continuous phase modulation method described in Sec. 3.

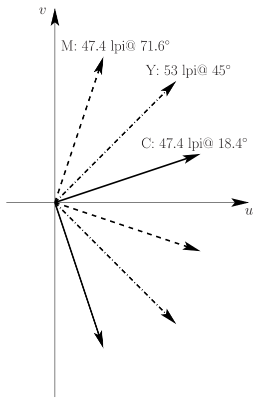
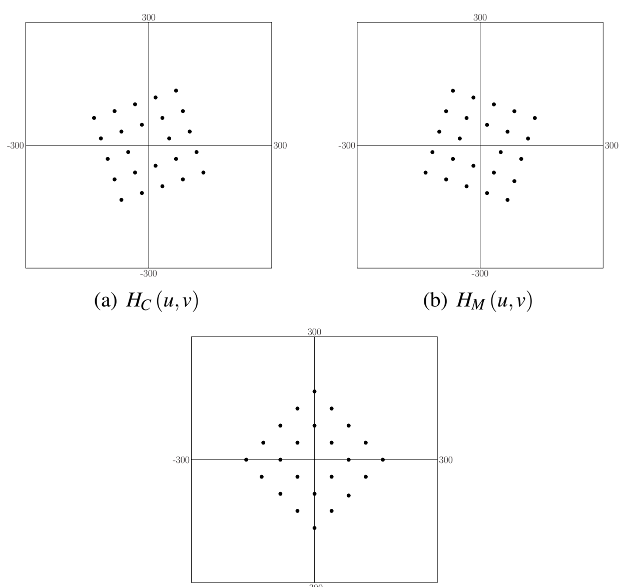


Figure 5. *Frequency vectors for C, M, and Y halftone screens.*

The resulting color halftone is printed on our test printer and scanned with a flatbed RGB scanner with optical resolution of 600×600 dpi. Estimates of C, M, and Y halftones are obtained according to Eq. (5) from, respectively, the R, G, and B channels of the scanned image. The spatial frequency separation filters utilized here are shown in Fig. 6. Note that these filters are designed for the frequency vectors shown in Fig. 5. Estimated halftone separations are then overlaid with the corresponding halftone masks to recover the watermark pattern.



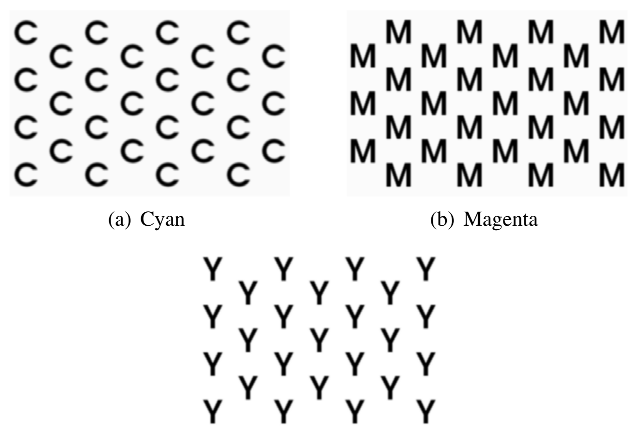
(a) $H_C(u,v)$ (b) $H_M(u,v)$

(c) $H_Y(u,v)$

Figure 6. *Spatial frequency separating filters for estimating the C, M, and Y halftone separations from the scanned R, G, and B channel images.*

We illustrate the operation of the proposed methodology by using the *Hats* image shown in Fig. 7. For our experiment, we embedded the watermark patterns shown in Fig. 8 in our C, M, and Y halftone channel separations. Fig. 9 shows the detection results obtained for our example. The watermark pattern in each separation are visible in the regions, where they are embedded. Particularly, the patterns embedded in the C and M separations are much more visible than the pattern embedded in the Y separation. This is due to the fact that the Y channel of the *Hats* image includes many dark regions with near 100% coverage, which do not allow for meaningful watermark embedding and extraction due to the absence of halftone structure.

Figure 7. *Contone CMY Hats image.*



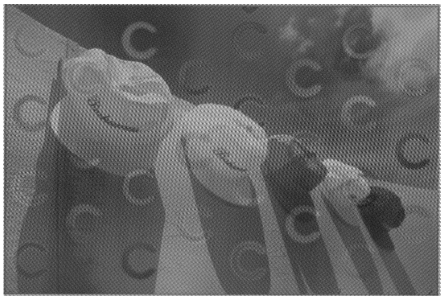
(a) Cyan (b) Magenta

(c) Yellow

Figure 8. *Watermark patterns for C, M, and Y colorant separations.*

6 Discussion

One important difference in printed color halftones as compared to monochrome printing is that the overlay of the colorant separations results in moiré. When the individual separations are subjected to phase modulation for the purpose of watermark embedding, their instantaneous frequencies in different spatial regions vary in a small region about their nominal values. With suitably designed continuous phase modulation this frequency variation is imperceptible for a single printed halftone. However, when considering the halftone overlay it is also necessary to ensure that the resulting moiré is imperceptible *in the presence of the phase modulation*. This requires a careful selection of the set of frequency vectors for the color halftone configuration. If the linear combination of low-order harmonics of the individual halftone



(a) Cyan

(b) Magenta

(c) Yellow

Figure 9. *Detection results on the estimated halftone separations from the scanned RGB channel images. Artifacts due to re-screening in the printing process may not allow clear observation of the detected watermark pattern in the printed version of these figures. Please refer to the electronic version of this paper to clearly observe the detection results.*

frequency vectors form a closed triangle, then the phase modulation may cause deviations around the DC frequency visible as objectionable color shifts localized around the modulated regions [21]. This would have the undesirable effect that the embedded watermark patterns would be visible (without any detection) in the printed color halftone image. Specifically, this is the case for the conventional analog $15^\circ, 75^\circ$, and 45° equi-frequency rotated clustered-dot and dot-on/off-dot color halftone geometries. Thus, for phase-modulation based halftone embedding, it may be preferable to choose configurations that are robust, from a moiré standpoint, to small changes in frequency, as opposed to moiré-free geometries.

The methodology of estimating colorant halftone separations from scanned images by spatially filtering out undesired colorant interactions may also be applied in order to extend other halftone watermarking methods to color. In particular, an extension of the recently proposed method for data hiding in monochrome halftones by dot orientation modulation [16] to color would be attractive within the framework presented here. We are currently working on such an extension. Additionally, we conjecture that the estimation of individual halftone separations could also provide a benefit in other document analysis applications.

Finally, we note that extending this methodology to the typical CMYK colorant printing scenarios is a challenging problem since the K colorant absorbs uniformly across the spectrum and therefore its absorption band overlaps the complete absorption bands of other colorants. The K halftone separation thus appears consistently in all of the RGB channels of the scanned image. The effectiveness of spatial frequency selection for the halftone configurations with suitable spatial filtering is the subject of an ongoing investigation. It seems in these scenarios, the separation based on spatial frequency is still likely to be useful, albeit this usefulness may depend on the specific watermark embedding method utilized. The use of additional "scanner" channels (such as ultraviolet) may provide a benefit in these scenarios and is also worthy of further investigation [22].

7 Conclusion

In this paper, we propose a methodology to embed watermark patterns in clustered-dot color halftones on per-channel basis. We demonstrate that by exploiting spatial frequency separability of clustered-dot color halftones, estimates of the individual colorant halftone separations can be obtained from scanned RGB images allowing for per channel detection to operate effectively. In this work, we demonstrated the efficacy of this methodology using continuous phase modulation for the embedding of per-separation watermarks.

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