Shape-Changing Spot Function for Digital Clustered-Dot Halftoning

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Abstract

In high-speed electrophotographic (EP) printing, clustered dot halftone screens are required to achieve consistent print quality. However, the shape of the spot in the screen plays a critical role in the quality of the printed output. For example, dot gain can cause unpleasant artifacts in midtone regions. We discuss a new spot function for EP systems that addresses artifacts from midtone dot gain and printer stress, demonstrating its suitability for use in a range of bitonal production printers.

Introduction

Screening in high-speed (i.e., more than 300 8.5" x 11" pages per minute) electrophotographic (EP) printers presents a number of challenges to the designer. Specifically, the halftone screen must be designed for print quality and consistency, despite the undesirable effects that high-speed printing can have on the electrostatics of the process. Some of the inherent problems that impact print quality are as follows:

- Mottling occurs on some high-speed printers when the spot function shape "stresses" the printer.
- Artifacts are present in midtone regions with some spot functions. These artifacts are caused by the interaction of spot growth and dot gain. Generally, a spot function is designed such that in the lighter regions, the spots are small enough not to touch, and in the darker regions, the touching of the spots creates the darker tones.

In this paper, we describe a spot function for digital EP halftoning that addresses these print quality issues:

- The spot function produces a circular shape in the lighter and darker regions, reducing the stress on the printer, and thus, reducing mottling.
- The spot function allows more control over the position and severity of the touching of spot functions in the midtone regions, addressing dot gain.

A related problem was addressed in Ref. 1, where two periodic signals (i.e., cosines) were modulated or compared to form a symmetric (i.e., x-y separable*) spot function. This screen allowed circular spots to be created in the light regions, while inverse circular spots were created in the dark regions, using a spot function of the form of $\cos(x)\cos(y)$. However, this form still suffers from the problem in the midtone (near 50%) gray levels, that the spots grow to touch, creating rectangular patterns, as shown in Fig. 1. The screen described in this paper changes the shape of the spots in the midtones in an asymmetric manner (i.e., non-separable in x-y) to reduce the artifacts.

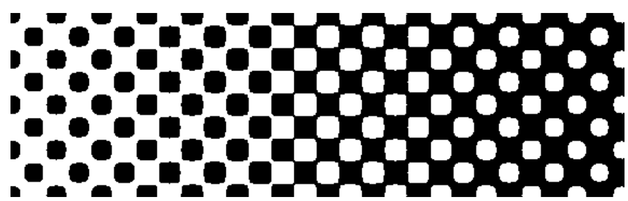

Figure 1. Screened gray scale ramp, showing rectangular patterns in the midtones, resulting in a jump in dot gain.

The spot function, f, that we introduce in this paper, combines two signals, adjusted by a scaling function. The scaling function is chosen to control the manner in which

* The word "separable" as used in this paper designates functions of more than one variable that can be factored into the product of functions in one variable only. For example, the function $\cos(x+y) + \cos(x-y)$ is separable into $\cos(x)\cos(y)$.

growing spots touch in the midtones.[†] For example, the conventional circular spot function of Ref. 1 consists of a spot which grows until it touches its neighbors in four places in the midtone region, causing a jump in dot gain near the touches, resulting in artifacts.

Elliptic spot functions (also called non-unity asymmetric spot functions) are currently used in some systems[2] to partially address the problem of having four corners of the spot touch at once. The spot function described in this paper has the additional advantage of allowing the spot function to vary in shape continuously over the range of gray levels. The result is that light and dark regions contain circular spots, which give lower stress on the printer, while elliptical spots are used only in the midtone regions. Continuous variation ensures that image regions of mixed gray levels will have spots of similar shape near each other when the gray levels are similar.

This halftone has been used to address gear noise, printer stress, and general print quality, where print engine stress causes degradation in print quality.

Notation

This section outlines the notation used in the description of the screen. A spot function,

$$f(x,y) : [-1,1]\times[-1,1] \rightarrow [-1,1]$$

is an analytic expression describing the tendency with which pels are set to black in a halftone screen. If we consider $f(x,y)$, the coordinates x and $y \in [-1,1]$ describe the position within the screen at which this tendency is being calculated. A larger value of $f(x,y)$ indicates a higher tendency toward being set to black. These tendency values are ordered to determine which pels will be painted as black, and which as white. A reasonable approximation is made by considering the pels to be compared to a threshold, L, which is chosen smoothly enough that the screen pel $s(x,y)$ for a particular grayscale level L is black if $f(x,y) \geq L$. Thus, the screen may be viewed as the projection of $f(x,y)$ onto a plane in (x,y,z) Euclidean coordinate space at $z = L$. This visualization allows the spot function to be designed for a particular set of requirements, since f may be formed by interpolating between the screen patterns at each of a set of grayscale levels.

The conventional circular spot function may be described in these terms as follows. If f is equal to the radius r,

$$r(x, y) = f(x, y) = (x^2 + y^2)^{1/2} \qquad (1)$$

the spot function in light areas will appear as a black circle, which grows to the edges of the screen as the gray level is increased.

[†] Patent applications have been filed on some of the material included herein.

Description

The scaling function described herein is designed as a function of radius, so that the shape of the spot can be changed with radius. Here, radius r is given by Eq. 1, where x and $y \in [-1,1]$ are the spot function ordinates. Thus, the shape change of the spot function with radius is realized as a change of spot shape with grayscale level. The radius is used here because it is the Euclidean distance from the center of the spot to the edges of the screen, and is related to the change in spot shape with gray level because of the plane-projection concept described above.

The problem of artifacts in the midtones is solved by designing the spot function to be changed in these regions (this is done through the scaling function, defined below), so that the manner in which growing spots touch other spots in adjacent cells is controlled. We define four parameters for our spot function f:

- p_x and p_y, which scale x and y in the symmetric base functions;
- p, which controls the shape change of the spot;
- p_m, which sets the maximum eccentricity of the spots.

Using cosines for the two signals, and a Gaussian shape as the scaling function, the spot function is described by

$$f(x, y) = [\cos(\pi x/p_x) + \cos(\pi y/p_y) / S(p, r)] / 2 \qquad (2)$$

where $S(p,r)$ is the scaling function, a function of radius, as described above, and p is a parameter that controls the shape change of the spot. In the Gaussian case,

$$S(p, r) = 1 + \exp[-(r2^{1/2} - 1)^2 / 8p^2] / p_m (2p)^{1/2} \qquad (3)$$

Parameters p and p_m in this particular case can assume any positive value. In the limiting case where $p \rightarrow \infty$, Eq. 3 becomes the equation for the spot function from Ref. [1]. The values of p_x and p_y will generally be taken equal to each other, and should always be close to unity to avoid changing the screening frequency; e.g., in what follows, $p_x = p_y = 1$. For example, with $p = p_m = 0.8$, the spots touch only along a single 45 degree orientation in the 50% gray regions, noting that the 45 degree orientation is that to which the human eye is least sensitive [1], and the rectangular angles are those to which the eye is most sensitive. This is shown in Fig. 2.

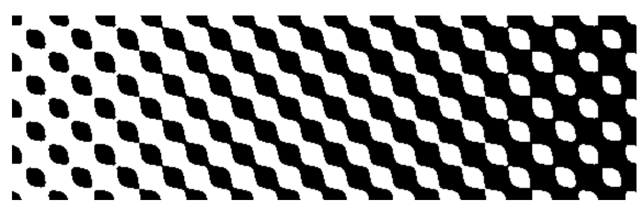

Figure 2. Spots touch along 45° orientation in midtone regions.

The approximate "symmetry" between light and dark regions can also be seen in this plot and those that follow. With $p = p_m = 2.5$, the spots touch in two places along the same 45 degree orientation, and almost touch along the other 45 degree orientation, reducing the rectangular pattern and the resulting dot-gain artifact. This is shown in Fig. 3.

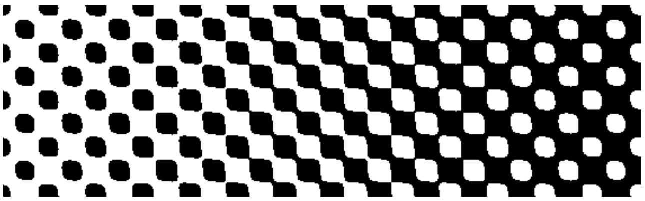

Figure 3. Reduced rectangular and diagonal artifacts.

An even more pleasing result may be obtained by using p and p_m different; e.g., $p_m = 0.8$. This controls the total amount of eccentricity that can occur in the shape-changing spot function, so that the parameter p controls only the regions where the spot function is approximately circular, and those where it is more eccentric. Fig. 4 shows the result of p=0.2.

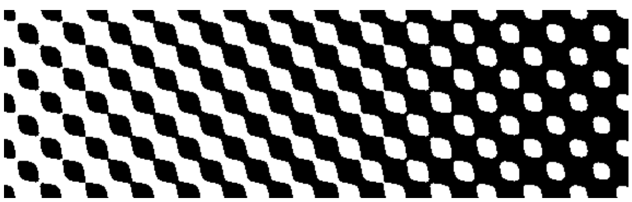

Figure 4. Reduced artifacts in both directions.

In one application that we tested, we found $p_m = p_y = 1$, $p_m = 0.8$, and $p = 0.265$ to produce desirable quality for 107 lpi (lines per inch). Parameters need to be adjusted for each resolution, potentially independently of the other resolutions, in a multi-linescreen system, or in an adjustable system such as that listed in Ref. 3. The parameters chosen for one resolution may work poorly for other resolutions, because of the order in which pels are turned on in the screen.

We have not included figures showing the improvement in the resulting printed images on production printers: the dot gain which aggravates the midtone artifacts is a function of the printer, and does not reproduce consistently on an unknown printer after being scanned as a figure for this paper. However, in print quality comparisons, the screen that we describe in this paper was chosen over separable screens at 71, 85, 106, and 141 lpi.

Angular orientation can be built into the spot function by rewriting the spot function. For example, the 45-degree orientation is built in by writing

$$f(x, y) = [\cos(\pi(x+y)/p_x) + \cos(\pi(x-y)/p_y) / S(p, r)] / 2 \qquad (4)$$

In this case, the effective screening frequency will be higher since each "square" contains one spot at the center with one quarter spot at each corner. This higher frequency must be taken into account in calculating threshold matrices. This does not change the shape of the spot function, only the orientation of screening cells.

To create a threshold array, the spot function is sampled appropriately to obtain the threshold values. The basic cluster cell for a 107 lpi screen in a 600 dpi (dots per inch) printer has a limited number of gray levels. A full set of gray levels is created from the basic cell by utilizing the constrained blue noise interpolation techniques in Ref. [4].

Conclusions

We have introduced a method of asymmetric modulation of spot functions in order to control the "touching" of adjacent spots, and to change the shape of the spots with the gray region. The resulting non-separable shape-changing spot function can reduce printer stress and improve print quality. In contrast, separable spot functions that are used conventionally in a number of systems result in midtone artifacts that the asymmetric, non-separable spot function avoids.

References

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