

DIRECT MULTI-BIT SEARCH (DMS) SCREEN ALGORITHM

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ABSTRACT

Multi-bit screening is an extension of binary screening, in which every pixel in continuous-tone image can be rendered to one among multiple absorbance levels. Many multi-bit screen algorithms face the problem of contouring artifacts due to sudden changes in the majority absorbance level between gray levels. In this paper, we have extended the direct binary search to the multi-bit case where at every pixel the algorithm chooses the best drop absorbance level to create a visually pleasing halftone pattern without any user defined guidance. This is repeated throughout the entire range of gray levels to create a high quality multi-bit screen.

Index Terms— Digital Printing, Digital Halftoning, Direct Multi-bit Search, Direct Binary Search, Screening.

1. INTRODUCTION

Digital halftoning is a technique for displaying a picture on a two-dimensional medium, in which small dots and a limited number of colors are used. The picture appears to consist of many colors when viewed from a proper distance. For example, a picture consisting of black and white dots can appear to display various gray levels.

A continuous-tone image typically has values from 0 to 255 (for each color plane). This corresponds to eight bits of image data. Higher bit depth is used in some applications and is becoming more popular. For example, starting with PostScript level II, twelve bit image and halftone data is supported primarily for image setter applications. To reproduce an 8 bit image at high quality on an output device, requires nearly all of the 256 output gray levels. Since most printers cannot print continuous-tone data directly, digital halftoning technology must be used to produce patterns of printed pixels, which when blurred by the Human Vision System (HVS), produce printed images resembling the desired continuous-tone image. Single drop size or single exposure capability is commonly referred to as "binary" or "bi-level" printing. Digital printers, which were initially pure black and white machines with a very coarse resolution, have evolved to accommodate colors, finer resolutions, and more recently, more than one bit of information per pixel. This new capability is

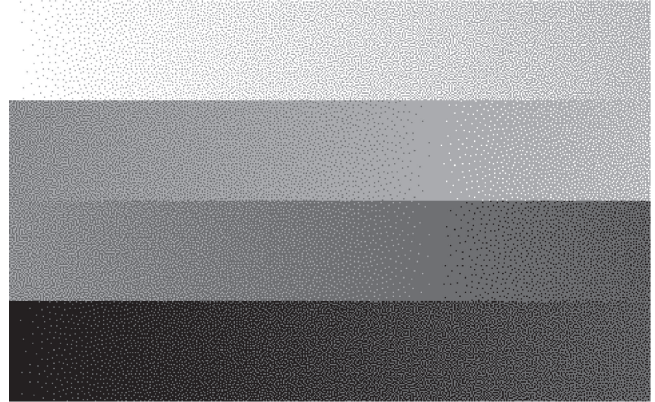


Fig. 1. Ramp generated from binary to multi-bit converted mask

referred to as "multi-bit" or "multi-tone". Multi-bit halftoning enables a selection among multiple drop sizes or exposure levels at each addressable pixel. With the prevalence of devices having multi-bit capability there is a potential to improve overall image quality of print jobs using multi-bit halftoning. The overall print quality of a printer increases more rapidly with bit depth than resolution[1].

Many digital halftoning algorithms exist in literature, but it is our view that there are very few high quality multi-bit screen algorithms. Several single bit halftone screen algorithms are available that may be extended to multi-bit. For example, Lin and Allebach [2] demonstrated the extension of single bit screening algorithm [3] to multi-bit using Direct Binary Search (DBS)[4] with the help of schedulers. Most algorithms introduce contouring artifacts i.e. flat areas near the intermediate output levels as shown in Fig.1. Few methods [2][5][6] are also proposed to reduce these artifacts in multi-bit screens. A detailed literature review can be found in [2]. In addition, these algorithms require many parameters to guide through the multi-bit screen creation.

In this paper, we propose a general framework of high-quality multi-bit screen algorithm. In the remainder of this paper we will use ink jet drop size to refer the output printer levels. It should be understood that everything described also

applies to other technologies (such as EP) where exposure or output level is used to describe the capability.

2. DITHER MASK

Screening is an efficient halftoning algorithm that is used commonly in practical implementations. A common binary screening method employs a matrix of thresholds known as “dither arrays” [7] replicated to the size of printable area. These replicated matrices are compared to the continuous-tone image to determine which PELs are ON or OFF. The printer then uses the screening algorithm to process the continuous-tone image and convert the image into an array of pixels. The result of the screening algorithm is a bitmap where each pixel may be ON or OFF which is referred to as a halftone image. The multi-bit screen consists of dither array for every drop size or exposure level. For example a two bit system having small, medium and large drop size requires three thresholds for each PEL to determine if the printed PEL drop size is none, small, medium or large.

Another way of representing this dither array is a dither mask. The design of a dither mask is equivalent to designing \mathfrak{R} (usually 256) halftone patterns, one for each of the \mathfrak{R} possible gray values from gray level zero through maximum gray level while satisfying the stacking constraint [8], i.e. the pixel locations of the black pixels in a pattern for a particular gray level must be a subset of those locations in a pattern for a darker gray. The maximum gray level is used to produce a solid, where all of the pixels are printed at the maximum output state. If we view the construction of the dither mask as halftoning η different uniform gray images, then dither mask construction is itself a halftoning problem.

3. PROPOSED DIRECT MULTI-BIT SEARCH SCREEN ALGORITHM

3.1. Direct Binary Search

Iterative, sometimes also referred to as search-based halftoning, require several passes of processing to determine the final halftone image. These methods minimize the error between the continuous-tone image and the output halftone image by searching for the best possible configuration of the available drop sizes in the halftone image. Iterative methods are the most computationally intensive of all digital halftoning methods, but they yield significantly better output quality than ordered dithering and error diffusion.

Direct Binary Search (DBS)[4] was independently proposed in 1992 by three different groups. DBS is an outgrowth of earlier research involving digital holography. It has been shown that DBS can produce high-quality halftone images. We have extended DBS to incorporate selection among multiple absorptance values α_S at each addressable pixel in a single operation, thus calling it Direct Multi-bit Search (DMS).

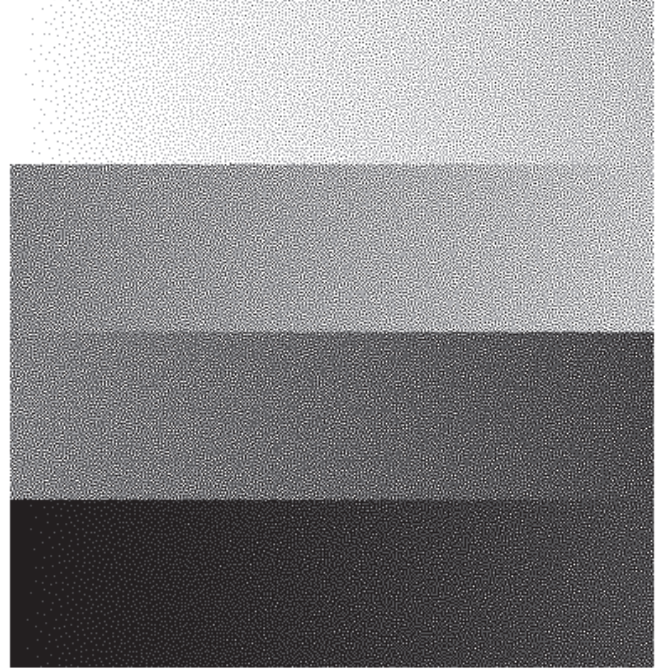


Fig. 2. Ramp generated from the proposed algorithm output with $\alpha_1 = 0, \alpha_2 = 1/3, \alpha_3 = 2/3, \alpha_4 = 1$ absorptance levels

When extended to the multi-bit case, DMS can be expected to yield high-quality multi-tones as well. We propose a methodology called Direct Multi-bit Search Screen Algorithm for multi-bit screen design based on DMS algorithm. In the remainder of the paper we will use notations similar to Allebach’s paper[4].

3.2. Direct Multi-bit Search (DMS)

DMS can be thought of as an iterative/recursive optimization, which is used to minimize a cost function ϵ , defined as error between the perceived halftone image and the perceived continuous tone image:

$$\epsilon = |h(x, y) * g(x, y) - h(x, y) * f(x, y)|^2 dx dy$$

where $**$ denotes 2-dimensional convolution, $h(x, y)$ represents the Point Spread Function (PSF) of the human visual system, $f(x, y)$ is the continuous tone original image and $g(x, y)$ is the corresponding rendered halftone image, which are assumed to lie between 0 (white) and 1 (black). The halftone image itself incorporates a printer model

$$g(x, y) = \sum_m \sum_n g[m, n] p(x - mX, y - nX)$$

which represent the combination of $g[m, n]$ with a spot profile $p(x, y)$ having a device PEL spacing X , where X is the inverse of the printer addressability DPI. Superposition is assumed in this model for the interaction between overlapping

spots. The digital halftone image $g[m, n]$ can have any absorptance value between 0 (white) and 1 (black).

DMS is a computationally expensive algorithm that requires several passes i.e. iterations through an image before converging to the final halftone. DMS starts by generating an initial halftone image, then a local improvement in the halftone is produced by swapping and toggling. Swapping is defined as the operation of switching the absorptance values of nearby pixels and toggling is defined as the operation of changing the absorptance value of individual pixels. The cost function ε can be represented as

$$\varepsilon = \langle \tilde{e}, \tilde{e} \rangle$$

where $\langle \cdot, \cdot \rangle$ denotes the inner product and $\tilde{e}(x, y) = h(x, y) * (g(x, y) - f(x, y))$ represents the perceptually filtered error. We will assume that the continuous-tone image $f(x, y)$ can also be expressed in terms of its samples $f[m, n]$ where (m, n) are coordinates on the halftone array, using the same structure as given above for the halftone image in terms of the printer spot function. Then the perceived error is given by

$$\tilde{e}(x, y) = \sum_{m, n} e[m, n] \tilde{p}(x - mX, y - nX)$$

where, $e[m, n] = g[m, n] - f[m, n]$, and $\tilde{p}(x, y) = h(x, y) * p(x, y)$ is the perceived printer spot profile. Considering the effect of a trial change, the new error will be $\tilde{e}' = \tilde{e} + \Delta\tilde{e}$. Substituting this and expanding the inner product, we obtain

$$\varepsilon' = \varepsilon + 2 \langle \Delta\tilde{e}, \tilde{e} \rangle + \langle \Delta\tilde{e}, \Delta\tilde{e} \rangle$$

assuming all signals are real-values. Either a toggle at pixel (m_0, n_0) or a swap between pixels (m_0, n_0) and (m_1, n_1) can be represented as

$$g'[m, n] = g[m, n] + \sum_i a_i \delta[m - m_i, n - n_i]$$

As a result,

$$\Delta\tilde{e}(x, y) = \sum_i a_i \tilde{p}(x - m_i X, y - n_i X)$$

and

$$\Delta\varepsilon = 2 \sum_i c_{\tilde{p}\tilde{e}}[m_i, n_i] + \sum_{i, j} a_i a_j c_{\tilde{p}\tilde{p}}[m_i - m_j, n_i - n_j]$$

where, $c_{\tilde{p}\tilde{e}}[m, n] = \langle \tilde{p}(x, y), \tilde{e}(x + mX, y + nX) \rangle$, and $c_{\tilde{p}\tilde{p}}[m, n] = \langle \tilde{p}(x, y), \tilde{p}(x + mX, y + nX) \rangle$.

DMS is heavily dependent on HVS models, and for different HVS models DMS yields different halftone patterns. In our work, a richer class of HVS model is implemented that yields enhanced halftoning results. This model is proposed by Kim and Allebach [9] based on mixed Gaussian functions whose functional form is

$$c_{\tilde{p}\tilde{p}}[u, v] = k_1 \exp(-\gamma/2\sigma_1^2) + k_2 \exp(-\gamma/2\sigma_2^2)$$

where $\gamma = u^2 + v^2$ and the constants $k_1, k_2, \sigma_1, \sigma_2$ are 43.2, 38.7, 0.02, 0.06 respectively. Assuming that $c_{\tilde{p}\tilde{p}}$ is symmetric, then

$$\Delta\varepsilon = 2 \left(\sum_i c_{\tilde{p}\tilde{e}}[m_i, n_i] + \sum_{i < j} a_i a_j c_{\tilde{p}\tilde{p}}[m_i - m_j, n_i - n_j] \right) + \sum_i a_i^2 c_{\tilde{p}\tilde{p}}[0, 0]$$

Assume that a given printer can produce S possible output drops with absorptance levels $\alpha_1, \alpha_2, \dots, \alpha_S$. The value of a_i represents the amount of change in the gray level for a toggle:

$$a_i = g_{new}[m_i, n_i] - g_{old}[m_i, n_i]$$

In the above equation, the a_i is computed for all $g_{new}[m_i, n_i] = \alpha_1, \alpha_2, \dots, \alpha_S$, and the operation that yields maximum error decrease in $\Delta\varepsilon < 0$ is selected. A swap between pixels i and j is equivalent to two toggles with $g_{new}[m_i, n_i] = g_{old}[m_j, n_j]$ and $g_{new}[m_j, n_j] = g_{old}[m_i, n_i]$ and thus the above equation is written as:

$$a_i = g_{old}[m_j, n_j] - g_{old}[m_i, n_i]$$

$$a_j = g_{old}[m_i, n_i] - g_{old}[m_j, n_j]$$

Thus $a_j = -a_i$ except for $j = 0$ (e.g., toggle, $a_0 = 0$). The operation that yield maximum error decrease in $\Delta\varepsilon < 0$ among toggles or swap is selected. Any accepted operation requires updating of $c_{\tilde{p}\tilde{e}}$ at $g(m, n)$ using

$$c_{\tilde{p}\tilde{e}}[m, n]' = c_{\tilde{p}\tilde{e}}[m, n] + a_i c_{\tilde{p}\tilde{p}}[m - m_i, n - n_i]$$

When no operations are performed in the last iteration, the end criteria is met.

3.3. Pseudo Code

The framework of the proposed DMS screen algorithm is explained below:

1. Generate a continuous-tone image $f_\eta(m, n)$ of size $N \times N$ with all pixels values set to η , where η is gray level = $0, 1/\mathfrak{R}, 2/\mathfrak{R}, \dots, 1$. Assuming an eight bit screen design, \mathfrak{R} would be equal to 255.
2. Generate an initial halftone $g_{0-initial}(m, n)$ of size $N \times N$ with all pixels values set to α_1 (usually zero).
3. Compute the auto-correlation function $c_{\tilde{p}\tilde{p}}[m, n]$.
4. **for** each gray level from 0 to η **do**
repeat
Compute the initial error $c_{\tilde{p}\tilde{e}}[m, n]$ between $f_\eta(m, n)$ and $g_{0-initial}(m, n)$.
for each pixel (m, n) **do**

- Compute the change in $c_{\tilde{p}\tilde{e}}[m, n]$ caused by
 - (a) Toggling pixel $g_{\eta-initial}(m, n)$ with all the possible output states α_S , and
 - (b) Swapping pixel $g_{\eta-initial}(m, n)$ with a neighbor
- Find the operation with maximum error decrease in $\Delta\epsilon$ which satisfies the stacking constraint.
- Update $c_{\tilde{p}\tilde{e}}[m, n]$ and $g_{\eta-initial}$ with accepted change.

end for

until end criteria are met

save $g_{\eta-initial}$ as g_{η}

copy g_{η} as $g_{\eta+1-initial}$

5. **end for** when all gray levels \mathfrak{R} are processed.

Note that the distribution of different absorptance levels at each gray level is determined by the proposed DMS screen algorithm instead of any user defined guidance such as schedulers.

4. RESULTS

In this paper, we have chosen four absorptance states $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ as 0, 1/3, 2/3 and 1 respectively. A gray level ramp halftoned using the DMS multi-bit dither mask with the above absorptance levels is shown in Fig.2. Note that the output states α_S and number of gray levels η are not restricted to be a power of 2. The calculated fraction of pixels with these absorptance levels at each gray level of the DMS multi-bit dither mask is shown in Fig.3. The proposed algorithm utilizes HVS model to spatially arrange all the absorptance levels almost at every gray levels minimizing any contour artifacts usually caused from traditional multi-bit screen algorithms and create a smooth and visually pleasing halftone textures.

5. CONCLUSION

We propose a multi-bit halftoning algorithm where the output of a multi-tone capable printer can be increased even at lower resolutions with no contouring artifacts which are inherent in many multi-bit halftoning algorithms. Generally, iterative and search based halftoning algorithms are computationally expensive and time consuming. A parallel implementation of the general DBS algorithm was implemented in Graphics Processing Unit(GPU)[10] to increase the performance and speed.

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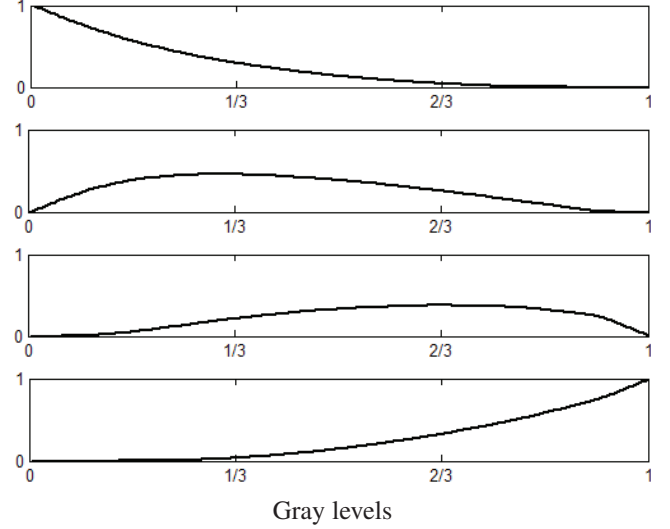


Fig. 3. Fraction of pixels in the multi-bit mask for $\alpha_1=0, \alpha_2=1/3, \alpha_3=2/3, \alpha_4=1$ (top to bottom)

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