CONTINUOUS PHASE MODULATED HALFTONES AND THEIR APPLICATION TO HALFTONE DATA EMBEDDING

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ABSTRACT

We propose a generalization of periodic clustered-dot halftones, wherein the phase of the halftones is modulated using a secondary signal. The process is accomplished using an analytic halftone threshold function and allows halftones to be generated with different phase variation in different regions of the printed page. We demonstrate that ensuring continuity of the phase assures that the resulting halftone images are free from visible artifacts despite the modulation in phase. We present, applications of the proposed method to halftone data embedding, wherein the changes in phase or in frequency encode the embedded information. For the frequency embedding, using continuous phase modulation, we also consider the limitations on signals that are embedded within our framework. For both applications, we demonstrate how the embedded signals may be recovered from the printed halftones either using the image as a self-reference which reveals the watermark when it is shifted and overlaid with itself or by employing a separate transparency mask.

1. INTRODUCTION

Halftoning is the process of representing a continuous tone (*contone*) image by a bi-level image such that when viewed from a suitable distance the bi-level image gives the same impression as the continuous tone image. Over the long history of halftoning, a large number of halftoning techniques have been developed which are adapted for different applications. Due to their stability and predictability clustered dot halftoning [1] is the primary choice for xerographic printing systems. Traditional clustered dot halftones were restricted to a single frequency because they were generated using periodic gratings that could not be readily varied spatially. Digital halftones generated using threshold arrays that tile the image plane were also originally designed to be periodic for simplicity and in order to minimize memory requirements. With the increase in computational power and memory, these constraints become less stringent and one can therefore consider methods in which the frequency or (more generally) the phase of the halftones changes over the printed image.

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In this paper, we exploit the freedom offered by digital halftoning, wherein instead of using a threshold array, we define the halftone using an analytic threshold function, whose phase can be modulated independently using an separate channel. Since phase discontinuities produce visible artifacts in the halftones, we impose a requirement of continuity on the halftone phase and using the analogy with continuous phase modulation in digital communications, refer to the resulting halftoning technique as *continuous phase-modulated halftoning*. We show that the phase and frequency variation produced using continuous phase modulation may be advantageously used for data embedding in halftones. We consider both embedding in phase and in frequency using continuous phase modulated halftones and particularly analyze the constraints of frequency embedding. For ease of recovery, we consider methods for which the decoding may be performed using either a simple scan-shift-overlay process or a reference transparency.

2. RELATED WORK

The flexibility of digital halftoning may also be exploited in a more limited way by designing large threshold arrays which incorporate phase shifts between the multiple "halftone cells" within the larger tile [2]. Such a method has also been applied (among other things) to the process of data-embedding in clustered-dot halftone images [3, 4]. As opposed to prior methods for halftone data-embedding in clustered dot halftones that rely on the generation of a (relatively) large threshold array with the embedded information built into the phase variation over the multiple cells in the array [3, 4], the method we present here allows the information to be dynamically determined.

Note that the referenced methods and those presented here are attractive because the embedded information, typically in the form of a visual pattern, can be extracted either with simple computer processing or visually by using an inexpensive transparency decoder [3] or no additional equipment at all [4]. The methods though can also be utilized with computer detection of the corresponding phase and frequency changes.

An alternate application of continuous phase modulated halftoning is to modify the halftone frequency according to the frequency content of the image [5] so as to break the spatial and tonal resolution trade-off of conventional fixed frequency halftones.

3. CONTINUOUS PHASE MODULATED HALFTONES

3.1. Analytic Halftone Generation

Clustered dot halftones are normally generated by comparing the image values $\tau\left(x,y\right)$ against a periodic halftone threshold function $K_T\left(x,y\right)$. The halftone image can be represented as

$$H(\tau;K_T)=\begin{cases}1 & \text{if } K_T(x_0,y_0)\le\tau(x_0,y_0);\\ 0 & \text{if } K_T(x_0,y_0)>\tau(x_0,y_0),\end{cases} \tag{1}$$

where the values 1 and 0 correspond respectively to the respective decisions that ink is, or is not, deposited at the position (x_0,y_0). A discrete array of thresholds is commonly used for defining the threshold function $K_T\left(x,y\right)$. An alternative is an analytical representation such as the one defined by Pellar [6, 7] as:

$$K_T\left(x,y\right)=2\cos\left(2\pi f_x x\right)\times\cos\left(2\pi f_y y\right), \tag{2}$$

where f_x and f_y represent the frequencies along the orthogonal x and y axes, representing horizontal and vertical directions, respectively.

3.2. Phase and Frequency Modulation in Halftones

In Eq. 2, the sinusoid $\cos\left(2\pi f_x x\right)$ represents a threshold function for a horizontal line screen having frequency f_x. This function can be generalized by incorporating a spatially varying phase modulation $\Psi_{\mathbf{X}}(x,y)$ to obtain:

$$\cos\left(2\pi f_x x+\Psi_{\mathbf{X}}(x,y)\right). \tag{3}$$

Performing a similar phase modulation along the vertical direction, we obtain a generalization of the threshold function as:

$$\begin{aligned}K_T\left(x,y\right) &= 2\cos\left(2\pi f_x x+\Psi_{\mathbf{X}}(x,y)\right)\times\\ &\quad\cos\left(2\pi f_y y+\Psi_{\mathbf{Y}}(x,y)\right).\end{aligned} \tag{4}$$

where $\Psi_{\mathbf{Y}}(x,y)$ is the phase modulation along the vertical direction. Discontinuities in the phase terms $\Psi_{\mathbf{X}}(x,y)$ and $\Psi_{\mathbf{Y}}(x,y)$ can produce artifacts in the halftone images. Hence, we will here forth consider situations where these are constrained to be continuous functions and refer to the resulting halftones as continuous phase modulated halftones.

One may also consider the impact of the phase variation in terms of the instantaneous frequencies for the function in (4). If the phase terms $\Psi_{\mathbf{X}}$ and $\Psi_{\mathbf{Y}}$ do not vary along vertical and horizontal direction respectively, they can be represented by two 1D functions $\Psi_{\mathbf{X}}(x)$ and $\Psi_{\mathbf{Y}}(y)$. Then using the separability of (4), we can see that the instantaneous frequencies along horizontal and vertical directions are:

$$f_{ix}(x,y)=f_x+\frac{1}{2\pi}\frac{d\Psi_{\mathbf{X}}(x)}{dx}, \tag{5}$$

$$f_{iy}(x,y)=f_y+\frac{1}{2\pi}\frac{d\Psi_{\mathbf{Y}}(y)}{dy}. \tag{6}$$

We can therefore use the threshold function of (4) with appropriately chosen function $\Psi_{\mathbf{X}}(x,y)$ and $\Psi_{\mathbf{Y}}(x,y)$ to obtain either halftones with spatial phase variation or with a separable frequency variation (as indicated above). For both purposes, however, sudden changes in the phase or frequency will generate visible artifacts in the halftone screen as a result of phase discontinuities. Thus, the phase functions should be continuous and smooth enough to maintain the clustering of the halftone dots. One may also note that the separability requirement imposed above may be slightly relaxed and we may still utilize the approximation indicated above with the derivatives replaced by the corresponding partial derivatives provided the variation along the other direction is very slow. This indicates that the method is applicable for frequency modulation for halftones either for functions which are separable or those that can be "locally approximated" by separable functions.

However, sudden changes in the phase will generate visible artifacts in the halftone screen. Thus, the phase functions should be continuous and smooth enough to maintain the clustering of the halftone dots.

3.3. Data Embedding with Phase Modulation

The variation in phase may be used to embed data in the halftone images. While the functions embedded may be arbitrary subject to the continuity requirement, we consider here the embedding of visual patterns similar to those used in[3, 4]. A watermark pattern to be embedded is mapped as a 2D phase map and embedded on the halftone screen through the phase modulation as indicated above. An example of such a pattern is a bi-level text image, which can be smoothed by a low-pass filter to prevent phase discontinuity. Specifically, we embed watermark using one of the phase modulation terms in Eq. 4 setting the other phase term as 0. For convenience, the 2D phase map can be normalized between $[0,\pi]$ to obtain maximum possible phase shift for the threshold function. This normalization, makes the watermark more visible after extraction.

A useful technique to retrieve the digitally embedded data from the the printed halftone image $H_{(\Psi_{\mathbf{X}},\Psi_{\mathbf{Y}}=0)}(\tau(x,y))$ can be overlaid with a zero modulated constant gray level thresholded mask halftone image $H_{(0,0)}(\tau_0)$ printed on transparency. This operation can be viewed as correlating the two halftone screens. However, without the knowledge of the carrier frequencies f_x and f_y, designing the transparency mask is rather impossible. A simple solution to this problem is shown in Fig. 1. The image is divided into certain number of row blocks and the watermarks can be embedded by keeping a row block with no marking between the row blocks which have the watermark. After the printed image is scanned with scanning resolution satisfying Nyquist criteria, the order of the rows are changed such that a block with watermark is paired with a block with no mark on it. Then the images are multiplied to get the correlation between the images. The final image exhibit the watermark where a marked block is multiplied with a no mark block.

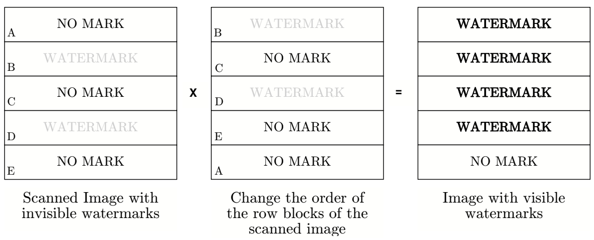

Fig. 1. Data embedding/extraction using phase modulation

3.4. Data Embedding with Frequency Modulation

Frequency modulation is a well known and widely used technique in analog and digital communication systems, where the transmitted signal is represented as $\cos\left(2\pi f_c t + 2\pi h \int_{-\infty}^{t} m(\tau) d\tau\right)$ and the instantaneous frequency at time t is given by $f_c + hm(t)$. For digital modulation, the continuity of the phase has also been studied [8]. This idea can be readily applied on the halftone threshold function K_T to modulate the frequencies along horizontal and vertical directions. The phase terms in K_T are given as:

$$\Psi_{\mathbf{X}}(x) = 2\pi h_x \int_{-\infty}^{x} \Phi_{\mathbf{X}}(\tau) d\tau, \tag{7}$$

$$\Psi_{\mathbf{Y}}(y) = 2\pi h_y \int_{-\infty}^{y} \Phi_{\mathbf{Y}}(\nu) d\nu, \tag{8}$$

where h_x and h_y are the modulation indices and $\Phi_{\mathbf{X}}(x)$ and $\Phi_{\mathbf{Y}}(y)$ are the frequency deviation indices along horizontal and vertical direction respectively.

This way the instantaneous frequency defined in Eq. 5 is found as:

$$f_{ix}(x) = f_x + h_x \Phi_{\mathbf{X}}(x). \tag{9}$$

The instantaneous frequency along the vertical direction can be found similarly. For convenience, the frequency deviation indices are taken between $[-1, 1]$ such that the maximum frequency deviation on the halftone screen can be between $[f_x - h_x, f_x + h_x]$. The method may then be used to embed a separable pattern as a frequency variation in the image. As in the case of phase variation, using a reference at constant frequency provides an easy method for decoding of the embedded variation in frequency. An advantage of the frequency variation technique over the phase variation method is that neither careful control of the frequency of the frequency or the alignment is required since the pattern is seen as a moire.

4. EXPERIMENTAL RESULTS

Software is developed to generate the clustered halftone screens described in Sec. 3. This enables us to generate different halftone images with different levels of frequency and phase modulation with the modification of the halftoning parameters.

For halftone watermarking using phase modulation, *Library* image shown in Fig. 2 is halftoned with *UR* letters representing *University of Rochester* used as watermarks. The halftone image is generated with a clustered dot printer model with a resolution of 1200 x 1200 dpi and screen frequencies 37.5 cpi along horizontal and vertical directions.

Fig. 2. Contone Library image

The marking image is blurred along the edges of the UR marks so that the phase function is continuous along those regions. The phase function is then mapped between $[0, \pi]$ such that the marked regions have the maximum possible phase difference compared to the non-marked regions. However, the phase shift between the marked and non-marked regions can be any value between these values.

On the next step, the halftone image is printed using a 1200 x 1200 dpi printer and scanned with the resolution 2400 x 2400 dpi. Fig. 3 shows the image demodulated using self demodulation algorithm. *UR* marks are clearly visible in this image. The marks can be seen better on the regions corresponding to midtone gray levels. However, on shadows and highlights they are still visible. Given the self-referencing nature, the method is clearly invariant to translations of the watermarked image. In addition our preliminary tests reveal that the watermark is detectable even for rotations or up-to $5°$ in the printing/scanning process.

For data embedding using frequency modulation, two bit sequences to modulate the frequency along horizontal and vertical directions are generated. For demonstration purposes the bit sequence $\{0, 1, 0, 1, 0\}$ is embedded along both directions. The halftoning parameters are chosen same as the parameters used for the phase modulation. In addition, we map the frequency deviation indices between $[0, 1]$ and h_x and h_y

Fig. 3. Demodulated image with UR marks visible

are chosen to be 5 such that the regions corresponding to data bits $\{0\}$ and $\{1\}$ have a frequency of 37.5 and 42.5 cpi in the screen direction respectively.

Fig. 4 shows overlay of the frequency modulated image with a constant gray level no modulation halftone mask generated with the same specifications as the previous halftone images via computer simulation. The frequency modulated regions are clearly visible and the embedded data sequence can be easily determined. This way, 10 data bits are embedded on the halftone image. The capacity is limited by the separability property of K_T. If M and N data bits are embedded along horizontal and vertical directions, a total of $M + N$ data bits can be extracted from the halftone image. Nevertheless, for specific types of applications less number of data bits would still be enough. An advantage in the frequency embedding case is that the technique is considerably more robust to angular rotation in the detection process (at least for visual detection). This is attractive in applications where rapid detection of the watermark may be required (for instance by scanning with a hand-held scanner).

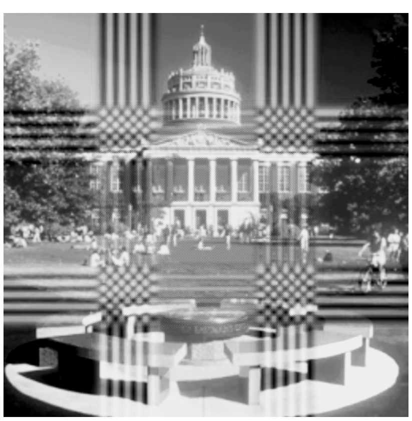

Fig. 4. Frequency demodulated halftone image

5. CONCLUSION

In this paper, we propose a generalization of clustered dot periodic halftones. Using an analytic representation of the halftone threshold function and modulating the phase using a continuous function, we obtain a more flexible class of halftones, which we refer to as *continuous phase modulated halftones*. The method can be used to generate halftones with phase and frequency variation in different regions without introducing visible artifacts due to phase discontinuity. We apply the technique for the embedding of watermark patterns in halftone images and demonstrate how text patterns may be invisibly embedded in the halftones using phase modulation and separable patterns using frequency modulation. For both cases, we present experimental results that also demonstrate simple methods for recovery of the patterns from scans of the halftone images.

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7. REFERENCES

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