

## Digital Halftoning of Images

*Most printers and some display devices are bilevel (black or white) and therefore not capable of reproducing continuous tone pictures. Digital halftoning algorithms transform digital gray scale images into bilevel ones which give the appearance of containing various shades of gray. A halftoning algorithm is presented in which novel concepts are combined resulting in an output image in which moiré patterns are suppressed and, at the same time, the edges are enhanced. Various other artifacts associated with the halftoning process, such as contouring due to coarse quantization or to textural changes, are also absent from the output images in the proposed scheme. The algorithm separates the image into many small clusters which are processed independently and, therefore, it is capable of parallel implementation.*

### 1. Introduction

Many displays and most printing technologies employ bilevel modulation techniques for image reproduction or recording. Examples include offset lithography and related graphics arts recording techniques. These processes employ classical screened halftone dot recording procedures whereby the size and the areal density of recorded dots is varied in direct proportion to the local gray tone values present in the original image. There are, however, many image technologies, such as liquid crystal and gas panel displays, as well as ink jet, wire matrix, and laser scanned electrophotographic printers, which employ bilevel recording techniques in which the recorded dot size is fixed. This constraint has led to the development of several image processing techniques whose major goal has been to eliminate spurious and distracting artifacts which arise during the scanning and digital halftone reproduction of various image types, e.g., continuous tone, graphics, and pre-halftoned images. Some of the techniques employed for reproduction of various types of images with binary printers are described in [1, 2].

The central problem associated with the reproduction of gray tone images on a binary printer/display device can be stated as follows: Given original intensity values  $x(i, j)$ , find a bilevel image  $y(i, j)$  such that  $d(x, y)$  is minimized, where  $d(x, y)$  is a predefined distortion measure. The choice of an appropriate distortion measure is as yet an unsolved problem

[3]. Similarly, the optimization problem is intractable. For these reasons, we have not used such mathematical approaches in this work.

Many digital halftoning algorithms have been developed for use with image presentation on binary printers/displays [1, 2, 4-9]. The most widely known and used algorithms are usually separated into two classes, (1) "ordered dither" and (2) "error diffusion." However, in any specific implementation of digital halftoning algorithms there is a trade-off between computational complexity and perceived image quality.

The use of digital halftoning techniques often leads to a considerable reduction in perceived image quality. Further, measures that are taken to alleviate one or more image degrading factors often lead to an enhancement of another problem. However, the major image quality trade-off with digital halftoning is between achieving an acceptable reproduction of gray tone image values in large areas (i.e., low spatial frequency rendition) and maintaining edge and similar high resolution information.

If, for example, the image raster is divided into  $3 \times 3$  pixel blocks and the dots inside these blocks are arranged according to the gray tone values, then there are only 10 possible

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Figure 1 Original test image.

gray tones in the output image. Increasing the size of the blocks allows more gray tone values to be reproduced. However, as larger digital halftone blocks are used, arranging the dots on the basis of local gray tone values alone reduces image resolution. The resultant image, therefore, appears more defocused. The decrease in resolution is linearly related to the increase in block size unless measures are taken to fill the halftone blocks on the basis of factors other than local gray tone values alone.

The most significant problems associated with digital halftoning of images fall into two major categories. First, there is a loss of resolution, which manifests itself as an inability to reproduce sharp and continuous edges, such as occur in line copy and graphics images. Second, digital halftoning techniques often result in "pattern noise" in the reproduced image. These patterns most often arise from either (1) aliasing errors, which occur during the image scanning and thresholding procedures (moiré patterns), or (2) digital halftone patterns, which result from the application of a particular halftoning algorithm (e.g., ordered dither).

Throughout this paper we assume, without loss of generality, that the resolution of an original gray tone image and its bilevel reproduction are identical. However, resolution of a bilevel rendition of an image must be much higher than that of the original continuous tone image if it is to have the same visual effect. When such "high resolution" printing criteria

are met, one can employ digital halftoning algorithms which interpolate between the neighboring low resolution continuous tone image pixels.

In this paper we introduce a digital halftoning algorithm based upon the use of a nonlinear edge enhancement operator, loosely referred to as a nonlinear Laplacian, *NL*. This operator is combined with an 18-pixel digital halftone block size and a five-level print prioritization method which is derived from an understanding of the mechanisms for, and appearance of, noise in digital halftone reproductions. This algorithm has successfully reproduced general images with good visual quality, in most cases devoid of the major distracting artifacts that have been associated with previous digital halftoning algorithms. Our image quality criteria have been based on subjective evaluations of such factors as edge sharpness and the absence of various artifacts, such as moiré patterns and artificial contours, as explained in detail in Section 2. We intentionally avoided applying a preprocessing recognition scheme that would first separate the image into its various regions (e.g., continuous tone, line copy, halftone) prior to applying special purpose thresholding-halftoning techniques in each region of the image. Our algorithm is inherently capable of efficient parallel implementation, since it separates the image into small areas each of which is processed independently of other areas. Unlike other algorithms with this property, however, it has features which suppress annoying "digital halftone" patterns in continuous tone areas while at the same time retaining good resolution and quality in fine text areas.

A brief description of image quality problems that arise when using bilevel output printers/displays is given in Section 2. In Section 3 we give a brief survey of the more familiar digital halftoning algorithms, while Sections 4–6 describe the novel features associated with our digital halftoning algorithm; the final section contains experimental results and conclusions.

All examples shown in this paper have been printed using a high quality photocomposer (APS5), which is installed in the IBM Thomas J. Watson Research Center. The printing resolution is 200 dots/inch. Figure 1 shows the portion of the IEEE facsimile test chart which was used for the experiments described in this paper. It was intentionally chosen since it contained separate fine text, continuous tone, and halftone image regions. Although the image was scanned at 200 pixels/inch, due to scanner imperfections the quality of the input data that we used is lower than other existing scanned versions at the same resolution.

## 2. Quality problems in digital halftoning

As mentioned above, halftoning techniques in general, and digital halftoning techniques in particular, sacrifice resolu-

tion in order to have a limited gray tone rendition capability. However, the problem associated with arriving at a suitable "design point" for the number of discernable gray tones *versus* resolvable detail in the image is only one of the problems. Other major factors associated with bilevel recording techniques, which require attention if severe degradation of the reproduced images is to be avoided, can be summarized as follows:

#### ● Edge enhancement

Techniques that employ edge enhancement are particularly desirable for improving image quality in areas of high resolution, such as sharp continuous edges (*e.g.*, text characters). In such regions it would be advantageous if the bilevel printing algorithm were not solely dependent upon methods for reproducing adequate gray tones but could also produce a compact set of printed pixels distributed along the edges and boundaries in the image. This need is particularly pronounced in cases where the scanned image contains very thin text or graphics on a very light background. Under such circumstances the recorded gray level values may not be enough for the printing algorithm to justify a solid set of black dots. Of course, this would tend to result in illegible characters and poorly defined graphics. In these cases it is desirable to enhance edges in the image despite the low gray level values. This results in overall increased legibility and enhanced image quality.

#### ● Coarse quantization contouring

This problem arises as a result of the constraints applied in using a halftoning algorithm. In general the digital halftoning algorithms which are used in image reproduction separate the image into small  $N$ -pixel blocks. This approach allows only a limited number ( $N + 1$ ) of gray levels to be reproduced. Under these circumstances false image contours, due to coarse quantization, can ensue if the number  $N$  is not large enough to adequately represent the tonal range of the image. False contours, due to the small value of  $N$ , are very visible in Fig. 2, which shows the reproduction of a low resolution image with  $N = 8$ -pixel blocks. In this image the 8-pixel blocks are arranged diagonally, and the black dots are clustered in the middle of each block. It should be noted that this artifact does not always appear together with the more general problem of textural contouring described below.

#### ● Textural contouring

This particular bilevel image reproduction problem manifests itself in the form of relatively regular patterns of halftone dots distributed throughout the image. The form the patterns take is inherent in the halftone processing algorithm; however, they are particularly annoying when the algorithm forces the dots to be distributed in a periodic pattern in areas of the image which are smooth. In such



Figure 2 Defocused image using 8-pixel blocks.

cases, a slight variation of the gray level in smooth areas often results in the formation of an artificial contour, simply because the dot pattern (texture) has been changed locally. Textural contouring can be observed in Figs. 3 and 4. Experience would lead us to conclude that, among all possible digital halftoning textures that can be generated, the one that most closely resembles analog halftoning (variable size dots arranged in a diagonal grid) is probably the least annoying.

#### ● Moiré patterns

This image degrading process is observed when the "high" spatial frequency at which the image is sampled and a strong spatial frequency component of the original image differ by a relatively small value. Under these circumstances very distracting low frequency beats, or moiré patterns, occur in the output image as a result of the "beating" between these two high frequency components. A theoretical treatment of moiré patterns is presented in [10]. These patterns are typically present, and particularly annoying, when the original scanned image contains areas which are already halftoned. In this case the original halftoning frequency provides the high frequency component which "beats" with the sampling frequency. (Figures 3, 6, 8, and 11 show examples of this moiré phenomenon.)

### 3. Brief survey of existing approaches

Among the various digital halftoning techniques, that known as "ordered dither" is one of the simplest. In this technique



**Figure 3** Test image processed by ordered dither (Bayer's configuration).

the scanned image is thresholded with a set of periodically changing thresholds [1, 2, 4, 5]. The spatial configuration of these thresholds can be chosen so that the resulting digital halftone approximates the diagonal dot pattern of analog halftone recording, which has been found to be most pleasing to the eye. However, this approach often leads to a loss in resolution or detail in the reproduced image. Alternatively, the threshold configuration can be chosen to maximize the high spatial frequency content of the output image [4]; this approach, however, can enhance the textural and moiré pattern defects in the reproduced image. In Fig. 3 we show the bilevel output of our test image using the ordered dither threshold configuration proposed by Bayer [4]. A significant advantage of the ordered dither techniques is that the thresholding can be done in parallel since the threshold values are all pre-assigned.

Another frequently used approach to digital halftoning is known as "error diffusion," originally described in [6]. Reference [8] presents a combination of error diffusion with a correction algorithm for circular dot overlap. The output quality achieved with this approach is higher than that of the ordered dither technique. The underlying principle of error diffusion is to diffuse the errors that occur when thresholding any given image pixel among closely neighboring pixels. A "corrected" intensity value is calculated for any pixel as it is to be processed by adding to its actual intensity value a weighted average of the errors that occurred as a result of the



**Figure 4** Test image processed by error diffusion.

bilevel printing of several of its neighboring pixels. This error-corrected value is compared to a constant threshold to yield a black/white decision, and the error resulting from this latter thresholding operation is then also diffused among the neighboring pixels which are subsequently printed.

Error diffusion results in the dots being more randomly and evenly distributed. As a result of this randomization, the reproduced images are substantially pattern-free. Figure 4 shows the output of the test image using error diffusion with a neighborhood of six pixels; we see that, despite its many advantages, there are distracting artifacts associated with error diffusion. For instance, unless the error neighborhood is sufficiently large, the bilevel image tends to have a "wormy" appearance in smooth areas, and there is also considerable difficulty in the rendition of sharp edges and fine text.

One of the potential disadvantages of using the error diffusion approach is that it requires a serial implementation (*i.e.*, the image pixels are processed in sequence), and the thresholding of each pixel requires significant computation.

Various halftoning schemes [1, 2] similar to but not identical with ordered dither have features that improve overall performance. Among these techniques is a particularly interesting one reported by J. White [7]. This method separates the image into 8-pixel blocks arranged diagonally so that the number (from 0 to 8) of black dots inside each

block is determined by the gray tone of the original image. These dots are arranged in clustering order to imitate the effect of analog halftoning. The resulting image is a "defocused," or low resolution, image in the sense that high spatial frequency information is lost. Some dither can be added to the 8-pixel blocks in order to increase the apparent capability of the technique for reproducing gray tone values from 9 to 33 levels. The high frequency detail in this defocused image can be improved, as shown in [7], by further processing of the image as follows:

A Laplacian operator is applied to the image, and the resultant image is then separated into three pixel classes, namely, those with high, those with intermediate, and those with low values of the Laplacian. This tri-level Laplacian operation is basically an edge extraction process, and the resultant image contains most of the high frequency details of the original image. The high (low) values of this Laplacian focused image are then used to override, or force, the thresholding decisions in the defocused image so as to print white (black) pixels. The output of the algorithm is basically the superposition of two images, namely, a focused and a defocused image, in the sense that the pixels with high (low) values of the Laplacian have their gray scale or defocused thresholding decisions overridden in favor of white (black).

In order to reduce the possibility of the occurrence or enhancement of moiré patterns, this "focused-defocused" image processing algorithm keeps, wherever possible, the number of black (white) pixels in each block equal to that in the defocused image. However, this condition may not be satisfied in those circumstances where there is not a sufficient number of black (white) pixels inside an 8-pixel block of the defocused image to both force the high (low) Laplacian pixels and also maintain the local gray tone value. Finally, for additional moiré pattern suppression,  $2 \times 2$  clusters of exclusively black or white dots are not allowed to occur.

The binary image processing and halftoning algorithm presented in this paper is closely related to the work reported in [7]. However, our algorithm has additional features that result in improved overall image quality. These features are described in the following sections together with a comparison with those existing in [7].

#### 4. 18-pixel neighborhoods

In order that processed binary images be capable of yielding a very good rendition of slowly varying tonal areas in the original image, the image is separated into blocks of pixels which are each processed independently. These pixel blocks are distributed along diagonal lines in the image. The number of dots to be printed black within each of these pixel blocks is dependent upon the gray level values present within

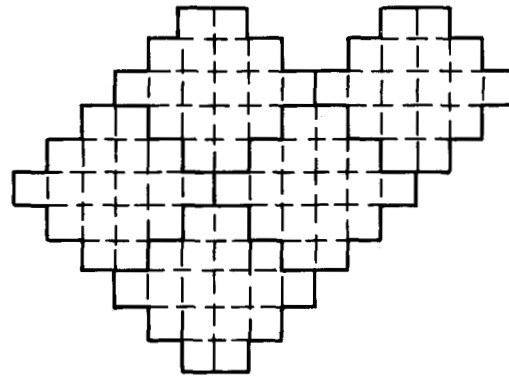


Figure 5 Separation of raster into 18-pixel blocks.

the identical area of the original image. The printed dots are clustered around the center of each block so that the output takes on an appearance similar to that associated with the electronic screening or analog halftoning technique.

In [7], the pixel blocks are arranged so that each block contains 8 pixels. The total number of gray levels in the original image that can be reproduced by this size pixel block is therefore 9. Dither added to the (higher level) gray values of the 8-pixel blocks (with period of 2 in both the horizontal and vertical directions) gives the appearance of a 33-level (i.e.,  $4 \times 8 + 1$ ) pseudo-gray tone reproduction. Without adding dither, false contours in the image (due to the limited number of gray tones) are very obvious and distracting. However, although dither improves the appearance of the output through its tendency to delocalize false contours, textural contours are often visible because of the big difference in the shapes of the 9 possible configurations in each 8-pixel block. Figure 2 shows an example of "defocused" image output without additive dither.

It is for the above reasons that we chose to divide the image up into larger pixel blocks, each block containing 18 pixels, as shown in Fig. 5. It is interesting to note that the area of the image cannot be divided into space-filling pixel blocks arranged in diagonal order which contain from 9 to 17 pixels, hence our choice of 18 pixels per block. It should be noted also that this statement is not contrary to the work demonstrated in [2, Fig. 18], where 17 pixels in a block are addressed for the purpose of displaying gray tones with a binary printer. In this example the printable pixels in each block do not quite cover all the area of the image because a single white dot cannot be addressed and hence always remains unprocessed, even for totally black regions in the original image.

Employing diagonally ordered 18-pixel blocks results in an ability to reproduce 19 gray tones, and the resulting binary

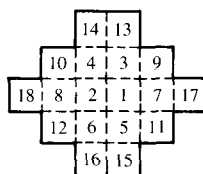


Figure 6 Defocused image using 18-pixel blocks.



Figure 7 Order of printing black dots inside a block.

images exhibit very acceptable quality. The advantage of using large pixel blocks is the elimination of false contours. Neighboring gray tone values are sufficiently close to each other that the digitization process does not result in the generation of false contours. Adding dither to the 18-pixel blocks further delocalizes and completely eliminates false contours from the reproduced image.

At resolutions of 400 pixels/inch the above approach results in excellent renditions of the smooth areas of images. (This is shown in Fig. 13, to which we refer later.) However, at a printing resolution of 200 pixels/inch the 18-pixel blocks are very visible but they have a pleasing appearance.

The reason that large pixel blocks are not used in the schemes reported in the literature is the unacceptable loss of resolution that they produce in the "defocused image." In our approach, however, this problem is solved by using nonlinear edge enhancement (explained in Section 5).

The binary printing algorithm specifies that, in smooth areas of the image, in order to arrive at the required gray tone value in the printed image, the pixels in each 18-pixel block are printed in a prespecified order, as given in Fig. 6. Figure 7 shows our test image separated into 18-pixel blocks and thresholded as explained above in "defocused" form.

It should be noted that this process of finding the average gray level inside each 18-pixel block, and then filling the block in a prespecified order until the correct gray tone value is achieved, is not equivalent to using an image processing technique in which 18 different threshold values are assigned to each pixel inside the block. The latter technique [2], a form of ordered dither, often results in a reproduction of some of the high frequency information in the image, because local intensity variations inside an 18-pixel block can be detected. For example, if a thin dark character stroke has very low intensity values, chances are that it will be thresholded black for most (but not all) pixels, while if the background is very light it will be thresholded white for most of the corresponding pixels. However, this approach results in imperfect rendition of the high resolution detail in the image, and we found it preferable to use more sophisticated techniques in order to reproduce the high resolution detail in the image. These techniques are explained in the following sections.

## 5. Nonlinear edge enhancement

As is understood from the above, one of the most important requirements for a high quality general purpose digital halftoning algorithm is its ability to reproduce sharp, solid, and smooth edges. This must hold true for both well-defined objects and for the text areas of images. A powerful way of achieving this objective, which is at the same time pleasing to the eye, is to print a stripe of black dots along the edges of the darker object together with a neighboring stripe of white dots around the lighter objects. For this purpose, it is necessary to use some operator that detects edges so that they can be processed independently.

One of the most widely used image processing techniques for edge location and enhancement is to operate on the image with the Laplacian operator. For each pixel of a sampled image, application of the Laplacian creates the difference between the intensity value at that pixel and an average intensity in a neighborhood surrounding the pixel. The Laplacian, a form of high pass filtering, is a linear operator.

Adding the values of the Laplacian to the original image yields an image with enhanced high frequency components. This means, of course, that not only are the edges in the original image enhanced but any high frequency patterns, including noise and texture, are also enhanced. It should also be noted that although moiré patterns are essentially low

frequency entities, they are also enhanced by the application of the Laplacian, as shown in the left column of Fig. 8. The reason for this result is that the Laplacian operator produces high values or enhanced edges at the positions of the halftone dots in the original image. This is equivalent to an increase of the amplitude of the high frequency components in the halftone information. Since the sampling frequency of the image remains the same, this results in an increase in the amplitude or intensity of the detected moiré beat. In the remainder of this section we describe a nonlinear edge enhancement technique which avoids many of these problems.

In order to obtain a relatively high quality reproduction of the image with a binary printing process it is necessary to add the high resolution detail in the original image to the bilevel gray tone output described above. A very convenient way to do this is to partially override the gray level ordering technique, for printing the black dots inside each 18-pixel block, in such a manner that we retain information about image detail within each block. In [7] the operator used to achieve this function is the linear Laplacian. The pixels are separated into three priority classes each of which can partially override the preassigned order. This approach has proven to be an excellent way to achieve edge emphasis, but, as explained above, moiré patterns are also enhanced by this technique.

In order to achieve edge enhancement while at the same time suppressing moiré patterns, we have found it advantageous to apply a new nonlinear operator,  $NL$ , to the image. The operator  $NL$  is derived by considering the pixel values in a  $3 \times 3$  window centered around each pixel (see Fig. 9) as follows. Using the notation of Fig. 9 we first define the quantities

$$A = x - \frac{1}{4}(a + c + f + h),$$

$$B = x - \frac{1}{4}(b + d + e + g).$$

The nonlinear Laplacian that we apply to the image is then

$$NL = \begin{cases} = \min(|A|, |B|) & \text{if } A > 0 \text{ and } B > 0, \\ = 0 & \text{if } AB < 0, \\ = -\min(|A|, |B|) & \text{if } A < 0 \text{ and } B < 0. \end{cases}$$

For comparison, the linear Laplacian  $L$  would be

$$L = \frac{1}{2}(A + B)$$

defined in a  $3 \times 3$  window around the pixel  $x$  (of course, a linear Laplacian defined on a bigger neighborhood can be preferable, especially for oversampled images).

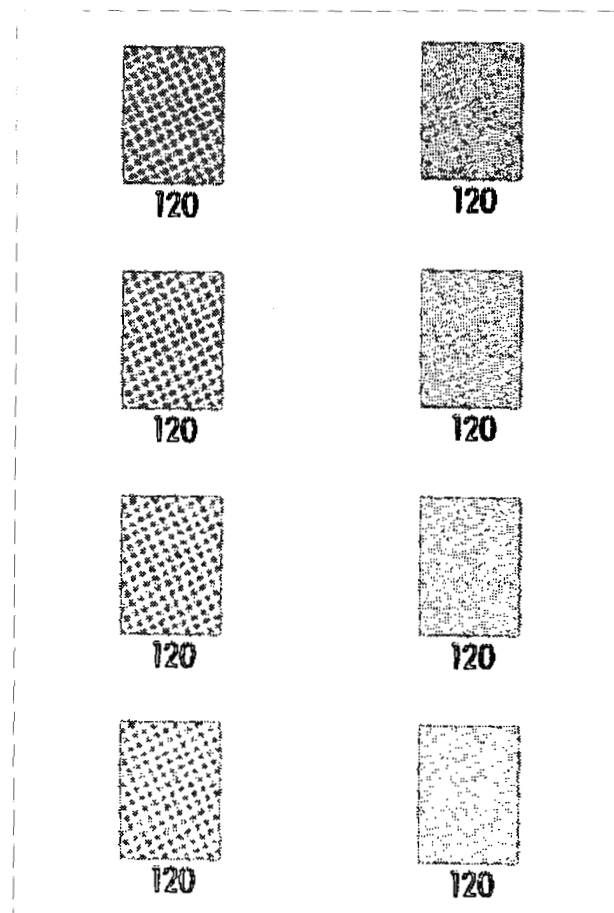
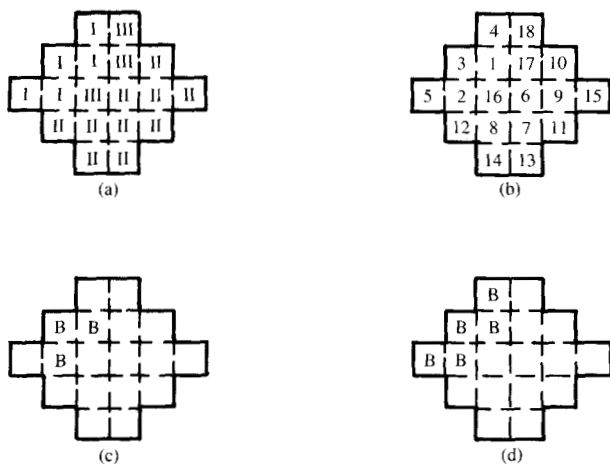


Figure 8 Demonstration of edge enhancement and moiré pattern suppression using "nonlinear Laplacian" operator.

|     |     |     |
|-----|-----|-----|
| $a$ | $b$ | $c$ |
| $d$ | $x$ | $e$ |
| $f$ | $g$ | $h$ |

Figure 9 Pixel notation for a  $3 \times 3$  window.

Therefore, all pixels having a high value of  $NL$  will also have a high value of  $L$ . The inverse is not true, however. It should be noted that if the value of the central pixel  $x$  is approximately equal to the average of its four neighbors in the horizontal, the vertical, or the diagonal direction, then the resultant magnitude of  $NL$  will be small, even though the magnitude of  $L$  may be high. This operator is found to be very helpful in reducing (but not totally eliminating) moiré patterns when the sampling frequency and the original halftone frequency are very close to each other. The reason



**Figure 10** Example of pixel order modification due to the priority classes.

for this property is that, in regions such as halftoned areas which are highly susceptible to the generation of moiré beats, the checkerboard configuration of light and dark pixels results in a value of  $NL$  which is zero due to the large directional dependence of the values of  $A$  and  $B$ . The nonlinear Laplacian, therefore, tends not to enhance moiré beats in these areas. However, the value  $NL$  approximates that of the linear Laplacian in other regions of the image. It should, however, be noted that the value of the linear Laplacian,  $L$ , will not tend to be zero in halftoned regions of the image.

In Fig. 8, we demonstrate the moiré suppression that can result from using the nonlinear Laplacian  $NL$  as the edge enhancement algorithm instead of the Laplacian  $L$ . The left four image segments are enlarged versions of the  $L$  function thresholded with four different thresholds, while the right four image segments are the corresponding images using the  $NL$  function. The image segment chosen is an original analog halftone. The annoying moiré patterns present in the left column of images are suppressed in those in the right column.

Of course, our definition of  $NL$  above is not unique, and according to the spatial frequencies of both the halftone and image sampling frequencies, one might obtain better results for moiré suppression by defining  $NL$  to be the minimum of more terms. For instance,  $NL$  could also take into account a larger number of pixels situated at greater distances from the central pixel. In all circumstances the use of  $NL$  tends to reduce moiré beats while also resulting in edge enhancement in non-halftoned regions of the image.

Following the application of our nonlinear operator,  $NL$ , the values of the nonlinear operator are used to define three

priority classes, into which all pixels are divided in a manner similar to that described in [7]. The priority class to which each pixel is assigned is used to partially override the printing order assigned on the basis of gray level alone. The priority classes are assigned as follows: Class I contains pixels in which  $NL < -T$ , where  $T$  is a constant threshold; class II contains pixels which satisfy the condition that  $-T \leq NL \leq T$ , and class III contains those pixels for which  $NL > T$ .

There are two ways in which the priority classes can be used to determine the order in which the pixels in the 18-pixel blocks are printed: In the first approach the pixels are printed first by priority classes I to III, and in each priority class the pixels are printed according to the relative order assigned by the "gray tone" algorithm. In Fig. 10(a) we show an example of this approach to improving image resolution in which the number of pixels inside the 18-pixel block that fall into each priority class is assumed to be 5, 10, and 3 pixels, respectively. Application of the above criteria then results in the order in which the pixels are printed being modified from that derived from the gray level values alone, as shown in Fig. 7, to that shown in Fig. 10(b). If the gray level data require that three pixels be printed inside the 18-pixel block, then the configuration of the printed pixels will be as shown in Fig. 10(c).

In the second approach to using the priority classification to determine the order of printing for the 18 pixels in a block, all pixels in class I are printed black and all pixels in class III are printed white, regardless of the number of black or white pixels that are required in the 18-pixel block in order to yield the gray tone values measured in the original image. If after employing this black/white override feature to pixels in classes I and III there is still a need to print more pixels in order to reach the required gray tone value, then pixels in class II are printed according to their relative order in the gray tone algorithm. An example of this approach is shown in Fig. 10(d).

The former method has the disadvantage that it eliminates or degrades fine lines in text whenever the average gray level in an area is so low that it results in the printing of too few black dots to give a solid appearance to the text.

This problem is solved if one follows the second approach. Under these circumstances, however, moiré patterns are enhanced, as shown in Fig. 11, which shows the type of results that accrue from using the features of our algorithm described up to this point.

For these reasons we have developed an additional improvement to the algorithm, as explained in the following section.

## 6. Priority assignments

In order to further suppress moiré patterns, while at the same time retaining a good solid rendition of fine text and superior rendition of smooth areas, we have applied the following algorithmic technique: Some of the pixels, which according to the above classification fall into either the highest or lowest priority classification, have their priority black/white print override classification reduced according to a strategy described later in this section. The basic result of this additional strategy is to increase the number of priority classes which ensue from the use of the nonlinear Laplacian operator from three to five. In this new priority classification approach, the intermediate priority class III plays the same role as class II in the earlier method described above. The decisions as to how to print each pixel in the 18-pixel blocks are then made using the following logic:

1. The highest (class I) and lowest (class V) priority pixels are always printed with black and white dots, respectively, even if this overrides the computed total number of black dots necessary to accurately print the measured gray tone value.
2. The remaining three priority classes modify the original gray tone prespecified printing order for the 18 pixels so that every pixel in a higher priority class is considered for printing before any consideration is given to pixels of lower priority classes. The process of printing black dots is continued until the correct number of black dots required to attain the measured gray tone value is reached.

The reduction of the priority class of certain pixels is directly aimed at suppressing moiré beats in the printed image. Those pixels whose priority is reduced from class I to class II or from class V to class IV are those that are arranged in spatial configurations which are most often associated with the appearance of moiré beats in the image. These are the high-*NL* pixels which are clustered in blocks of dimension either  $2 \times 2$  or  $2 \times 1$ .

The reason that clusters of pixels with high valued Laplacians are more likely to occur in regions associated with moiré patterns than in regions associated with real edge information is that real edges have a linear spatial configuration (along the edge), while aliasing tends to create dispersed or clustered high Laplacian pixels. Therefore, sharp elongated edges in the image create a strip of high Laplacian values with a width of one or two pixels and a relatively large length. However, moiré beats, between an original halftone frequency and a sampling frequency, which have been enhanced with a Laplacian operator, usually result in a set of small clusters.

It should be noted that the corresponding method for suppressing moiré beats, as described in [7], is based upon



Figure 11 Test image processed using three priority classes.

completely disregarding either high or low Laplacian values when they are associated with pixel clusters which entirely cover a  $2 \times 2$  block of pixels. This method is based upon the spatial configuration of pixels and the values of their Laplacians rather than their "nonlinear Laplacians," as described above. If all pixels in a  $2 \times 2$  block have high Laplacian values, then they will be treated as if they did not have high Laplacian values. This technique definitely tends to suppress moiré beats in the printed output; however, there is a high risk that in totally removing the priority assignment real edge information will be lost and result in an otherwise unacceptable reduction in the quality of the image. The loss in quality is particularly detrimental in those cases where the pixels actually belong to the real edges of a text character.

The novelty of the binary printing algorithm described in this paper is that instead of disregarding high or low "nonlinear Laplacian" values if they are associated with pixel clusters, we simply reduce the priority of these pixels and in doing so we retain some of the necessary edge information. Pixels inside high *NL* value clusters will not have a forced black/white override but will simply have a priority higher than pixels with a low magnitude of the nonlinear Laplacian, *NL*. As described earlier, the use of the nonlinear Laplacian alone tends to deemphasize the appearance of moiré patterns. However, this final step of reducing the priority associated with pixels in high *NL* clusters has the significant effect that it almost entirely suppresses the appearance of



Figure 12 Test image processed using five priority classes.

moiré patterns while minimizing image quality degradation in the neighborhood of edges and general text.

In Fig. 12 we show the final output image processed by our scheme using all five priority classes.

## 7. Results and conclusions

Optimum selection of a general purpose digital halftoning algorithm is often difficult. Several algorithms have been described in the literature which perform satisfactorily under particular well-defined conditions. For example, error-diffusion-like schemes have an excellent capability of suppressing moiré patterns and are therefore very appropriate for use when processing original halftoned images. However, the use of these algorithms is inappropriate if the original image consists primarily of text and line copy images.

Likewise, ordered dither, using either Bayer's or the "supercircle" threshold selection techniques, provides a very simple method of digital halftoning which is also suitable for use with certain kinds of pictures. While these techniques were also seen to have disadvantages, it should be noted that at sufficiently high printing resolution adequate results can often be obtained with this method.

For general purpose high quality digital halftoning, however, each of the available algorithmic approaches has been demonstrated to possess drawbacks. This paper has delineated

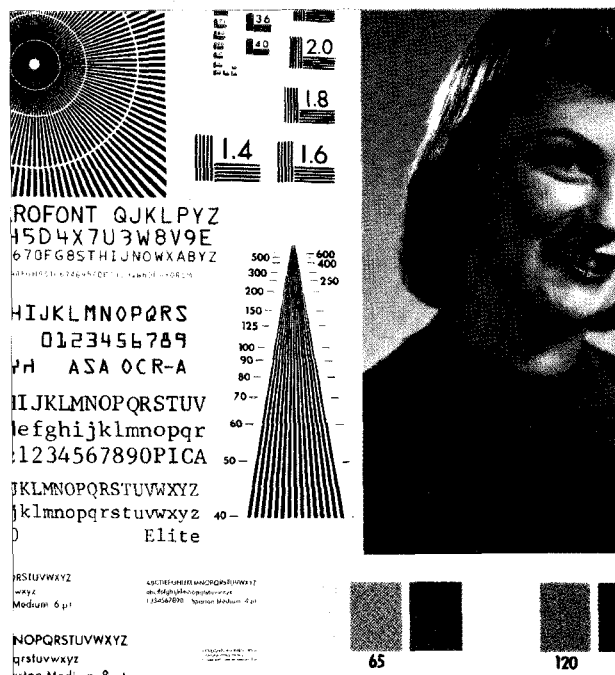


Figure 13 Test image processed at twice the scanned resolution.

these image-degrading factors and presented an image-processing algorithm which contains many features that are required in a robust, high quality digital halftoning algorithm. If a high implementation complexity is unacceptable in a particular application, it is possible to use just one or more of the features of this algorithm in order to improve the output quality and still retain the capability for a parallel hardware implementation.

The algorithm we have presented is also suitable for use in situations where the resolution of the printer is higher than that of the scanned image. As might be expected the image quality in such cases is improved even further and in many cases can be rated as excellent. Figure 13 shows the output obtained using our printing algorithm with a printing resolution twice that of the original scanned image. For the determination of this example each pixel of the original scanned image was replaced by a  $2 \times 2$  block of pixels with all the same gray tone values. This example is indicative of the quality that can be obtained using our entire digital halftoning algorithm which, of course, includes a basic 18-pixel digital halftone block. However, if the image had been calculated and printed with an algorithm which used 8-pixel digital halftone blocks, the image would have contained distinct false contours.

In conclusion we have described a digital halftoning algorithm which is amenable to parallel implementation

while at the same time minimizing virtually all of the image-degrading artifacts which have been shown to occur with the use of other state of the art digital halftoning algorithms.

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