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Minimization of Halftone Noise in "FLAT" Regions for Improved Print Quality

Harsha Narne

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Minimization of Halftone Noise in “FLAT” Regions for Improved Print Quality

by

Harsha Narne

A Thesis submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

In

ELECTRICAL ENGINEERING

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DEDICATION

This thesis dedicated to my family and friends.

To my cousin, Haritha, for her continued support, patience and encouragement.

To my parents, Narasimha Rao and Sukanya, for their never-ending love.

To my sister, Sravya, and friends for always being there for me.

To the Academy for Educational Development.
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Harsha Narne
ABSTRACT

The work in this thesis proposes a novel algorithm for enhancing the quality of “flat” regions in printed color image documents. The algorithm is designed to identify the “flat” regions based on certain criteria and filter these regions to minimize the noise prior and post Halftoning so as to make the hard copy look visibly pleasing. Noise prior to halftone process is removed using a spatial Gaussian filter together with a Hamming window, concluded from results after implementing various filtering techniques. A clustered dithering is applied in each channel of the image as Halftoning process. Furthermore, to minimize the post halftone noise, the halftone structure of the image is manipulated according to the neighboring sub-cells in their respective channels. This is done to reduce the brightness variation (a cause for noise) between the neighboring sub-cells. Experimental results show that the proposed algorithm efficiently minimizes noise in “flat” regions of minimal gradient change in color images.
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CHAPTER 1: INTRODUCTION

1.1 MOTIVATION

Color printing is the reproduction of image or text in color on paper. In the modern printing environment, process speed, print quality and cost of the color printed document have become major concerns for people at both offices and homes. Among them ‘print quality’ plays a vital role in benchmarking, trading, customer satisfaction and productivity. In recent years, there has been significant technological advancement in print industry resulting in improving the ‘print quality’ of the color images. Many algorithms were developed to better mimic the original continuous tone images on paper. But, apart from mimicking the original, these algorithms may introduce halftone noise at the time of printing.

Color images that appear noise free in digital form, may contain visible noise when printed. The “flat” regions in these photos are critical in judging the print quality. A region is said to be “flat” when it appears uniform in color (low covariance across all the channels) and also covers a major portion of the image. These regions visually appear noisy due to: 1) Improper image acquisition, 2) The limitations of the Halftoning algorithm, and, 3) Electro-mechanical forces in the printers’ hardware. Out of these, overcoming the limitations of the Halftoning algorithm has been very challenging and is the concern for us in this work. The major limitation of the present Halftoning algorithm is its quantization into a fixed number of four gray levels (i.e. 0, 85, 170 and 255). This produces an unwanted abrupt change in the brightness of the dots which appear as noise.
In monochrome (Black and White) halftones or higher bit color printers (i.e. printers that can produce more number of gray levels), this factor cannot be mitigated.

Current color halftoning algorithms are usually Cartesian products of three or four halftoned monochrome planes corresponding to the color components of the image. This generalization of the monochrome algorithms overlooks the fact that colored dots are not equally bright and its impact of abrupt change in brightness for the human eye. To produce a good color halftone one has to place colored dots so that the following criteria are optimally met: 1) The placement pattern is visually unnoticeable, 2) The local average color is the desired one, and, 3) The colors used reduce the noticeability of the pattern. The first two design criteria are easily carried out from the monochrome algorithms. However, the third cannot be satisfied by a simple generalization of monochrome halftoning but extended by changing the gray level of the pixels that cause the abrupt change in brightness. This results in a visibly pleasing hard copy.

The potential applications of this work being improved noise reduction, image enhancement, print quality improvement, render “flat” regions of different shapes and product development. The proposed work will solve brightness variation, a print quality artifact, related to a specific series of print engines. Improved rendering is directly linked to increased product market value. Proposed approach for printer output improvement can be reused for other printer engines with minimal modifications to reflect printer specific features.
1.2 CONTRIBUTIONS

In this thesis, we propose a method to automatically identify the “flat” region(s) and analyze them to minimize the perceived output halftone noise irrespective of shape, size and color of the identified regions. The flowchart in Figure 1 illustrates an overview of the proposed approach.

![Flowchart of proposed approach](image)

**Figure 1: Overview of proposed approach.**

A segmentation map of the input image and the original image itself are used to automatically identify the “flat” regions. This saves the computational time and ensures simplicity of the proposed work. The algorithm consists of three stages, which are incorporated into the original pipeline of the printer. Firstly, the input image is segmented and the “flat” regions are identified. Secondly, the identified “flat” regions are low-pass filtered, to minimize the noise prior to halftoning. The filter used is a combination of
Gaussian and Hamming filters. The first and second stages together make the Pre Halftone Noise Removal Module. The filtered image is processed through the original pipeline where it is transformed to the printer domain (CMYK) using Look-Up Tables (LUT) and then halftoned by a stochastic process. Finally, the sub-cells of the halftone pattern in the “flat” regions post halftoning is manipulated according to the neighboring sub-cells. The algorithm automatically identifies the channel(s) containing noise by adaptive thresholding and adjusts the pattern accordingly. This final stage is referred as Halftone Enhancement. The final modified image is printed directly on the paper. Its quality is evaluated objectively by the SNR value and observed subjectively by the human eye.

The proposed algorithm minimizes the noise in the “flat” regions produced by electro-photographic laser printers. It works on the image document prior and post halftoning without disturbing the printer workflow, which differentiates from the literature making the work new and original. The results on the hard copy are visually pleasing. The extent of noise removal depends on noise characteristics of the flat region. The document presents a detailed explanation of the algorithm and illustrates its performance on a specific printer.

1.3 THESIS ORGANIZATION

The rest of this thesis is organized as follows. Chapter 2 provides the literature review and background. Chapter 3 presents the experimental setup and describes the proposed algorithm. Chapter 4 demonstrates results and discussion. Conclusions are drawn in Chapter 5.
CHAPTER 2: LITERATURE AND BACKGROUND

2.1 LITERATURE REVIEW

Continuous tone (contone) images can be displayed on bi-level or multilevel devices by a halftoning process. Halftoning is the reprographic technique that simulates continuous tone imagery through the use of equally spaced dots of varying size. Dispersed dithering is one of the halftoning methods that have visually pleasing characteristics. Error diffusion is a well known and widely applied dispersed dithering algorithm to both monochrome and color images. This method was first proposed by Floyd and Steinberg [1]. The method diffuses the quantization error to the neighboring pixels to perform adaptive quantization. It inherently enhances high spatial frequencies, therefore produces sharp and visually pleasing halftones [2]. This error diffusion algorithm can be improved in terms of smoothness by adaptive selection of threshold or diffusion kernels [3], [4]. According to Ulichney [4], the visually pleasing effect of error diffusion is due to the blue noise characteristics.

Visual cost measures introduced by Granrath [8], Daly [9] and even Allebach [10] proved to improve the design of the dither matrices.

Analoui and Allebach [11] proposed a method using Direct Binary Search (DBS) to generate halftone images that are visually optimized for the display devices. This is computationally expensive as the algorithm searches for a binary array of pixel values that minimizes the difference between the perceived displayed continuous tone image and halftone image. Lieberman and Allebach [12] reported speed and quality improved over DBS.

Stochastic screening or frequency modulated (FM) screening is another efficient dispersed dithering algorithm that is based on point-to-point processing. It is faster than the techniques described earlier. Some of the FM techniques are blue noise mask [13], [14] and [15], void and cluster [16], and DBS screen [17]. The blue noise mask method constructs a dither array with given frequency domain characteristics, whereas the void and cluster method constructs a dither array in spatial domain. The DBS screen constructs a dithering array by utilizing optimization based direct binary search algorithm that searches for the closest visual match between a continuous tone image and its halftone. A review of blue noise matrix generation can be found in [18]. It also describes methods to extend the basic blue noise dither techniques for multilevel and color output devices.

Gentile [19] describes a quantizer that is used possibly in conjunction with halftoning. The effectiveness of both quantization and halftoning algorithms is dependent on the color space in which they are performed. A color stochastic screening technique, which applies Voronoi tessellation followed by tone level adjustment [20] to optimize the
halftone frequency, was another approach used to enhance the quality of printed document.

Due to the importance of good hardware capabilities in rendering devices, many approaches have been proposed for enhancing the printers’ abilities to reduce halftone noise and produce higher quality output. Multilevel halftoning (multitoning), an extension of bi-level halftoning, is a technique utilized to improve image quality by introducing extra gray levels. This enables the printer to print more states of color in a unit area without changing the dot size. For example, instead of the printer having just on/off state, the printer is empowered with, say, off/mid-off/mid-on/on states at each pixel location. This clearly improves the printer’s performance. Details of multitoning are better described in [21], [22] and [23]. They also describe the importance of minimizing the dot overlap to enhance the quality of images thereby reducing the halftone noise. An overmodulation technique is developed [24], where the dot patterns are manipulated around the intermediate output levels in multitoning to achieve the desired halftone patterns. It is a simple extension to the conventional multitoning scheme and also a mean-preserving process. It showed great results for inkjet printing. The most recently proposed approach is a combination of Error Diffusion, Dithering and Overmodulation for smooth multilevel printing, described in [25].

All these approaches are related to the halftoning algorithm, the halftone screens or the hardware capabilities of the printer pipeline. Doron and Nur [26] proposed Ink Relocation by arguing that brightness variation between color dots placed at neighboring locations is the major cause of color halftone noise. This post process relocates ink drops between neighboring drop locations in order to reduce local brightness variation. But, it
leads into other disturbing artifacts because of the interplay of the ordered dither. It also needs color correction and disabling at strong edges to reduce the blurring effect. Depending on the media (paper type), the colors intrinsically become more saturated.

So, in this work, we propose an algorithm that selects the “flat” region and manipulates the pixel values (between the fixed number of gray levels, four in this case) of the selected region in the noisy channel(s) (by adaptive thresholding) before the raster is turned on for printing. Finally, the choice comes down to choosing an algorithm/system that best suits the printer line, the halftoning technique and other commercial aspects of the product line.

2.2 BACKGROUND

As previously mentioned, a segmentation algorithm is required at the pre-processing stage of initial noise removal. A Halftoning Algorithm is present in the printer pipeline for rendering the image document. Summaries of the Segmentation Algorithm and the Halftoning Algorithm of the printer are introduced in the following Sections.

2.2.1 Segmentation Algorithm

The Automatic Image Segmentation by Dynamic Region Growth and Multiresolution Merging segmentation algorithm [27] is used in this work. This approach employs vector-based color gradient method [28] and Otsu’s automatic threshold [29] to perform a dynamic threshold-based segmentation. It segments the image by placing emphasis on the use of color-homogenous regions and color transitions without generating edges. The use of color gradient to aid in the region growing process rather than for generating edges avoids issues of threshold and disconnected edges.
A weighted vector-based color gradient map is used to provide the groundwork upon which seeds are generated and region growing is automated. Seeds here refer to 4-neighborhood connected pixels where gradient is below a specified threshold. A dynamic threshold operator is applied to this gradient map to govern the growth process. To ensure consistency of the segmentation with the image regions, region growing is followed by a similarity measure-based region-merging step. This produces an optimally segmented
image. Figure 2 shows the block diagram of the segmentation algorithm used in this work as given in [27].

2.2.2 Halftoning Algorithm

Halftoning is a technique that is commonly used in digital imaging to create the appearance of intermediate tones when only two colorant levels (i.e., ink or no ink) are available. It relies on the fact that an observer’s eye will spatially average over some local area of the image so that intermediate gray levels can be created by turning some of the pixels “on” and some of the pixels “off” in some small region. This is illustrated in Figure 3.

![Image of halftone dots and human vision](image)

Figure 3: Optical Illusion, (a) Halftone dots. (b) How the human eye would see (a) from sufficient distance.
A comprehensive review of the standard halftoning algorithm in use has been compiled by Ulichney [4]. In his text two major halftoning algorithms are discussed: dithering and error diffusion. The most common dithering algorithms are random dither [31], clustered-dot dither [32] and dispersed-dot dither [33]. Random dither was developed first, but it is rarely used because it produces the poorest image quality. The two remaining dither algorithms are in common use, with clustered-dot dither being the most prevalent and more suitable for use in ink-jet printers and dispersed-dot dither for laser printers because of their (printers’) ability/inability to print certain combination of dots. They are based on a threshold screen pattern that is generally a fixed size, e.g., 8×8 image pixels, which is compared on a pixel-by-pixel basis with the input digital image values. If the digital value is greater than the screen value, a maximum value or “on” is outputted and if it is less, a minimum value or “off” is outputted. The algorithms differ in the screen patterns. The simplest form of halftoning can be described by the threshold operation, where the output at a pixel location \((i, j)\) is defined by:

\[
HT_{out}(i, j) = \begin{cases} 
1 & \text{if } CT(i, j) \geq T_{screen}(i, j) \\
0 & \text{if } CT(i, j) < T_{screen}(i, j) 
\end{cases}
\]  

(1)

\(HT_{out}\) is the halftone output of the contone image \(CT\). \(T_{screen}\) is the threshold value at location \((i, j)\) on the Half Tone Screen/Mask. This screen is a periodic replication of the Halftone Cell, a group of threshold values that are computed and arranged taking into consideration various factors such as the physics of light, human visual system, etc. A good summary of the factors required to construct a good Halftone Cell can be found in [34, 35].
Figure 4: Three examples of color halftoning with CMYK separations. From left to right: The cyan separation, the magenta separation, the yellow separation, the black separation, the combined halftone pattern and finally how the human eye would observe it from a sufficient distance.

In the case of color images, each plane is halftoned separately & placed on one another to produce a multi-plane (color) output. The method used to ‘pile’ the individual halftones over one another is called as Halftone Dot Placement. The general idea is the same as grayscale images, by varying the density of the four primary printing colors, cyan, magenta, yellow and black (abbreviation CMYK), any particular shade can be reproduced. This is clearly illustrated in Figure 4. There are three types of dot placement techniques:

- **Dot on Dot:** All primary color dots overlap each other.
- **Dot off Dot:** Primary color dot are placed adjacent to each other without overlapping.
- **Rotated Dot**: Primary color screens are rotated by various angles during halftoning. There is partial overlapping.

*Dot off Dot* placement is mainly used in monitor displays & *Rotated Dot* placement is most widely used in printing systems as it is less sensitive to printing defects such as misregistration and banding.

The choice of halftoning is also determined by factors such as:

- Amplitude Modulation vs. Frequency Modulation.
- Bi-level / Multilevel Halftoning.
- Shape of the dots - *Elliptical, Round* or *Square*, elliptical being the most commonly used shape.
- Size of screening cells – large cells mean more ink absorption (color quality), but less details; whereas, small cells mean more details and less ink absorption.

A good description of the above mentioned factors can be found in [36, 37 and 38]. There are many halftoning techniques prevalent in the industry and this science has evolved greatly over the years. Halftoning still continues to be an area of active research, a comprehensive study of various existing halftoning models and techniques can be found in [39, 40].
CHAPTER 3: PROPOSED ALGORITHM

3.1 EXPERIMENTAL SETUP

The experiment aims to identify and modify the “flat” regions in an image to make the printed copy look visually better. In other words, to minimize the visible noise present in printed photos, thereby making them look pleasing to human eye. The theory of point-to-point processing in halftoning helped to build the proposed algorithm.

3.1.1 ORIGINAL EXPERIMENTAL SETUP

Figure 5 illustrates the original experimental setup. The test image is processed through a Look-Up Tables (LUT) for conversion from the present color space (i.e. RGB) to the printer domain (CMYK). This contone CMYK image is referred to as the indump. The indump is halftoned resulting in a halftone image. This halftone image is referred to as the outdump and is printed directly on paper.

![Figure 5: Original Printer Pipeline.](image-url)
3.1.2** MODIFIED EXPERIMENTAL SETUP**

Figure 6 illustrates the modified experimental setup. It mimics the original with the exception of Pre Halftone Noise Removal block and Halftone Enhancement block. The Pre Halftone Noise Removal block ensures the *indump* to be moderately noise free, whereas the Halftone Enhancement block minimizes the noise added to the *outdump* by the halftoning process. Then the raster is released for printing. Both the blocks are designed to interrupt the original pipeline of the printer and make the printed hard copy look visibly better.

3.2** PROPOSED ALGORITHM**

Color images/photographs that appear noise free in digital form (on display devices), may contain visible halftone noise when printed. Doron and Nur [26] proposed Ink Relocation to minimize the visible color halftone noise. They believe that brightness
variation between color dots placed at neighboring locations is the major cause of color halftone noise. This post process relocates ink drops between neighboring drop locations in order to reduce local brightness variation. But, it leads into other disturbing artifacts because of the interplay of the ordered dither. It also needs color correction and disabling at strong edges to reduce the blurring effect.

Hence, we propose a novel algorithm to enhance the print quality by removal of halftone noise in the “flat” regions of the photographs. The block diagram of the proposed algorithm is shown in Figure 7. The algorithm consists of three stages, which are incorporated into the original pipeline of the printer. All the stages are explained in detail in the following sections with an overview here.

Firstly, the input image is segmented using Automatic Image Segmentation by Dynamic Region Growth and Multiresolution Merging segmentation algorithm [27]. The “flat” regions are identified from the segmentation map. The identified “flat” regions are low-pass filtered, to minimize the noise prior to halftoning. The filter used is a combination of Gaussian and Hamming filter. At this stage, the pre halftoning noise in the image is minimized. Secondly, the filtered image is processed through the original printer pipeline where it is transformed to the printer domain (CMYK) using Look-Up Tables (LUT) and then halftoned by a stochastic process (explained in Section 3.2.2). Finally, the halftone pattern of the sub-cells in the “flat” regions post halftoning is manipulated according to the neighboring sub-cells (explained in Section 3.2.3). The algorithm automatically identifies the channel(s) containing noise by adaptive thresholding and adjusts the pattern according to the channel selected. This final stage is referred as Halftone Enhancement.
Figure 7: Block diagram of the proposed algorithm.
**3.2.1 PRE HALFTONE NOISE REMOVAL**

The *indump* (as shown in Figure 6) is required to be relatively noise free to reduce the effect of the printer halftoning process on the quality of the printed color image. The first step in this process is to segment the given input image. The *Automatic Image Segmentation by Dynamic Region Growth and Multiresolution Merging* segmentation algorithm [27] is used for this work to find the segmentation map. Other segmentation algorithms can be found in [30].

Once the image is segmented, the “flat” regions are identified and selected. According to the criteria used, “flat” regions in an image are those having the least covariance across the three *RGB* channels and also cover a reasonably significant area, perhaps more than 20% of the image area. These two conditions help us identify and select the “flat” regions of an image. The selected “flat” regions are subjected to a low pass filter, in spatial domain, on every channel individually. A detailed explanation of the filter selected is given below.

In the literature, there are many techniques used for noise removal. Hence, we have implemented several approaches on a cropped image (of size 96×234, as shown in Figure 8) to select the best technique for our application. Sorting and selecting one out of them has to be done carefully and efficiently.

**Method 1:** In this approach, the Signal-to-Ratio (*SNR*) in each R, G, B channels is computed and the channel with the lowest *SNR* is replaced by its mean. Hence, its signal power to noise power ratio is enhanced. The *SNR* in each channel is calculated by the given formula,

\[
SNR_j = 10 \times \log_{10} \left( \frac{\mu_j}{\sigma_j} \right)^2
\]  

(2)
where, $\mu_j$ and $\sigma_j$ are the mean and the standard deviation in the $j^{th}$ channel.

Method 2: Principal Component Analysis (PCA) is used to enhance the $SNR$ value. The noisy component is replaced by its own mean value. The principal components are obtained from,

$$Y = W^T X$$  \hspace{1cm} (3)

where, $X$ is an $n \times N$ data matrix. $N$ is the number of observations and $n$ is the dimension. The matrix $W$ is the eigenvectors of the covariance matrix ($C$) corresponding to the highest principal component. $C$ is computed using,

$$C = \frac{1}{N} X^T X$$  \hspace{1cm} (4)

Method 3: In this approach, filtering is done using Singular Value Decomposition (SVD). 10% and 50% of the highest singular values are considered and the rest are removed as they contain noise. The SVD is applied in two ways, 1) considering the whole image, and, 2) dividing the image into $16 \times 16$ blocks with an overlapping order of $10 \times 10$.

**Figure 8: Cropped Region.**
Method 4: K-Nearest Neighbor (K-NN) Filtering is a popular non-linear technique where the pixels within a rectangular window of size N pixels (here, 10000) are ranked with respect to the center pixel value and the K pixels which are closest to the center pixel value are selected. The filtering operation consists of replacing the center pixel by the average of the selected K (here, 100) pixels. This technique is a compromise with the image detail and structure due to averaging and normally used on photographs.

Method 5: Using Wavelet Soft-Thresholding algorithm on each of the R, G and B channels. Hard-Thresholding can be described as the usual process of setting to zero the elements whose absolute values are lower than the threshold. The hard threshold signal $Y_h$ is,

$$Y_h = \begin{cases} X & X > THR \\ 0 & X \leq THR \end{cases}$$

(5)

where, $X$ is the original signal and $THR$ is the threshold value. Soft-Thresholding is an extension of Hard-Thresholding, first setting to zero the elements whose absolute values are lower than the threshold, and then shrinking the nonzero coefficients towards 0. The soft threshold signal $Y_s$ is,

$$Y_s = \begin{cases} \text{sign}(X) \cdot (X - THR) & X > THR \\ 0 & X \leq THR \end{cases}$$

(6)

where, $\text{sign}(X)$ is the signum function of $X$.

$$\text{sign}(X) = \begin{cases} 1 & X > 0 \\ 0 & X = 0 \\ -1 & X < 0 \end{cases}$$

(7)

Figure 9 illustrates the above thresholding process on a sample signal uniformly distributed from -1 to 1 with 100 observations.
Method 6: In this method, each channel of the image is decomposed into 1-level wavelet coefficients (as shown in Figure 10). Then high frequencies are removed leaving low frequencies. Similarly obtaining 2-level coefficients and removing high frequencies while retaining only low frequencies is also implemented.

![Wavelet Decomposition](image)

**Figure 10: Wavelet Decomposition.**

Method 7: A simple Gaussian filter together with a Hamming window to minimize the effect of side lobes is considered. Mathematically it is expressed as,

\[ h(m, n) = h_G(m, n) \times h_H(m, n) \]  

(8)
where, $h_G(m,n)$ is a $9 \times 9$ Gaussian filter with standard deviation of 5000 expressed as,

$$h_G(m,n) = \frac{1}{\sqrt{2\pi \sigma}} e^{-(m^2+n^2)/(2\sigma^2)}$$

$h_H(m,n)$ is a zero phase circularly symmetric Hamming window of same size, given by,

$$h_H(m,n) = w_H(\sqrt{m^2 + n^2})$$

where, $w_H$ is a 1-dimensional Hamming window. The frequency response, $H(\omega_1,\omega_2)$, of the low-pass filter is shown in Figure 11 and given by,

$$H(\omega_1,\omega_2) = H_G(\omega_1,\omega_2) \ast H_H(\omega_1,\omega_2)$$

where, $H_G(\omega_1,\omega_2)$ is the frequency response of the Gaussian filter and $H_H(\omega_1,\omega_2)$ is the frequency response of the Hamming window. $\omega_1$ and $\omega_2$ are the frequencies.

The Signal-to-Noise Ratio (SNR) values in each channel are calculated and compared individually to the different methods discussed above. They are also tabulated in Table 1. Higher the SNR values better the filtering method. Hence, a Gaussian filter together with a Hamming window given by Eq.(4) is selected. At this point, the filtered image is moderately noise free. It is a contone image in the original RGB color space.

![Figure 11: The combination of a Gaussian filter and a Hamming window.](image)
Figure 12 presents both the original test target and the filtered image. Note the effectiveness of the pre-processing module in minimizing the noise prior to halftoning.

Figure 12: (a) Original Image, (b) Filtered Image
3.2.2 **ORIGINAL PRINTER PIPELINE**

Figure 13 illustrates the original printers’ pipeline, comprising of the color space conversion and the halftoning algorithm. The filtered image is transformed from RGB to the CMYK color space using LUT. It is then subjected to halftoning, which is a clustered-dot dithering method. At this stage, the number of gray levels in the contone CMYK image (*indump*) are quantized from 256 to a fixed number (4 in this case, say, 0, 85, 170, 255) in the halftone CMYK image (*outdump*). This quantization is done by a stochastic process between the *indump* and the halftone screens (*H*₁ and *H*₂, as shown in Figure 14) to every channel individually. Halftone screens vary in size and levels from channel to channel. Each pixel in the image is compared to the corresponding pixel in *H*₁. If pixel value is greater than corresponding value in *H*₁ then it is mapped as 170 else 0. Similarly, each pixel in the image is compared to the corresponding *H*₂ pixel. If pixel value is greater than corresponding value in *H*₂ then it is mapped as 85 else 0. If pixel is mapped as both 85 and 170 then it is mapped as 170. Mathematically it is given by,

\[
HT_{\text{out}}(i,j) = \begin{cases} 
170 & \text{if } CT(i,j) \geq H_1(i,j) \text{ and } CT(i,j) \geq H_2(i,j) \\
85 & \text{if } CT(i,j) \geq H_2(i,j) \text{ and } CT(i,j) \leq H_1(i,j) \\
0 & \text{elsewhere}
\end{cases}
\]  

(12)

where, *HTₜₒᵤₜ*(i, j) is the halftoned output (*outdump*) of the contone input image *CT*(i, j) (*indump*), (i, j) specifies the location of the pixel. *H*₁ and *H*₂ are the halftone threshold screens. This process is explained through an example in Figure 14. The halftone screens are periodic, having different screen angles for individual channels. So it is a *Rotated Dot – Halftone Dot Placement* technique. Typically these screen angles for C, M, Y and K are 105°, 75°, 45° and 90° respectively (as shown in Figure 15).
Figure 13: Original Printer Pipeline
Example showing the Halftoning Process based on Equation (12):

<table>
<thead>
<tr>
<th>124</th>
<th>122</th>
<th>128</th>
<th>125</th>
<th>127</th>
</tr>
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<td>121</td>
<td>142</td>
<td>125</td>
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<tr>
<td>124</td>
<td>150</td>
<td>146</td>
<td>131</td>
<td>140</td>
</tr>
</tbody>
</table>

\[
\begin{array}{cccccccc}
120 & 130 & 135 & 123 & 129 \\
130 & 125 & 217 & 55 & 32 \\
250 & 178 & 210 & 87 & 195 \\
103 & 150 & 172 & 65 & 43 \\
111 & 130 & 215 & 183 & 211 \\
\end{array}
\]

\[
\begin{array}{cccccccc}
129 & 180 & 35 & 23 & 129 \\
130 & 215 & 217 & 155 & 232 \\
250 & 178 & 210 & 87 & 95 \\
103 & 150 & 172 & 67 & 43 \\
211 & 130 & 215 & 147 & 195 \\
\end{array}
\]

\[
\begin{array}{cccccccc}
170 & 0 & 0 & 170 & 0 \\
0 & 0 & 0 & 170 & 170 \\
0 & 0 & 0 & 170 & 0 \\
170 & 0 & 0 & 170 & 170 \\
170 & 170 & 0 & 0 & 0 \\
\end{array}
\]

\[
\begin{array}{cccccccc}
85 & 85 & 0 & 0 & 85 \\
85 & 85 & 0 & 0 & 0 \\
0 & 0 & 0 & 85 & 85 \\
85 & 0 & 85 & 0 & 0 \\
0 & 85 & 0 & 0 & 0 \\
\end{array}
\]

\[
\begin{array}{cccccccc}
170 & 85 & 0 & 170 & 85 \\
85 & 85 & 0 & 170 & 170 \\
0 & 0 & 0 & 170 & 85 \\
170 & 0 & 85 & 170 & 170 \\
170 & 170 & 0 & 0 & 0 \\
\end{array}
\]

**Figure 14:** Numerical example of Halftoning Process, (a) input matrix, (b) \( H_1 \) halftone screen, (c) \( H_2 \) halftone screen, (d) result from (a) & (b), (e) result from (a) & (c), and (f) final output matrix.
3.2.3 HALFTONE ENHANCEMENT

The above halftoning process generally results in rendering the “flat” regions with sub-optimal quality. This is primarily because of restricting the number of possible gray levels for a pixel which leads to abrupt change in brightness. This introduces much of the halftone noise in the “flat” regions. To overcome this, Halftone Enhancement (detailed flowchart in Figure 16) is designed to maintain the pattern of the halftone image along the screen angles in the “flat” region for each channel or in the channel containing the noise based on the Signal-to-Noise Ratio (SNR) of that channel given by, Equation (2).

Figure 15: Periodic Structure of each individual channel along with screen angles.
This SNR is compared with a threshold $T$, given by

$$T = \frac{1}{n} \sum_{j=1}^{n} SNR_j$$

(13)

where $SNR_j$ is the SNR value of the $j$th channel. $n$ is the number of channels.

Then the next step is to divide the halftone pattern in the outdump ($HT_{out}$) into smaller periodic sub-cells (having their periodicity along the screen angle in their respective channels as shown in Figure 15) in order to determine the pixel locations in $HT_{out}$ that are candidates for enhancement. Later, at each location in $HT_{out}$, the pixel value is compared to the corresponding position pixel value in the previous and next sub-cells, $Pix_i^{k-1}$ and $Pix_i^{k+1}$ respectively, where $Pix_i^k$ represents $i$th pixel in the $k$th sub-cell. If the result is true (both equal), the algorithm proceeds to the next pixel in raster order. However, if the result is false (does not equal any), the current pixel value is replaced by the corresponding position pixel value of the previous sub-cell. Therefore, the existing halftone prior to the modification is not disturbed but rather enhanced as required to improve the quality of the output.
Figure 16: Halftone Enhancement.
CHAPTER 4: RESULTS AND DISCUSSIONS

The proposed algorithm has been implemented using Matlab 7.2® and successfully illustrated on a database of color images provided by Hewlett-Packard. Each of these test targets is in RGB color space with an average resolution of $2016 \times 3040$. They should be printed at 600dpi. Our algorithm is mainly developed for the “flat” regions (namely, the “sky” and the background “wall”) in these images. These regions should be large in area and also have minimal interference with other regions of the image in that area. To eliminate the artifact at the boundary of the “flat” regions caused by the low-pass filter (used in pre halftone noise removal stage), the algorithm neglects outer 10 pixels along the boundary.

Several techniques have been implemented to select the best filter in this application. They are described in Chapter 3. The results are tabulated in Table 1 and the resulting filtered images are shown in Figure 17.

<table>
<thead>
<tr>
<th>Filtering Method</th>
<th>SNR (in dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R-channel</td>
</tr>
<tr>
<td>Original Image</td>
<td>20.3789</td>
</tr>
<tr>
<td>SNR</td>
<td>NA</td>
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<tr>
<td>PCA</td>
<td>20.3794</td>
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<tr>
<td>SVD (10)</td>
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<td>Nearest K-Filter</td>
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<td>Wavelet Soft thresholding</td>
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<tr>
<td>1-Level Wavelet Method</td>
<td>20.5363</td>
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<tr>
<td>2-Level Wavelet Method</td>
<td>20.7441</td>
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<tr>
<td>Gaussian Filtering</td>
<td>21.6156</td>
</tr>
</tbody>
</table>

Table 1: Experimental results for Cropped Image.
Figure 17: Illustrating different filtering methods, (a) Cropped Image, (b) SNR Filtered, (c) PCA, (d) SVD(10), (e) SVD(50), (f) SVD block, (g) Nearest K-filter, (h) Wavelet Soft Thresholding, (i) 1-Level Wavelet Method, (j) 2-Level Wavelet Method, (k) Gaussian.

<table>
<thead>
<tr>
<th>Filtering Method</th>
<th>SNR (in dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R-channel</td>
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<tr>
<td>Original Image</td>
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<td>SNR</td>
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<td>SVD (10)</td>
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<td>Wavelet Soft thresholding</td>
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<td>1-Level Wavelet Method</td>
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<td>2-Level Wavelet Method</td>
<td>17.473</td>
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<tr>
<td>Gaussian Filtering</td>
<td>17.7578</td>
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</table>

Table 2: Experimental results for Simulated Noisy Image.
All the techniques implemented on the cropped image are also applied to a simulated noisy image (shown in Figure 18(a)). The results are tabulated in Table 2. Observation of the SNR values concludes that Gaussian filtering is the ideal one in this case. The filter parameters are derived on empirical basis and the results are tabulated in Table 3. Filter size is chosen as $9 \times 9$ to overcome the blurring effect as we go higher.

<table>
<thead>
<tr>
<th>Filter Window Size</th>
<th>SNR (in dB)</th>
<th>R-channel</th>
<th>G-channel</th>
<th>B-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Image</td>
<td></td>
<td>18.4105</td>
<td>26.91</td>
<td>36.209</td>
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<tr>
<td>5x5</td>
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<td>17.2687</td>
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<td>7x7</td>
<td></td>
<td>18.622</td>
<td>27.1851</td>
<td>37.7693</td>
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<tr>
<td>9x9</td>
<td></td>
<td>19.8853</td>
<td>27.2062</td>
<td>37.8825</td>
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<tr>
<td>11x11</td>
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<td>19.9892</td>
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<td>13x13</td>
<td></td>
<td>20.2221</td>
<td>27.2252</td>
<td>37.965</td>
</tr>
</tbody>
</table>

Table 3: Experimental results for varying filter window size.

Figure 18: Illustrating different filtering methods, (a) Simulated Noisy Image, (b) SNR Filtered, (c) PCA, (d) SVD(10), (e) SVD(50), (f) SVD block, (g) Nearest K-filter, (h) Wavelet Soft Thresholding, (i) 1-Level Wavelet Method, (j) 2-Level Wavelet Method, (k) Gaussian.
Figure 19 illustrates the steps of the algorithm. In particular, we show 1) The Original Image (Figure 19a), 2) The Filtered Image (Figure 19b), and 3) The Modified Halftone Image (Figure 19c). For the convenience of vision, a small part of the “flat” region is zoomed out and shown beside every image. The filtering process, as seen in Figure 19b, minimizes a significant amount of speckle and random noise. The noise added by the halftoning algorithm is taken care by maintaining the pattern according to the sub-cells. Note the difference in noise between Figure 19a and 19c. The impulsive noise that is visible in the original image (Figure 19a) is not present in the modified halftone image (Figure 19c). This demonstrates the efficiency of the proposed algorithm.
Figure 19: (a) Original Image, (b) Filtered Image, and (c) Modified Halftone Image

In Figure 20 the “sky” with a different color tone is considered. A small region of it is zoomed out for viewing purpose. The difference between the zoomed out portion in both Figure 20(a) & Figure 20(b) can be clearly seen under keen observation.
A background “wall” is also demonstrated. The “wall” in Figure 21 has a high contrast compared to the “sky” regions in Figure 19 and 20. Annoying speckle noise is clearly visible in the “wall” as shown in Figure 21(a). This noise is minimized greatly by the proposed algorithm as can be seen in Figure 21(b).
Figure 21: (a) Original Image, (b) Modified Halftone Image

Figure 22, 23 and 24 show some more examples of “sky”. Experimentations showed that in the case of a “sky” region, the noise is mostly present in the cyan channel and hence only the cyan is considered in the post processing block. In the case of a “wall,” noise is found in both the cyan and magenta channels. Therefore, the proposed algorithm is sufficiently intelligent and efficient to minimize the noise present in one or more channels.
Figure 22: (a) Original Image, (b) Modified Halftone Image
Figure 23: (a) Original Image, (b) Modified Halftone Image
Figure 24: (a) Original Image, (b) Modified Halftone Image
CHAPTER 5: CONCLUSIONS AND FUTURE WORK

This paper describes a noise minimization technique capable of making a photo visually pleasing when printed on paper. The proposed algorithm was demonstrated on a database of images with pertinent results. The halftone noise added to the document by the electrophotographic printers is minimized to a great extent. The algorithm is computationally efficient and allows for either hardware or software implementation without disturbing the internal printer pipeline. The minimization of noise is most clearly visible in regions with high contrast and those with low contrast. The results are best when the region of interest has no gradient or has a minimal gradient. The quality of the algorithm is based on human observer. Regions with steeper gradient are not currently handled by our technique. Future work can be done on steeper gradient regions and also on developing a metric to evaluate the quality of the printed photo.
REFERENCES


