A Survey of Electronic Techniques for Pictorial Image Reproduction

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Abstract—**This paper is a tradeoff study of image processing algorithms that can be used to transform continuous tone and halftone pictorial image input into spatially encoded representations compatible with binary output processes. A large percentage of the electronic output marking processes utilize a binary mode of operation. The history and rationale for this are reviewed and thus the economic justification for the tradeoff is presented.**

A set of image quality and processing complexity metrics are then defined. Next, a set of algorithms including fixed and adaptive thresholding, orthographic pictorial fonts, electronic screening, ordered dither, and error diffusion are defined and evaluated relative to their ability to reproduce *continuous tone* input. Finally, these algorithms, along with random nucleated halftoning, the alias reducing image enhancement system (ARIES), and a new algorithm, selective halftone rescreening (SHARE), are defined and evaluated as to their ability to reproduce *halftone pictorial* input.

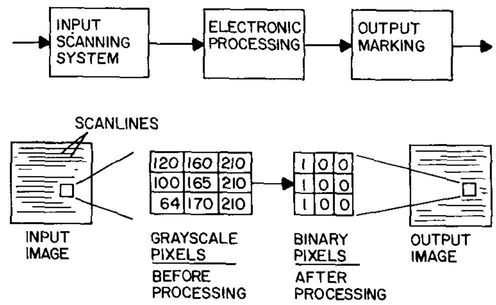

Fig. 1. Functional block diagram of image processing system mapping continuous tone or halftone scanned input into a "spatially encoded" gray scale rendition of the input using binary (two-tone) pixels.

I. INTRODUCTION

THIS paper deals with the "encoding" of pictorial imagery for reproduction on binary display/printing systems. The input imagery is restricted to be one of two classes of pictorial input, *continuous tone* and *halftone* input. Continuous tone imagery is that class of imagery containing multiple gray levels with no perceptible quantization to them. Example images in this class include natural scenes as viewed through a TV camera or a photograph scanned in a facsimile transmitter. On the other hand, halftone pictorial input is composed ideally of only two gray levels, black and white. The halftone image appears to have multiple gray levels because the microstructure (halftone dots) varies the average area coverage, thereby providing the appearance of continuous shades of gray.

As a further restriction, the pictorial "encoding" is restricted to binary output devices such as plasma display panels, laser xerography, lithography, or ink jet printers. This restriction is motivated by the dominant role these marking processes play in pictorial communication systems.

From the above restrictions, therefore, one can model the problem addressed in the following report as shown in Fig. 1. The input is restricted to be a continuous tone or halftone pictorial input (excluding, therefore, line copy or graphical input). Furthermore, the output is a printed or displayed pictorial, composed fundamentally of binary pixels.

The problem, therefore, is to develop an algorithm to process pictorial input so it may be represented with high fidelity on a binary output array. The output is thus an encoding of the input gray scale information for an electronic scanning system. Such systems are of ever increasing importance since they are the key to *image manipulation, storage, and communication*; and, therefore, the problem studied below is motivated by the desire to build electronic scanning systems capable of pictorial reproduction.

Scanning system concepts and technologies are well documented in the literature [1]-[5]. For that reason, no review is presented here. The following focuses attention on the "processing" function in the system model shown in Fig. 1. To facilitate discussing the processing of a scanned pictorial image, the following notation will be used throughout.

M	the number of pixels per scan line in the image
N	the number of scan lines in an image
$O(x,y)$	the output value (black = 0, white = 1) of a processed pixel
$P(x,y)$	the gray scale value of a pictorial image at location (x,y).

A. Binary Marking/Display Technologies

A review of the mass reproduction technologies for pictorial imagery would include a review of relief printing (letter press), intaglio (gravure), and lithography. Although the history of these technologies dates back to the 8th century, one will find that the most efficient mode for their operation was binary, i.e., they generate two-tone microstructure composed of regions with or without ink. Today, virtually all printed pictorials are truly composed of microstructure which is "binary;" either ink or paper is located at a given spot. Even full color pictorials in magazines, etc., are essentially composed of four inks operating in this binary mode.

A large number of printing and display techniques have been developed in the 20th century, exploiting the advances

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being made in photoconductors and electronics. Included among these techniques are cathode ray tube displays, xerography, stylus printing, plasma display panels, and ink-jet printing. These techniques do not conveniently fall into the three classical printing categories developed above, but they do represent commercially viable methods of printing or displaying pictorial imagery. Historical or technical discussions of the details and variants of these "new" methods will not be provided, since these technologies are well documented in the literature. It is sufficient simply to examine the dominant modes of their operation and note that they are frequently driven as binary output processes. Furthermore, if one couples computers, word processors, and other electronic information systems into these printing technologies, then it is even more likely that cost effective system design will motivate a binary printing mode.

B. Summary

The dominant theme throughout this review is the utilization of *binary printing and display processes* for economic image reproduction and this binary output philosophy is assumed throughout the remainder of this paper. Hence, grayscale imagery will be reproduced with spatially distributed, black and white picture elements. Various gray levels are measurable in the microstructure, but the motivating concept is that of attempting to place black and white picture elements on the page.

Although lithography, xerography, etc., have different microstructural characteristics, the algorithms investigated below are compatible in varying degrees with all of them. The optimization of the algorithms for the different marking processes, however, will not be reviewed.

The following sections will define more explicitly the categories of imagery under study. In addition, a set of image quality metrics will be defined to assist in evaluating the alternative processing algorithms that may be used for reproduction. Subsequently, a set of processes which enable reproduction of a continuous tone input will be analyzed along with their characteristic results. Next, a set of algorithms appropriate for halftone pictorial reproduction will be analyzed and their results will also be characterized. Finally, some conclusions will be drawn with regard to the efficacy of the processes analyzed.

II. IMAGE CATEGORIES

A. Continuous Tone Imagery

A continuous tone image is one which contains an apparent continuum of gray levels. Some scenes, when viewed by humans, may require more than 256 discrete gray levels to give the appearance of a continuum of gray levels from one shade to another. Continuous tone images are exemplified by television (CRT) images, photographic images, and real world scenes viewed by a Viticon camera. Continuous tone imagery, therefore, is composed of "natural" images and the approximations to them.

B. Halftone Imagery

As an approximation to continuous tone images, the printing industry developed in the mid-19th century a technique for approximating the continuum of gray scales available in "natural imagery." There were, as there are now, three dominant printing technologies—lithography, letterpress, and gravure; and all of these produced a page via the presence or absence of opaque ink on a page. In order to represent "natural" scenes, therefore, high frequency line and dot structures were printed which have their width varied spatially throughout the scene to yield a varying percent reflectance across the page. The end result is that when such images are viewed at normal viewing distances (about 14 in) the dot or line structure is not noticeable, but the varying average gray level produces an approximation to a natural scene.

All pictorial imagery in magazines, books, and other mass printed media are represented via halftone technologies. This technology creates an extremely large number of pictorial images daily.

C. Line Copy Imagery

Line copy imagery is imagery composed of alphanumeric characters, straight line segments, and solid areas of a single gray level. The image is essentially made up of only two gray levels; but, unlike halftones, only lines and dots of visible size are created. Except for their halftone pictorials, magazines, books, maps, etc., are two-tone line copy.

Fig. 2 shows examples of the three classes of imagery: continuous tone, halftone, and line copy. The figure exposes the microstructural differences between the three classes of imagery as defined above. (This article is reproduced via lithography; hence, the continuous tone pictorial blowup is truly a graphic, as may be seen under a loop.)

III. IMAGE QUALITY METRICS

This review focuses attention on the binary spatial encoding of pictorial imagery, and to this end a subset of the large class of image quality metrics may be utilized [3], [6]-[15]. Three classes of metrics will be utilized below to compare the various algorithms, and although quantitative descriptors may be utilized, the review below will present a *qualitative* evaluation for each of the three metrics chosen. This will avoid presentation of volumes of psychophysical test results and the arbitrary definition of application classes and system scan resolutions for these processing algorithms. Utilizing the three metrics below, one may rank order the algorithms of interest for his specific application.

Subsequently, specific system parameters may be optimized utilizing psychophysical experimentation for a specific application.

A. Low Frequency Rendition

The first metric to be utilized for evaluation will address the "accuracy" with which the process can reproduce the low frequency pictorial information in the input. The key issue in most all systems is that the output process is seldom capable

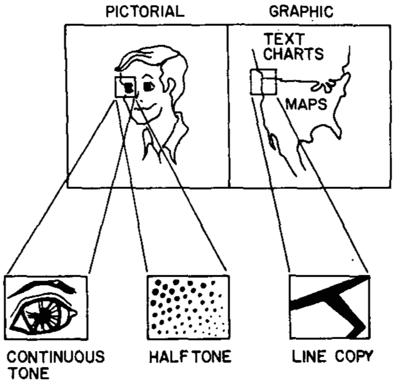


Fig. 2. Display of image categories with a view of the microstructure in each.

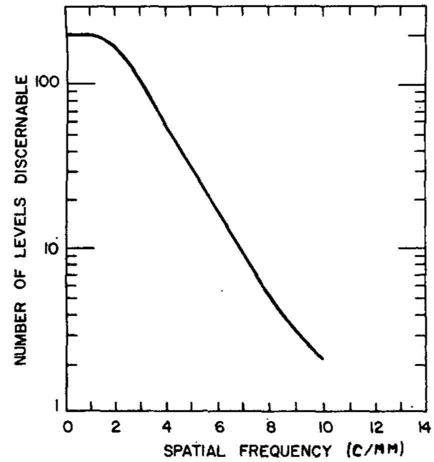


Fig. 3. Plot of the number of discernible gray levels versus the spatial frequency of the input (from [16]).

of producing the complete tone scale required for the 1:1 reproduction of the input. This is predominantly an issue of dynamic range requiring a detailed understanding of the output process, especially the noise properties [7], [9], [12], [15]. This review concerns itself only with binary output processes and, therefore, the following algorithms will be evaluated relative to their capability of delivering a *complete gray scale* at normal viewing distances of 12-14 in. The tone reproduction curve capabilities will be evaluated along with the likelihood of having problems printing the particular "gray scale code."

It will be an important assumption of the following analyses that output marking processes capable of highly reliable fine microstructural detail will be more expensive than those utilizing spatially larger atomic elements to manifest gray scale. In its simplest form, this concept simply means that, for example, processing algorithms demanding high resolution output scanning will be considered more expensive and less desirable than those capable of utilizing a lower resolution of output scanning process.

B. High Frequency Rendition

This metric simply refers to the capability of a particular process to reproduce fine detail. The ability of a given algorithm to reproduce 150 μm, 50 percent contrast modulation input as a similar contrast fine line of equal width makes that procedure superior to one which reproduces such fine detail with lesser or no output contrast. In this sense, therefore, the MTF capabilities of the given pictorial process can be thought of as a measure of its image quality [8], [12].

Clearly, a multiplicity of imaging system metrics have been developed around the MTF figure of merit, but, as above, we will not make quantitative calculations for all configurations of all of the algorithms presented below. A qualitative comparison, however, based on the detail reproduction capabilities, including edge blur, of each algorithm will be provided.

It is important to remember that most practical algorithms for visual display take advantage of the fact that the eye is more capable of gray level discrimination with low frequency detail. As the visual angle of the imaginal detail decreases, the detail becomes more difficult to detect and the number of discernible gray levels diminishes. Fig. 3 is an attempt to plot this relationship for a specific set of conditions [16], [17].

C. Processing Artifact

This category contains those visual details in the output image that are not part of the original image, but are the result of the image processing algorithm. To maintain the generality of this review, we will not attend to the specific artifacts of the marking processes. This review attends to the artifacts created by the signal processing done prior to marking.

There are three main types of artifacts created by the algorithms reviewed below. The first artifact is the false detail known as moiré. This is created most often by the "beating" between two relatively high frequency processes resulting in a signal whose spatial frequency is low enough to be seen by the viewer [18]-[20].

The next class of artifacts is simply that known as *"false contours."* These contours are the result of gray scale quantization steps which are sufficiently large to create a visible contour when the input image is truly a smooth, gradual variation from one to the other [10], [21].

The third class of artifacts is similar to the second, but it is caused by artificial changes in the image texture. By definition of the fact that the output marking process is fundamentally a binary process, gray scale information must be encoded via a pattern over some area which results in an average percent reflectance equivalent to a desired output gray level. Such output patterns can create a variety of textures. For some algorithms, when the input gray levels vary slowly and smoothly, the output will generate an artificial boundary between the textural patterns for one gray level and the textural patterns for the next gray level. Such false textural *contours* are clearly an imaginal artifact [22], [23].

The above image quality metrics have been selected to provide the greatest level of discrimination for the algorithms reviewed below, and as noted above, they will be utilized in a qualitative manner. Furthermore, these metrics will be applied to the algorithms utilized for continuous tone reproduction as well as those utilized for halftone pictorial input.

IV. PROCESSING COMPLEXITY

Another metric of value when comparing and evaluating processing algorithms is the complexity required to implement them. The algorithms below are relatively simple to implement, but the primary issue when applying these algorithms is the desire to perform them in real time; and therefore, the relatively small computational difference between the following algorithms is in fact a worthy measure.

All the algorithms lend themselves to either software or dedicated hardware implementation, depending upon the bandwidths of the hardware selected as well as the application. Furthermore, should a specific algorithm have application in a high volume product or space/power constrained environment, then the opportunity for LSI is availed by any of these algorithms.

To avoid detailed reviews of circuit designs for each of the algorithms reviewed below, a single measure of implementational complexity has been selected to provide interalgorithm comparisons. The measure utilized below is simply the context required by each of the algorithms. The context for each algorithm is defined to be that size of memory required for the determination of the color of a given output picture element. If an algorithm, such as single level thresholding, simply makes a binary decision given the gray level of the input picture element, then the context is one pixel. On the other hand, if a local average is required prior to establishing the "color" of the output picture element, then the number of picture elements in this local average computation will be referred to as *the context*.

The above measure does not address the fine details of the implementation, such as the number of multiplications, the ability to use recursive filtering structures, etc. The goal is to attend to the relative merits of an algorithm's capabilities and not to focus attention on the cleverness applied to its implementation. Having developed a valuable algorithm, one often finds a series of perspicacious implementation strategies that may slightly improve the cost performance of the algorithm but do not alter the fundamental characteristics.

V. CONTINUOUS TONE PICTORIAL REPRODUCTION

This section reviews six electronic techniques for reproducing continuous tone pictorial input. For each processing technique, the characteristic results will be evaluated utilizing the image quality metrics and complexity measure described above. A summary comparison is presented in Section V-G.

A. Globally Fixed Level Thresholding

1) *Definition:* The basic concept of globally fixed level thresholding is simply the comparison of the gray level for an input sample from a continuous tone image with a fixed constant. If the gray level is above such a value, then the result will be assumed to be white. Otherwise it is black. Fig. 4 shows the schematic diagram for a globally fixed level thresholding process with input pixel $p(x,y)$ and output $o(x,y)$.

The threshold is selected prior to processing a given image, and the output marking process simply generates black and white pixels, depending upon the gray level of the input image at that location. A number of methods exist for selecting the fixed threshold [25], but once selected, it is the same for all pixels in the image, i.e., globally fixed.

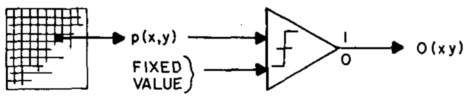


Fig. 4. Signal processing flow diagram for globally fixed level thresholding.

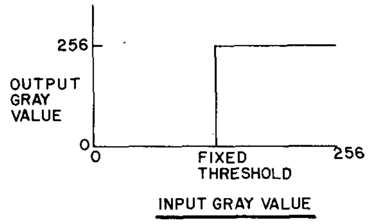


Fig. 5. Tone reproduction curve (TRC) for globally fixed level thresholding.

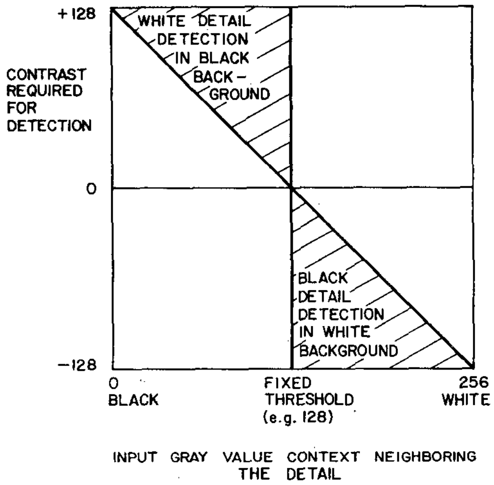


Fig. 6. Contrast required for detail detection versus "background" gray value for fixed level thresholding.

2) *Evaluation:* The tone scale reproduction capability of fixed level thresholding is very limited. As shown in Fig. 5, one has an effectively infinite *gamma* tone reproduction curve with the end result that only edge detail is manifest in the output image. The two ends of the gray scale are reproduced accurately, but the remainder is severely distorted.

The detail rendition capabilities of fixed level thresholding depend upon the gray level of the detail being analyzed. Fine detail which has gray level swings above and below the value of the threshold will be "seen." Hence, midrange fine detail is very often reproduced with a fixed level threshold in that region. On the other hand, highlight (the lightest end of the input tone scale) and shadow (the darkest end of the input tone scale) detail are seldom if ever seen. Overall, the detail rendition is limited to a very small range, but very high frequency capabilities are enabled in that range. Detail the size of an input pixel can be detected. See Fig. 6.

Two of the three dominant classes of imaginable artifact are created by fixed level thresholding. First, false contours are made visible as black/white boundaries in the output from a fixed level thresholding process. However, there is no moiré generated by the process, with the exception of "sampling moiré," which is caused by an insufficient input sampling rate. Fixed level thresholding will make sampling moiré most visible since it enables a broad spectrum of detail to be visible (provided there are contrast swings about the fixed level). However, this problem is less of an issue for continuous tone input, and a more complete description of sampling moiré is provided for halftone input in Section VI.

The major artifact associated with fixed level thresholding is the "amplification" of low noise levels which are riding on gray levels near the threshold value. Such noise may be caused by practical limits to signal-to-noise in the scanning systems, but the end result is a visible artifact, not a part of the input scene. It is not uncommon to see "streaks" in an output image where a slowly varying gray scale input makes the transition from white to black. Small gray scale differences are amplified by the thresholding process.

The processing complexity of this algorithm is clearly the minimum of all algorithms in this review. Only one pixel of context is required for the above computations. The selection of the threshold value is not considered for this study.

B. Locally Adaptive Thresholding

In a sense, all of the remaining algorithms in this review may be considered locally adaptive thresholding since all perform some "local" function and convert a gray input pixel to a binary output. However, the term will be used in this review to refer to direct extensions of fixed thresholding.

There are two manifest strategies for extending the globally fixed level thresholding to perform in a superior way depending upon local context. The first strategy attempts to suppress the additional gray scale information that is found so that only edge detail is output. These algorithms are directed specifically towards facsimile and OCR scanning applications with the intention of optimizing the process for *line copy* imagery as opposed to pictorial input [23]-[28].

The second extrapolation of globally fixed level thresholding attempts to provide extended tonescale range so that continuous tone information may be reproduced [29], [30]. A brief review of the *line copy adaptive* thresholding class of algorithms is provided followed by an evaluation of the "constrained average" thresholding algorithm intended for *continuous tone* and line copy reproduction.

1) *Definition: Line Copy Adaptive Thresholding:* A large number of algorithms have been developed that attempt to adapt a fixed level threshold to the local context of an image and thereby provide high quality line copy output. For a review of many of these algorithms, see [25] and [26].

All line copy adaptive thresholding algorithms have one or both of two technical strategies behind them. The first strategy is to detect edges within the input image. A large variety of edge detectors exist in the image processing community [24], and nearly all of them have been utilized in this application. Once an edge is detected, the predominant strategy is to update the value of the threshold to be some arithmetic function of edge pixels.

The second strategy is to utilize a memory of observed gray levels within the image to estimate the distribution of white to black picture elements within the image. Ultimately, one may scan the entire image, computing a histogram of observed gray levels for the entire image. Most often the within-page histrogram takes the form of a local maximum and minimum gray scale memory. Again, a computation is performed to *estimate* the desired threshold level which will discriminate the line detail.

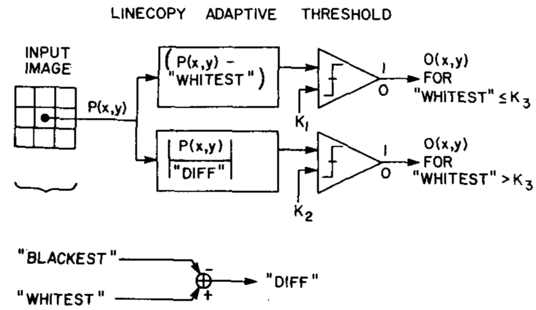


Fig. 7. Signal processing flow diagram for line copy adaptive thresholding algorithm, due to Ullman [26].

As an example of a specific algorithm, the algorithm due to Ullman [26] will be described briefly here. Fig. 7 shows the general logic for a line copy adaptive thresholding process. A threshold value is selected to be the average of the locally estimated whitest and blackest pixels. These local estimates are updated when a gradient operator detects a gradient above a predetermined level. The end result is therefore a threshold which is set midway between the whitest and blackest picture elements found on the edges of the most recent image detail.

A wide variety of algorithms, such as described above, exist in the patent and professional literature. An example algorithm [26] is outlined in the flow diagram in Fig. 7. Such algorithms have as their goal the output of high quality line copy imagery, and gray scale is intentionally suppressed. Therefore, they will not be reviewed in this survey.

2) *Definition: Constrained Average Thresholding:* As an example of an algorithm that represents an extrapolation of fixed level thresholding to *incorporate gray level information* in the output, the "constrained average" thresholding algorithm of Jarvis and Roberts [29] will be presented below. Others, such as Morrin, have developed similar strategies to extrapolate the fine detail rendition capabilities of fixed level thresholding to incorporate gray scale rendition [30].

Fig. 8 shows the fundamental computations required to process an image. One first computes a local average (in this case over a 3 × 3 pixel array). The threshold for the central element of this neighborhood is then simply the linear sum of the local average and a constant.

In [29], a more detailed description of the effects of varying the constants is provided along with a motivation for utilizing certain values. It is important to note here that, by utilizing the constraints described in the reference, one generates a varying amount of edge emphasis. This results from the fact that the threshold is to a great extent composed of the local average, and therefore a central pixel which differs from the average will generate a "color change."

3) *Evaluation: Constrained Average Thresholding:* The low frequency tone scale capabilities of the constrained average algorithm are far superior to fixed level thresholding. See Fig. 9. Microstructural detail generated by the "noise" in the system results in a relatively complete tone scale capability if the noise statistics are appropriate [29].

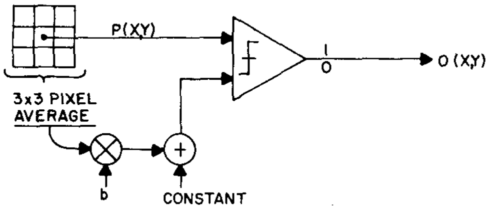


Fig. 8. Signal processing flow diagram for "constrained average thresholding" algorithm.

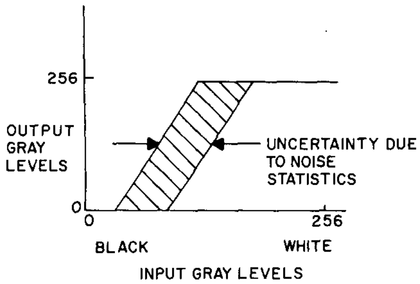


Fig. 9. Tone reproduction curve for constrained average thresholding.

Utilizing system noise, as proposed in the original document, results in microstructural detail of unlimitedly small size (single isolated black pixels in a white background and isolated white pixels in black surrounds). Such fine detail is statistically less well reproduced by practical marking systems, and therefore there will be a greater sensitivity to tone scale errors for this class of algorithms than for those which have constraints on the textural patterns utilized for gray scale rendition.

On the whole, however, an important advantage of this algorithm is that it is capable of reproducing highlight and shadow as well as midrange detail, unlike globally fixed level thresholding.

In terms of high frequency rendition, the edge enhancement characteristic of the algorithm can be utilized to emphasize edges and, therefore, impart an effective enhancement to fine detail. In this algorithm, however, such detail enhancement is provided at the expense of increased edge noise.

Because of the use of image context for threshold establishment, *edge locations* will vary for a given detail. The edges will therefore appear more blurred than if fixed level thresholding had detected them.

The ability of this algorithm to reproduce gray scale depends on the underlying noise statistics for the image [29]. The end result is that the image contains some low frequency noise samples which are visible to the eye and represent imaginal artifacts. The overall appearance of an image reproduced with the constrained average algorithm is one which is more spatially nonuniform and "dirtier" than algorithms with more regular structure.

In terms of processing complexity, this algorithm is just slightly more expensive than fixed level thresholding. A simple average is computed for the local context, and a weighted sum of this average plus a constant becomes the local threshold value. Clearly, a simple FIR filter can be utilized for this computation.

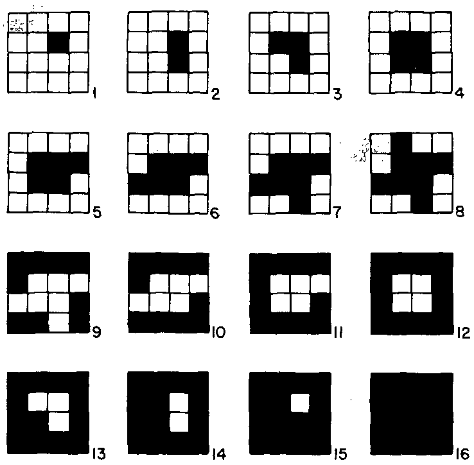


Fig. 10. Example "orthographic" gray scale font used to display 16 gray level pictorial information.

C. Orthographic Tone Scale Creation

In this section we review the techniques which utilize an "$n \times n$" array of binary pixels in the form of a gray scale "character" to represent pictorial imagery. These characters together form a gray scale "font" which, when printed with minimal intercharacter spacing, can yield a reproduction of pictorial information.

1) *Definition:* A number of authors have described techniques utilizing "fonts" to generate pictorial information [17], [30]. The general design problem for developing such a font of gray scale characters can be thought of simply as a pixel assignment problem wherein B pixels in an $m \times n$ array are turned on if the percent reflectance of the pixel at that location is intended to be $B/(m \times n)$. One such optimization attempt, performed by Hamill [31], resulted in a font similar to that shown in Fig. 10. (The original font was not discretized into sampled pixels.)

The fundamental algorithm is simply a table lookup process shown in Fig. 11. It should be clear from the diagram that the assumed resolution of the output system is higher than the input sampling system enabling the printing of an $(m \times n)$ array for every input sample. A compromise is usually developed for such systems since making m or n large enough to reproduce a sufficient tone scale results in a coarse pictorial sample resolution.

2) *Evaluation:* Because such systems require relatively high output pixel resolutions, systems designed with this approach usually result in relatively coarse tone scales. The quantization steps are relatively large, as exemplified in Fig. 12, and hence some tone scale errors will be created.

On the other hand, the constraints of the marking process are *best* handled by this algorithm. Each region of the tone scale may have a "character" ideally designed for its use with the particular marker.

In terms of detail rendition, again the output resolution for a given marking process will be hindered by a factor of m or n from displaying spatial frequencies requiring that "addressability." Orthographic tone scale reproduction techniques, therefore, result in a limited frequency response, less than $1/2n$ horizontally and $1/2m$ vertically.

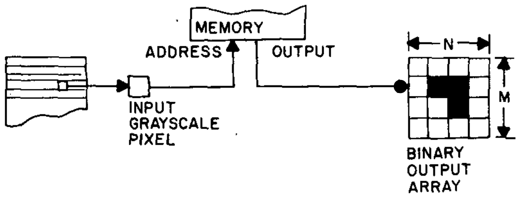


Fig. 11. Signal processing flow diagram for orthographic gray scale generation of pictorials.

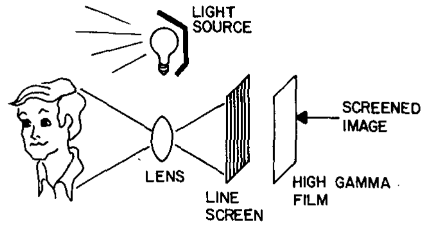


Fig. 13. Fundamentals of multiplicative screening process.

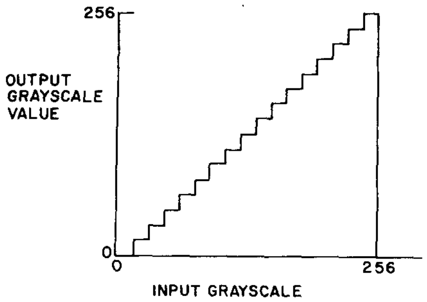


Fig. 12. Tone reproduction curve for orthographic, font generated pictorial imagery.

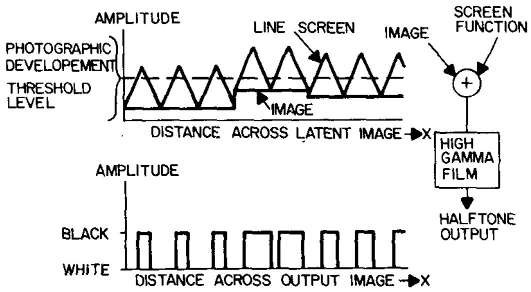


Fig. 14. Microdensitometric view of *additive* screening along with the signal flow diagram indicating the addition of the image signal and line screen followed by the development of a halftone rendition of the input.

Because of the coarseness of the tone scales invariably developed with such systems, it is common to see false contours in pictorial images reproduced by orthographic tone scale reproduction techniques. Also, depending upon the selected fonts, one often sees dramatic texture contours in output images from such systems. Finally, the coarseness of the output samples may result in the visibility of the actual "characters" used to create the gray scale.

The processing complexity is simple, requiring a single pixel table lookup. Orthographic reproduction, in fact, is used by graphic arts scanners today because of its simplicity [33], [34]. However, the scanners are often sampling at approximately 1500 samples/in and the output is in the form of one quarter of a halftone dot (a quadrant). Thus, if resolution is not excessively costly, this procedure can be a good fit.

D. Electronic Screening

Photomechanical screening developed in the mid-19th century as a vehicle for mechanically reproducing pictorial imagery rapidly and inexpensively, and the most economic strategy was to utilize photography in a unique way to create a binary image. This section, therefore, begins with a brief historical review of photomechanical screening and continues with a definition and evaluation of electronic screening, the most recent technical enhancement to this process [22], [33], [34].

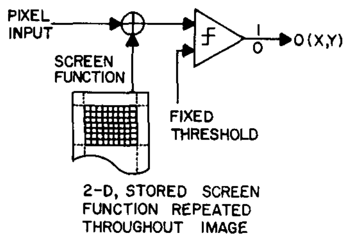
1) *Definition:* The first technique (Talbot) utilized a system that is shown in Fig. 13. A transparent glass "screen" with ruled lines was placed between the camera lens and the film plane. The result was that the image had superimposed on it an intensity modulation that was sensed by the photographic film. The film/printing process was operated in a high gamma mode, thereby resulting in an image which was literally composed of high frequency lines whose width varied in proportion to the average gray level of the image being photographed.

Rather than modulate the image multiplicatively as shown in Fig. 13, it is also possible to *add* the screen function to the exposed image at the film plane. Fig. 14 shows the microdensitometric view of this photomechanical process.

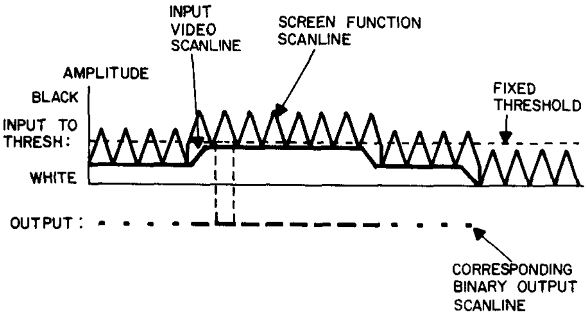
There is a long history of research examining the accurate spacing of the line screen to the film plane [15] as well as a number of other optomechanical parameters. Today the screening process is predominantly performed by "contact screens" at the film plane coupled with dot shapes rather than line screen patterns. For a review of screen function designs, the selection of screen angles, and especially the utilization of multiple screen functions, such as four color pictorial reproduction, see [15] and [22].

Electronic screening is predominantly the electronic analog of the photomechanical process [35]. The graphic arts industry has developed this technology to a high level, with great attention being paid to the electronic implementation of what truly is a photomechanical technique. Fig. 15 shows a schematic view of the electronic screening process. Sample image picture elements are compared with a single threshold, and a black/white decision is made. The thresholds are selected in sequential order from a two-dimensional matrix defined to be the *halftone cell threshold set*. The set of thresholds and their arrangement within the threshold set determine the gray scale range, the frequency, angle, and other properties of the halftone pictorial image [9].

Fig. 16 shows a typical electronic halftone function unit cell. The pattern is simply a sampled and quantized version of the common photomechanical dot screen. When repeated horizontally and vertically, the unit cell creates the entire screen function. Fig. 17 shows the possible "*isophots*" obtained in low detail regions of an image using the unit cell in Fig. 16. Fig. 18 shows the accuracy of rendition for high contrast detail input. Unlike the "orthographic gray scale" genera-



(a)



(b)

Fig. 15. Electronic screening. (a) Signal flow diagram (analogous to photomechanical screening). (b) "Scanline view" of the processing.

		167	200	
230	210	94	72	
153	111	36	52	193
	216	181	126	222
	242	232		

Fig. 16. "Unit cell' for electronic halftoning, with 18 possible gray levels, used as a 45° angular screen.

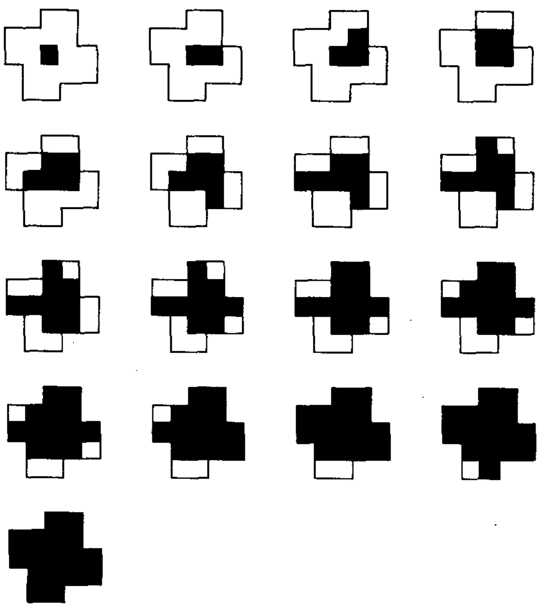
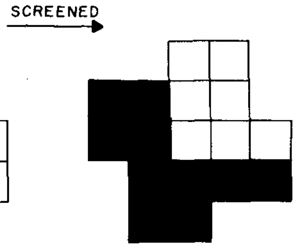


Fig. 17. Possible "nonwhite" halftone dots which may be generated by the screen function of Fig. 16 in *nondetail* regions of an image. These are defined to be the isophots for that function.

		200	200	
50	50	200	200	
50	50	200	200	200
	50	50	50	50
	50	50		

INPUT GRAYSCALE PIXELS



OUTPUT BINARY PIXELS AFTER SCREENING WITH FUNCTION IN FIGURE 5.4.4

Fig. 18. Input gray scale pixels with edge detail included along with the corresponding output if screened by the function in Fig. 16. This nonisophot detail is a "partial dot" which exemplifies the superior detail rendition capabilities of screening.

tion technique, the output resolution of the screening process is capable of detail rendition at the pixel sample resolution.

2) *Evaluation:* In terms of *low frequency* rendition, the classic electronic halftoning procedure results in a complete range of tone scale being generated. The highlight and shadow dots are the most difficult to reproduce, but since the textural patterns are coalesced masses of either black or white pixels, most binary marking processes provide more noise free reproduction of these features than complex, fine microstructure.

In terms of fine *detail rendition*, electronic halftoning is capable of reproducing high contrast detail, provided the frequency is simply below the Nyquist rate of the input sampling system. This is the most remarkable feature of the halftoning process, since it very naturally allows the highest possible frequencies of fine detail to be preserved while still generating a full gray scale. If the high frequency detail is a very low contrast, then the screen function will interact with it and limit the frequency response. Therefore, electronic screening can be viewed as providing the best high frequency capabilities (equivalent to fixed thresholding) for high contrast input, and gradually less detail rendition capability for lower contrast input, with the limit being a capability of reproducing the smallest of gray scale detail at the halftone cell frequency.

One should note the relatively ideal tradeoff being made by this algorithm in comparison to the capabilities of the human visual system. See Fig. 19 from [17].

The primary *artifact* generated by electronic halftoning is the high frequency dot pattern. For normal viewing distances, a dot frequency of 100 cells/in or higher results in a relatively invisible (human eye) artifact. At 85 cells/in and below, one must trade off this artifact with the fact that there are limited false contours and textural contours with this process. Utilizing elliptic halftone dots and monitoring the "chaining" of midtone dot structures for a given image, high quality pictorial imagery is mass produced from this process. Virtually all mass-produced (magazines, newspapers, etc.) printed pictorial imagery is produced via this technique today.

The processing complexity of electronic screening is quite small. Only one pixel is required at a time, and a simple table lookup for the threshold in the unit cell is all that is required. This is only slightly more complex than fixed thresholding.

E. Pseudorandom Thresholding, Ordered Dither

1) *Definition:* Techniques for minimizing the number of gray levels required to manifest acceptable pictorial imagery

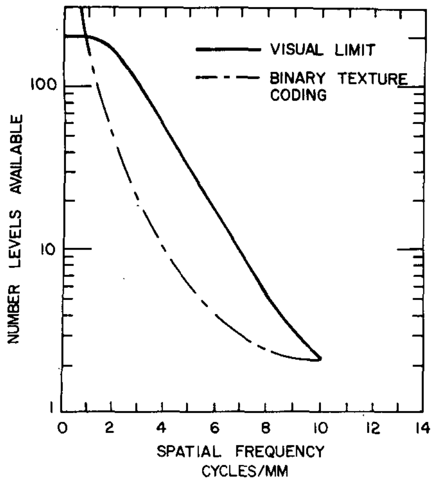


Fig. 19. Plot of the largest number of gray levels developed by electronic screen functions assuming an output sampling rate of 10 samples/mm (254 samples/in) [16].

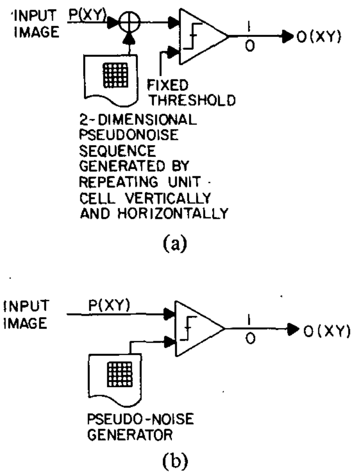


Fig. 20. Signal flow diagram for (a) Pseudorandom thresholding or "ordered dither;" (b) equivalent processing to (a) but alternate implementation.

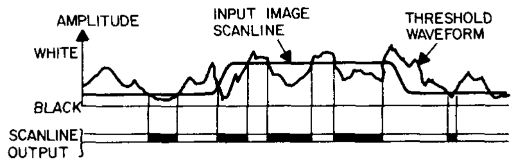


Fig. 21. "Scanline view" of pseudorandom thresholding via implementation of Fig. 20(b). Equivalent to electronic screening process, Fig. 15.

have been worked on for well over two decades. One of the early contributions was that of Roberts [29] in his use of pseudonoise sequences which were added to imagery prior to quantization with a small number of gray levels and subsequently removed. The end result was a reduction in the number of gray levels required to represent "acceptable" pictorial imagery.

Roberts utilized two-dimensional pseudonoise sequences prior to quantization to as few as 4 bits/pixel (16 gray levels). Subtracting this same sequence from the quantized image prior to display on a CRT (capable of continuous tone display), he was able to spatially distribute the gray scale errors created by the quantization step. This technique greatly reduced the appearance of false contours in the output image since the observer was actually capable of "seeing" a near continuum of gray levels by averaging in a "natural way" over a small, two-dimensional region.

In this review, we have focused attention on binary output marking processes. Interestingly, the principles underlying the success of Roberts' technique are again useful. Specifically, one may add a two-dimensional pseudonoise sequence to an input image prior to quantization to *two gray levels.* The end result is that the spatial distribution of the errors allows an observer to integrate the average percent reflectance in a small region and, therefore, "see" a near continuum of gray level. Fig. 20 shows schematically the general technique for pseudorandom thresholding. Pseudorandom thresholding, or "ordered dither" with binary quantization, is the result of research by Lippel, Kurland, Limb, and Jarvis and Bayer [36]-[39].

One should note that pseudorandom thresholding procedure is simply a form of electronic screening. Adding a known waveform to the imaginal signal prior to comparison to a fixed threshold is equivalent to comparing the input signal with a variable threshold of the same shape as the waveform added. See Fig. 21. On the other hand, a unique feature of pseudorandom thresholding is that it results in a dispersed set of black and white dots instead of a single "dot" as in the analog of the photomechanical screening process. In fact, there will be a multiplicity of visible frequency components from pseudorandom thresholding, depending upon the gray level values in the input.

The two-dimensional pseudonoise threshold signal is referred to in the literature as a *dither signal.* The optimization of dither signals for use in displaying continuous tone imagery has been studied by a number of authors [19], [36], [40], [41]. The preliminary goal was 1) to provide sufficient numbers of distinct threshold values so that false contouring did not occur and 2) to spatially order the threshold values such that the spectral energy of the output "dots" is the highest possible. Fig. 22(a) shows an example of the results of one optimization process by Bayer [19]. Similar work was done by Lippel and Limb with specific attention to binary panel display technologies. Fig. 22(b) shows a 4 × 4 dither matrix (Nasik pattern) utilized by Lippel, and Fig. 22(c) shows a 4 × 4 matrix developed by Jarvis. Each author has techniques for generating larger matrices and it is important to utilize matrices with roughly 64 distinct thresholds if false contours are to be eliminated.

The task of generating arbitrary dither signals for various binary marking processes has resulted in additional optimization studies such as that by Allebach [18] that describes a computer-aided design algorithm for generating dither signals appropriate for specific applications.

The above techniques have been referred to as ordered dither thresholding, "grating dot" screening, and some other technical names. In practice, these all represent forms of electronic screening using selected screen functions. The graphic arts industry also has developed a variety of multifrequency and "random dot" screen functions. These are much

0	16	4	20	1	17	5	21
24	8	28	12	25	9	29	13
6	22	2	18	7	23	3	19
30	14	26	10	31	15	27	11
1	17	5	21	0	16	4	20
25	9	29	13	24	8	28	12
7	23	3	19	6	22	2	18
31	15	27	11	30	14	26	10

(a)

$D^4 =$

0	14	3	13
11	5	8	6
2	12	1	15
9	7	10	4

(b)

$D^4 =$

0	8	2	10
12	4	14	6
3	11	1	9
15	7	13	5

(c)

Fig. 22. Dither threshold matrices developed by (a) Bayer, (b) Lippel and Kurland, and (c) Jarvis.

more complex than that shown in Section V-D, and they have primarily been used for special effects, tone scale extension, and contour elimination, as opposed to detail resolution enhancement [42], [43].

2) *Low Frequency: Evaluation:* By selecting a dither signal with a sufficient number of thresholds, minimal contouring will be visible with ordered dither as with classical electronic screening. There will be multiple "dots" per halftone cell, but the resultant low frequency rendition will be as accurate as that of the "single dot per cell" halftone version.

The printability of the multidot halftone cells, however, places relatively higher demands on marking processes as compared to the classical halftone dot structure. Even in midtone regions, very high frequency components are being developed by the dither patterns. These are constraining the output process to respond with tight tolerances throughout the tone scale, whereas classical halftoning has its most difficult printability constraints in the highlights and shadows.

On the other hand, pseudorandom thresholding, ordered dither, results in the highest level of capability to detect fine detail for a given halftone cell frequency. Fine detail detection, therefore, is the area of superiority for these thresholding techniques. In fact, it is this capability that may motivate one to utilize ordered dither thresholding for workstation displays instead of classical halftone patterns.

The most critical artifact that one detects from pseudorandom thresholding, ordered dither, is the artifical texture that often accompanies the images. Furthermore, there may be a number of "texture boundaries" that amplify the visibility of the artifical textures within the image. Developing a dither signal that provides high detail rendition but which also has minimal textural boundary visibility between adjacent gray levels is an *ongoing* research activity.

The processing complexity of this technique is the same as electronic screening. One might utilize a slightly larger "unit cell" for the pseudonoise sequence than for a classical halftone pattern, but the processing is equivalent.

F. "Error Diffusion" Techniques

1) *Definition:* Again utilizing the viewer's capability for spatial integration of black and white pixels to provide gray scale rendition, other researchers have created a different generation strategy. The fundamental strategy is simply that of direct spatial distribution of the *errors* created by coarse gray scale quantization, and it can be applied to two or more gray level marking processes.

In the original work in this area [44], Schroeder was constrained by a COM (computer output microfilm) marker which had a limited number of output gray levels. In order to provide high quality pictorials, he distributed the error between the gray level he utilized to print a given pixel and the value of the input pixel at that location to neighboring picture elements to the right and below the picture element being processed. When these neighboring picture elements are quantized, the errors will be corrected to a first order, with the errors going to zero over distances which are a function of the weighted distribution of the errors as well as the values of the input image.

In its simplest form, the above approach was utilized for binary displays [45]. In this case, one simply makes a binary decision about the output picture element, given the gray value of the input pixel. As above, the error between these two extreme quantization levels is dispersed (diffused) to the right and below the processed pixel. Fig. 23 shows a flow diagram representation of the error diffusion technique. Fig. 24 shows the spatial distribution of the percentage error being distributed for a given pixel used in [45].

2) *Evaluation:* Error diffusion processes, like screening, are capable of reproducing a complete tone scale, but it should be clear that the spatial frequencies in the printed image will be a function of both the gray level being reproduced and the input image detail. For example, the horizontal distance between black pixels in an image highlight area will be very long as compared to that distance for midtone gray levels, whereas electronic screening and ordered dither processes result in a lower limit on the frequency characteristics in the output.

One should note that there is no control over the shape of the TRC provided by this algorithm. Highlight enhancing or other TRC variations must be done prior to processing, and dark images must be preprocessed to lighten them.

In terms of printability, error diffusion techniques often result in relatively isolated and very unconstrained microstructural detail. As with ordered dither, such detail imposes repeatability requirements on the marking process to avoid tone scale errors throughout the range.

The detail rendition capabilities of diffusion are excellent. Highlight, midtone, and shadow detail are all capable of being reproduced. However, the phase of detail in the image is not

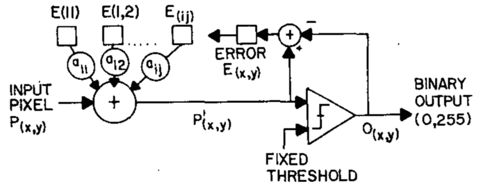


Fig. 23. Signed flow diagram for error diffusion assuming two-level quantization and error context ($E_{11}, \cdots, E_{ij}$).

3	6	10	6	3
6	10	15	10	6
10	15	$P_{(x,y)}$		

$$P'_{(x,y)} = P_{(x,y)} + \sum_{ij\epsilon} a_{ij} \cdot E(ij)$$

$$O_{(x,y)} = \begin{cases} 0 & P' \leq \text{THRESHOLD} \\ 255 & P' > \text{THRESHOLD} \end{cases}$$

Fig. 24. Spatial distribution of error context in the image. Numbers in matrix are percentages that multiply the gray scale errors for those pixels prior to addition of gray scale for $P_{(x,y)}$.

always reproduced consistently. Edge location, for example, will be translated spatially depending upon the *image content* above and to the left of the edge. Furthermore, straight edges will most often be represented with various amounts of edge noise because of the dependence of this process on context.

As alluded to above, the error diffusion process is capable of creating output signals which have relatively low spatial frequencies and are therefore more visible than, say, electronic screening, which has a *constraint on the low frequency patterns* it generates. Furthermore, these low frequencies can occur throughout the tone scale.

Another artifact, which is most visible in highlight or shadow regions, is the "avalanche" structure of the output. In a large, uniform highlight region of an image, for example, utilizing the error diffusion weighting structure of Section V-F-1, the output image will contain relatively widely separated, near diagonal (northeast to southwest) line structures. This follows because the process is taking a uniform input value and essentially "snowplowing" it ahead while outputting white pixels until the accumulated error is above the threshold and a black pixel is output. Processing left to right and top to bottom, the process then results in black pixels predominantly distributed as diagonal structures that are not part of the input image. It should be noted that this diagonal artifact is a relatively infrequently seen artifact compared to some of the others discussed above.

It is possible to reduce the context for error minimization calculations to a very small number (1), but the resultant detail structure is very oscillating and "noisy." Empirically it was found [39] that a minimum of 12 pixels will likely be needed for most applications. Furthermore, the summation of terms must be done on the "error" terms, differences between the output pixel value and the input gray level of the pixel. The result is a context of 12 pixels (3 scanlines), and an equivalent number of additions.

G. Summary–Continuous Tone Reproduction

In the above sections, a number of processes were reviewed that enabled the generation of pictorial imagery utilizing binary marking processes. There are a number of tradeoffs which one must evaluate in order to select the optimal procedure for a given application, but the metrics utilized in this evaluation should enable that selection for most applications. Table I summarizes the reviewed algorithms along with their characteristic features viewed along the dimensions utilized for interalgorithm comparison in this review.

Figs. 25-31 show example outputs of the algorithms studied in this review. Magnified subimage areas are shown alongside each output image to facilitate comparison of microstructural detail.

The images shown in Figs. 25-31 are output on a Versatec plotter, with a sampling resolution of 200 samples/in and a spot size of approximately 5 mils. The input was scanned on a Joyce Loebel drum scanner with a 250 sample/in input resolution and a trapezoidal input aperture function with a 4 mil "top" and 6 mil "base." This manuscript is reduced for publication to 75 percent of the original size; thus the journal imagery has an *effective* output sample resolution of 266 samples/in.

VI. HALFTONE PICTORIAL REPRODUCTION

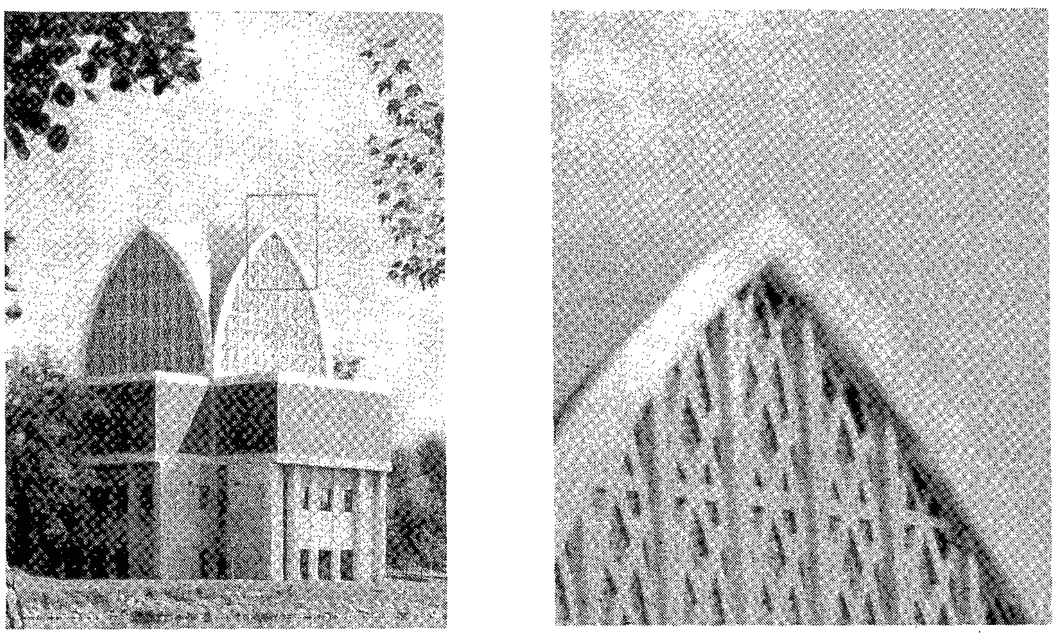
As noted above, halftone pictorials appear to the viewer as being continuous tone imagery. However, they are comprised of microstructural detail which is to a first order either black or white. The difficulty with electronic reproduction of halftone input is due to two main facts. First, the microstructural detail that composes the input is small and requires very high scanning/sampling rates in order to be resolved. The second issue is that the halftone images have a strong spatial frequency component that is *not part of the input image*, the halftone screen frequency.

Halftone images have a spectrum that is composed of a baseband representation of the original input image coupled with nonlinearly weighted versions of that input spectrum centered around the screen frequency and its harmonics [46]. This is a relatively complex spectrum to deal with, and empirically it has been found that if one utilized a fixed threshold on a 120 cell/in (common letter press) halftone screen function, then a scanning/sampling rate of 1000-1200 samples/in is required to guarantee a minimally visible artifact due to aliasing [47]. Therefore, this simple reproduction algorithm is not always a cost-effective answer for an electronic reproduction system with halftone input. The remainder of this section will review alternatives.

This paper focuses attention on "binary" output marking processes as the vehicles to display pictorial information. Representing halftone pictorials thus requires conversion of gray input pixels, and hence algorithms such as discussed in Section V will be considered. The following analysis, therefore, begins with a review of the application of Section V algorithms to halftone reproduction, and the remainder of this section examines novel algorithms created to solve the reproduction problem. Finally, a summary of algorithm perform-

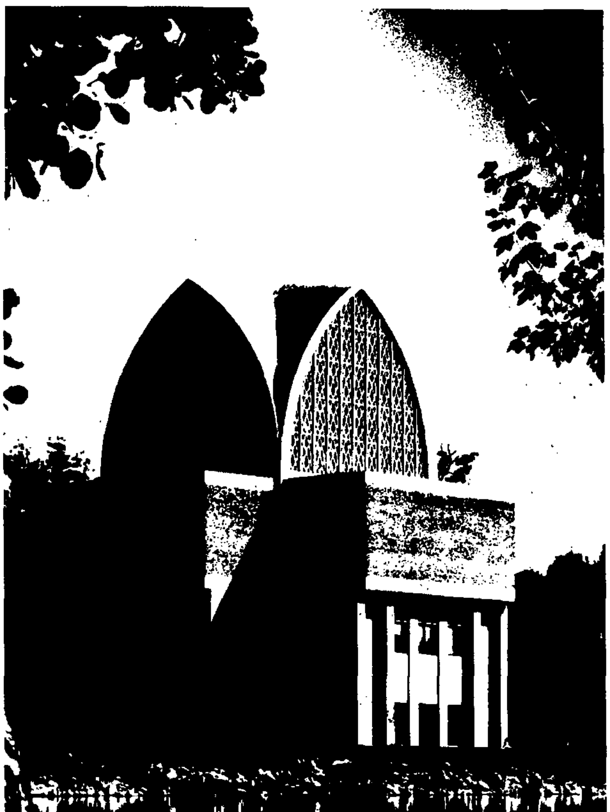
TABLE I
SUMMARY OF ALGORITHM PERFORMANCE—CONTINUOUS TONE REPRODUCTION

	LOW FREQUENCY RENDITION (PRINTABILITY)	HIGH FREQUENCY RENDITION	ARTIFACT	PROCESSING COMPLEXITY
THRESHOLDING (GLOBALLY FIXED)	• POOR PICTORIAL REPRODUCTION, NO TONE SCALE.	• LIMITED HIGHLIGHT, SHADOW DETAIL. • EXCELLENT EDGE LOCATION, WITH MINIMAL BLUR.	• FALSE CONTOURS. • VISIBLE STREAKS, NOISE NEAR THRESHOLD GRAY LEVELS.	• 1 PIXEL CONTEXT REQUIRED.
THRESHOLDING (LOCALLY ADAPTIVE "CONSTRAINED AVERAGE")	• *GOOD TONE SCALE*, POTENTIALLY FULL SCALE. ACCURACY LIMITED BY PRINTABILITY OF UNCONSTRAINED MICROSTRUCTURE.	• ENHANCED DETAIL DETECTION THROUGHOUT TONESCALE. • EDGE LOCATION VARIABILITY DUE TO CONTEXT.	• MODEST LEVELS OF VISIBLE NOISE. • SOMEWHAT MOTTLED GRAYSCALE.	• MINIMUM 3 x 3 PIXEL CONTEXT, SIMPLE AVERAGE COMPUTATIONS.
ORTHOGRAPHIC TONE SCALE GENERATION	• FULL TONE SCALE, BUT TRADEOFF COARSE QUANTIZED GRAYSCALE WITH HIGH RESOLUTION MARKING PROCESS REQUIREMENTS. • EXCELLENT CONTROL OF PRINTABILITY (FONT DESIGN) AND TRC.	• FOR A FIXED OUTPUT RESOLUTION, TRADEOFF DETAIL RENDITION WITH GRAYSCALE QUANTIZATION.	• POSSIBLE COARSE TRC GENERATING FALSE CONTOURS. • POTENTIALLY VISIBLE FONT SYMBOLS.	• 1 PIXEL CONTEXT, TABLE LOOKUP.
ELECTRONIC SCREENING	• FULL RANGE, LOW FREQUENCY GRAYSCALE RENDITION. • EXCELLENT CONTROL OF PRINTABILITY (SCREEN FUNCTION) AND TRC.	• GOOD DETAIL RENDITION. HIGHEST CONTRAST DETAIL ALWAYS DETECTED. LOWER CONTRAST DETAIL SOMEWHAT BLURRED BY SERRATED EDGE MICROSTRUCTURE.	• POTENTIALLY VISIBLE SCREEN DOT PATTERNS IF THE FREQUENCY GETS WELL BELOW 100C/IN.	• 1 PIXEL CONTEXT REQUIRED, STORED SCREEN FUNCTION.
PSEUDORANDOM THRESHOLDING (ORDERED DITHER)	• FULL SCALE, LOW FREQUENCY GRAYSCALE RENDITION. • EXCELLENT CONTROL OF TRC, BUT DEMANDS PRINTABILITY OF ISOLATED BLACK OR WHITE PIXELS (HIGH FREQUENCY RESPONSE).	• GOOD DETAIL RENDITION. SUPERIOR TO CLASSICAL ELECTRONIC SCREENING BUT ALSO "BLURS" NONMAXIMAL CONTRAST EDGES.	• POTENTIALLY VISIBLE PATTERNS IF LOWEST FREQUENCY IS BELOW 100C/IN. • SOME FALSE TEXTURE BOUNDARIES RISK VISIBILITY.	• 1 PIXEL REQUIRED, STORED THRESHOLD FUNCTION.
ERROR DIFFUSION	• FULL SCALE, LOW FREQUENCY RENDITION. • NONTRIVIAL CONTROL OF TRC. • NO CONSTRAINT ON THE OUTPUT MICROSTRUCTURE AND HENCE DEMANDS RELIABLE ISOLATED PIXEL PRINTING.	• BEST OF ALL ALGORITHMS ON AVERAGE. • EDGE LOCATION ACCURACY VARIES, DEPENDING ON CONTEXT.	• FALSE TEXTURES IN UNIFORM AREAS. • VISIBLE LOW FREQUENCY MICROSTRUCTURE POSSIBLE.	• TWELVE PIXEL CONTEXT, (2-D). • WEIGHTED AVERAGE COMPUTATION CONTINGENT UPON BLACK/WHITE DECISIONS.



(a) (b)

Fig. 25. (a) Continuous tone original. (b) Photographic blowup (~8×) of subimage in (a).


(a)

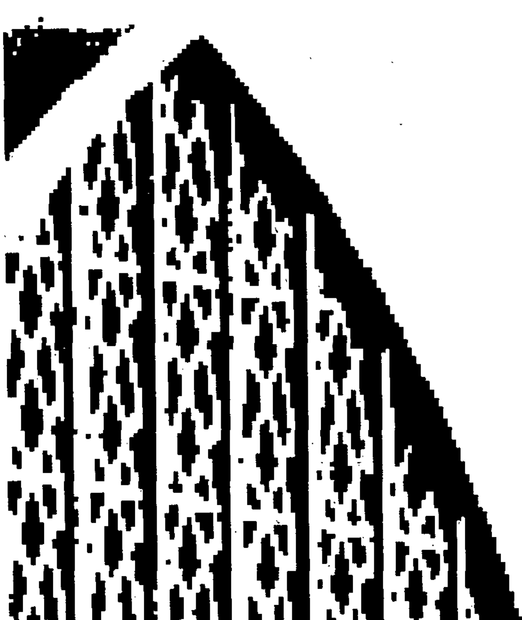
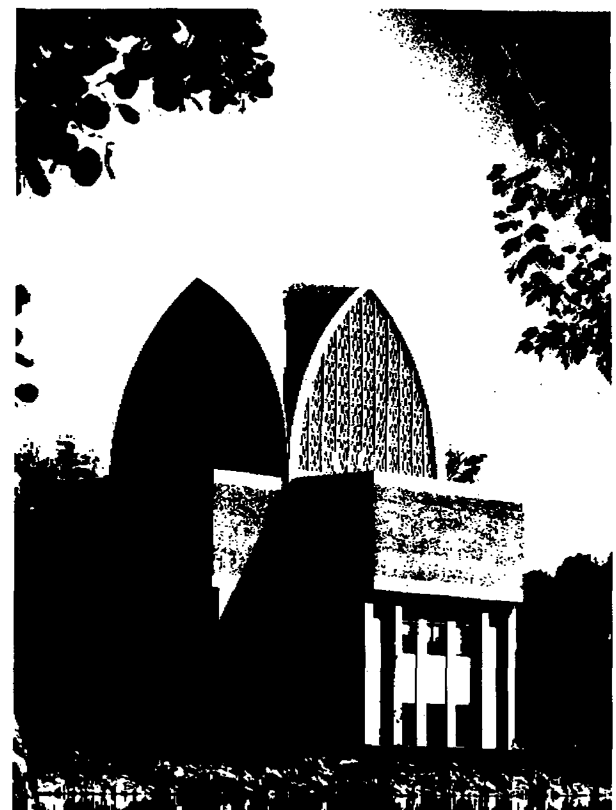

(b)

Fig. 26. (a) Fixed threshold output. (b) Magnified subimage of (a).


(a)

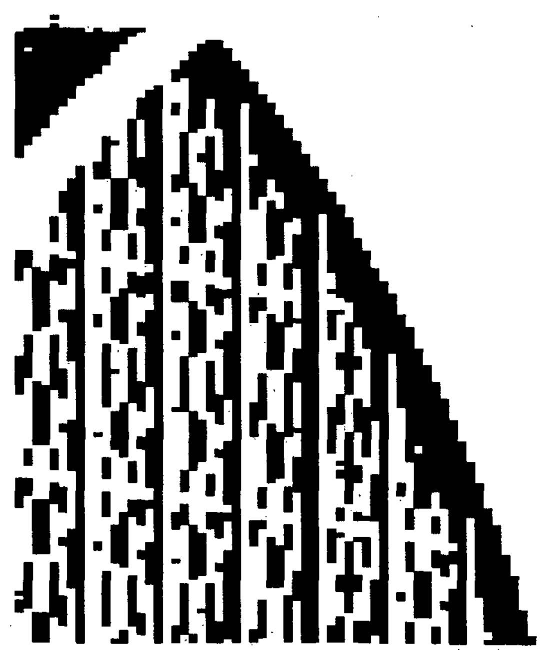
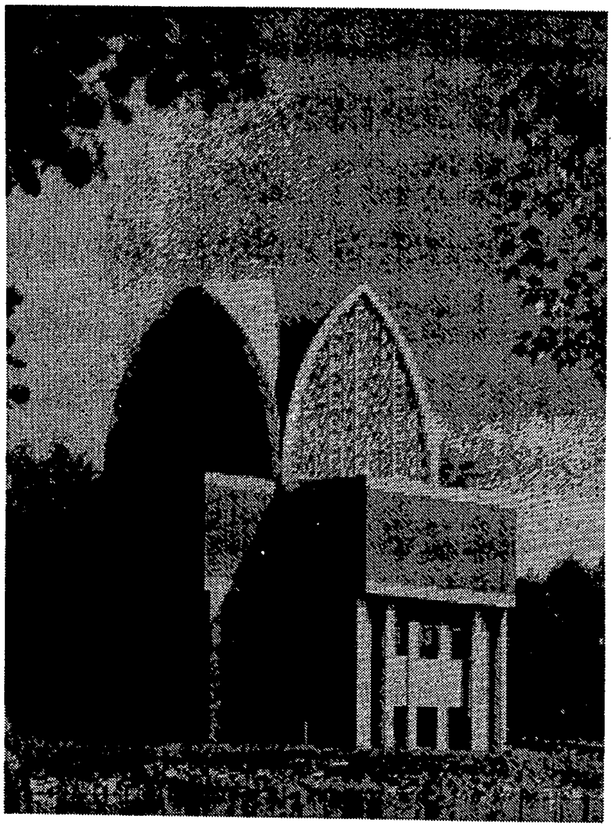
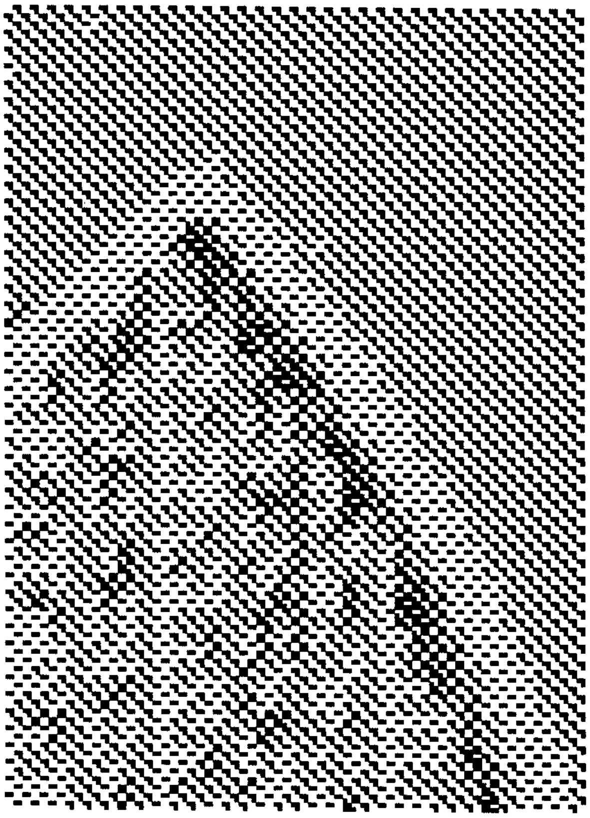

(b)

Fig. 27. (a) Constrained average output. (b) Magnified subimage of (a).

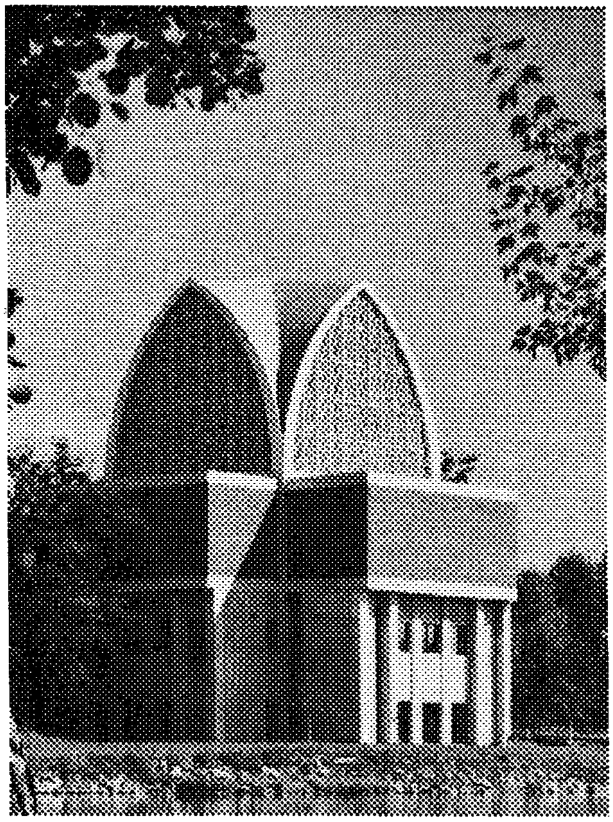


(a)

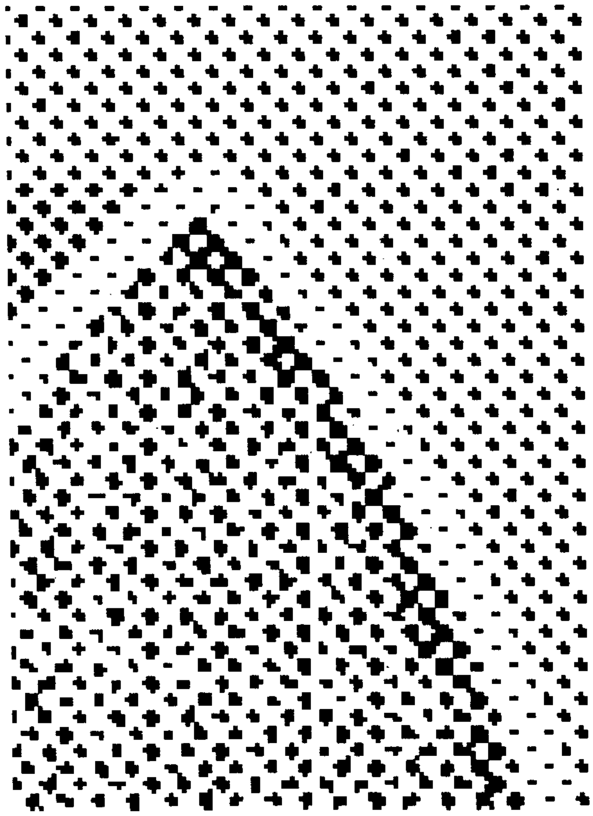


(b)

Fig. 28. (a) Orthographic font output. (b) Magnified subimage of (a).

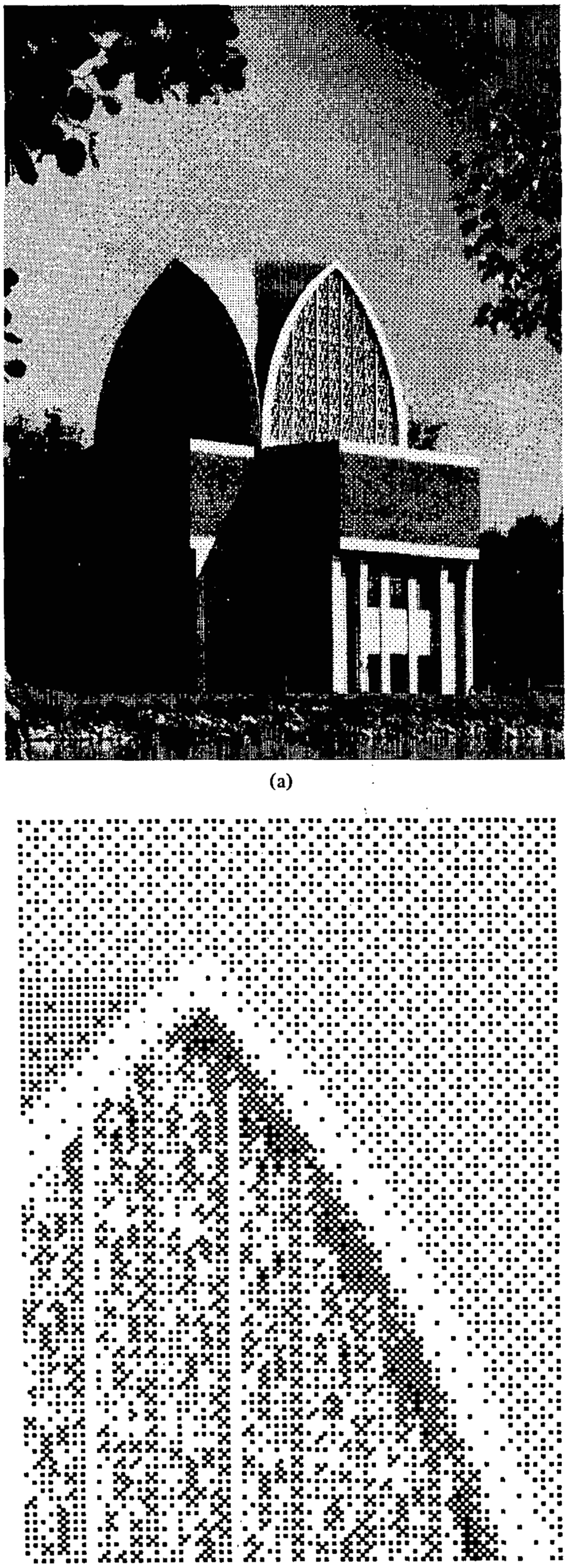


(a)



(b)

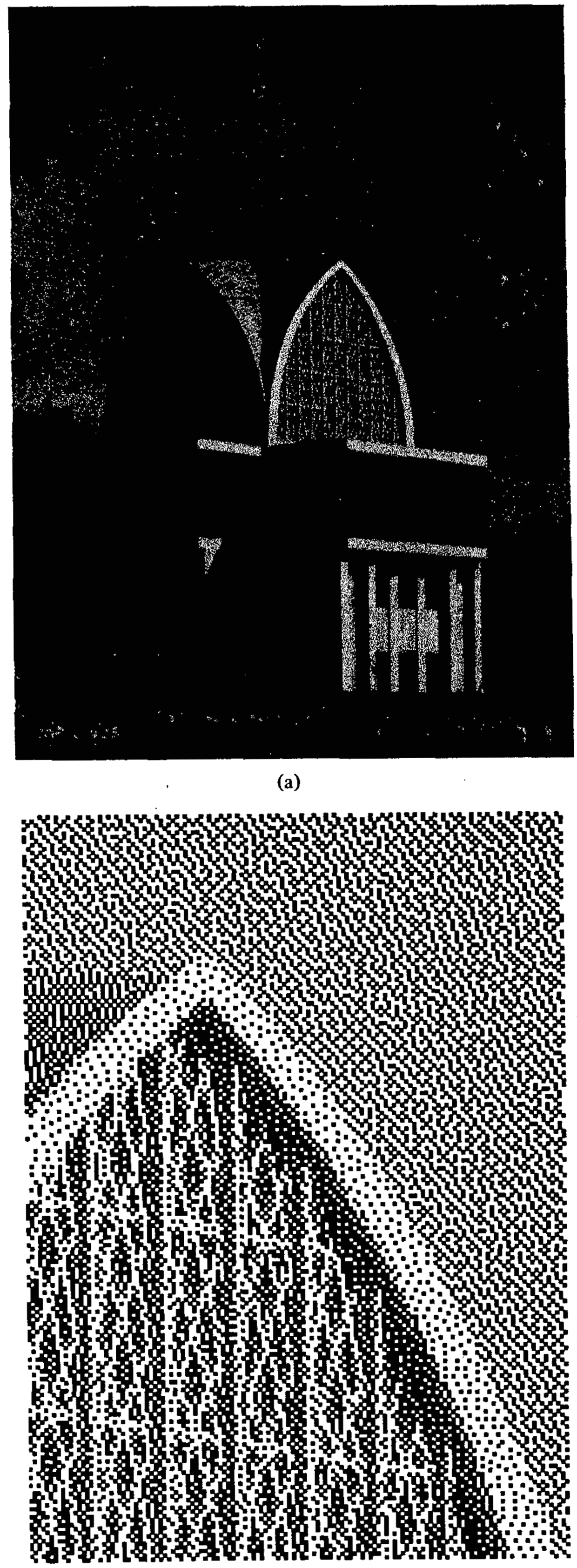
Fig. 29. (a) Electronic screening output. (b) Magnified subimage of (a).



(a)

(b)

Fig. 30. (a) Ordered dither output (Bayer's). (b) Magnified subimage of (a).



(a)

(b)

Fig. 31. (a) Error diffusion output. (b) Magnified subimage of (a).

ance is presented, displaying the performance tradeoffs to be considered when selecting an algorithm for a specific system application.

One should note that the processing discussed in this section enables *spatial encoding* of halftone pictorials for display/printing. More classical *redundancy reduction encoding* of halftone pictorials is addressed in [48]-[51].

A. Globally Fixed Level Thresholding

Since the halftone pictorial image is, to a first order, a binary encoding that manifests gray scale, then a fixed level threshold is a likely candidate to reproduce the input halftone. The technique would be simply to scan/sample the input image and to threshold the input at some *a priori* specified level.

A difficulty with simple thresholding techniques is that the sample resolution requirements are very high. Empirical studies [47] of the required sample resolution that yield moiré-free output have indicated that a factor of 8-10 times the input screen frequency is required. With screen frequencies commonly going as high as 150 cells/in, the cost of such a reproduction system is greatly increased. (For a review of the theoretical issues and the development of the Fourier spectrum of a halftone image, see [2], [46].)

A popular conception is that one may prefilter (low-pass) the halftone input image and thereby reduce the sampling rate required if fixed level thresholding is utilized. Explicitly, the concept is to provide a low-pass filter prior to sampling and thresholding and, therefore, reduce the energy in the aliased image output from the process.

Such an approach does not work, however. If the low-pass filter is such that its bandwidth includes only the baseband of the halftone input, then one has totally eliminated the halftone dot structure, resulting in a continuous tone image being thresholded (Fig. 32, "A"). As shown in Section V-A, thresholding such an image results in a very poor tone scale reproduction.

On the other hand, should the low-pass filter allow some of the halftone structure to pass, then aliased frequencies remain in the thresholded image. Fig. 32 "B" shows the resultant waveforms after partial screen removal filtering. The thresholded signal has lost some highlight and shadow detail, but the thresholded output obviously has a very broad spectrum regardless of pictorial image content. (E.g., a uniform midtone region will result in something like a square wave with a 50 percent duty cycle. The associated spectrum has a sinc^2 envelope with many significant high frequency components.) Furthermore, one should note that sampling before or after thresholding is immaterial, i.e., they are commutative. The qualitative argument above can be presented with complete quantative detail. However, the fundamental principles are sufficiently simple that this is not included.

In conclusion, for those linear filters that reduce the spectral content to simply the baseband representations of the input image, a very poor output image is generated by thresholding. On the other hand, allowing some of the halftone detail to be passed through the thresholding process results in artifact (aliasing) being generated unless the sampling rate is 8-10 times the screen frequency of the input.

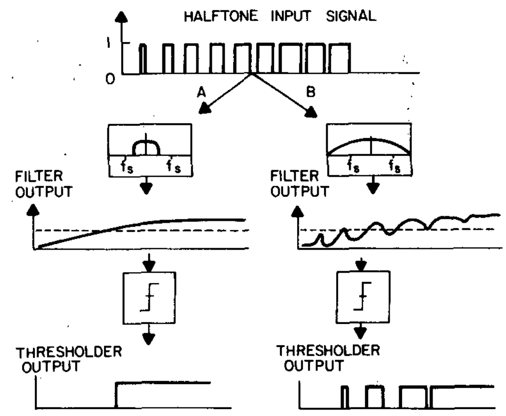


Fig. 32. Prefiltering strategies for halftone image input. Case "A" has suppressed the halftone carrier, F_s, resulting in no tone scale. Case "B" has partially retained the halftone carrier resulting in lost tone range and the liability of sampling moiré.

2) *Evaluation:* From the above definition, it is clear that fixed thresholding alone is a relatively limited process with regard to quality reproduction of halftone pictorial input. For evaluation purposes, we will assume that sampling rates on the order of 2-5 times the halftone screen frequency are utilized since they represent many practical scenarios and cases of greater than 8 times the screen frequency are simply excellent but expensive solutions. For example, low frequency, 65 cell/in halftones are well reproduced with a sampling rate of 520/in, but the 120 cell/in letter press halftones will have the results outlined below.

Both highlight and shadow detail will be at risk in terms of reproduction with single level thresholding. This is due to the fact that the bandwidths of nonaliased scanning systems will limit the amplitude of the fine detail (MTF rolloff). Thus, midtone gray scales will be fairly accurately represented, whereas highlight and shadow gray scales will be abbreviated. (See Fig. 32.) Furthermore, much fine detail will exist in the image and may not be reliably printed by the marking process. This will also tend to abbreviate the tone scale and make it somewhat "noisy."

Assuming limited low-pass filtering prior to thresholding, only highlight and shadow detail is at risk with the fixed threshold process. Edge locations are reproduced at the sampling resolution. Thus, if the detail is of high enough contrast to generate a dense structure greater in size than a sample contrast, then it will be reproduced with this technique. Fixed thresholding, therefore, has relatively good detail rendition capabilities and excellent high contrast edge reproduction, but the highlight and shadow regional detail will be lost.

As noted above, with a limited sampling frequency, the output images are highly likely to contain moiré artifacts due to aliasing. There is a wide range of halftone input frequencies (65-150 cells/in) and thus visible aliased frequencies may be generated for any sampling frequency up to the range 1200-1500 samples/in. Not all images will manifest this moiré, but quality reproduction motives result in system designs which protect against these artifacts.

It is also important to note that for low frequency halftone input ($\leqslant 1/8$ the sample frequency) as well as *line copy*, fixed level thresholding yields quite good reproduction. A broad range TRC with good detail rendition and minimal artifacts results. This is important since halftone pictorial imagery is most often combined with line copy on the same page.

B. Locally Adaptive Thresholding

1) *Definition:* As discussed in Section V-B, many adaptive thresholding techniques have been developed that exploit the local context to compute the threshold for a given pixel. Either of the two classes of adaptive thresholding algorithms discussed in Section V-B may be applied to halftone input. The *line copy* class of algorithms will compensate to some extent for the scanning system MTF and reproduce fine detail in the halftone structure that is missed by a globally fixed thresholder. The *combination* (line copy plus continuous tone) algorithms, represented by the constrained average algorithm, will also detect better highlight and shadow detail by moving the threshold up and down. Furthermore, the "gray pixels" sensed by the finite bandwidth scanning system will be statistically represented in the output.

In both of the above algorithm classes, there is no change in the phase relationship of the black and white microstructural detail in the halftone input. Hence, black/white edges will be represented as accurately as the sampling system will allow. For this reason, the sampling moiré discussed above represents a major risk unless the sampling rate is increased to the 1200–1500 sample range.

2) *Evaluation:* The adaptive thresholding techniques tend to extend the tone reproduction range well beyond that of the globally fixed level threshold. Nearly full tone scales are reproduced with these techniques, provided the output marking process can reliably reproduce the fine detail. As with fixed thresholding, however, the *printability* of single, isolated white and black pixels becomes a requirement since there are no constraints placed on the microstructural detail generated in this process.

Most of the adaptive thresholding algorithms tend to compress the tone scale of the halftone input slightly. Gray scale values are squeezed towards the midtone region from both ends since the "detail enhancement" of these algorithms will provide relative broadening, for example, of highlight dot structures. Other than this, the TRC has a near unity gamma (i.e., the slope of the gray scale transfer function is roughly equal to one).

High frequency detail present in the input will likely be reproduced via these algorithms since locally adaptive thresholding manifests more detail in the highlight and shadow regions. High contrast edges, for example, will be very accurately reproduced by both the fixed and adaptive classes of algorithms, but a 20 percent contrast edge in a highlight region is likely to be detected only by the adaptive algorithms. To detect such detail, the scanning system sampling rate (and input MTF) must be sufficiently high so as to detect very fine halftone dot structures, i.e., roughly 1000 samples/in.

There is minimal additional structure generated by adaptive thresholding algorithms and, therefore, the only artifact of much concern is the moiré visible with insufficient sampling. Because these algorithms enhance the fine detail and reproduce edge phases accurately, sampling moiré is more evident in output from these algorithms than from globally fixed thresholding. A more complete view of the tone scale in the input image is made visible and all edges are enhanced.

C. Orthographic Techniques

1) *Definition:* Section V-C describes the generic representation of gray scale output via binary processes utilizing a "font" of two-dimensional binary arrays that represent the gray scale. For this application, the technique is to represent each sample of the input (halftone) image by a gray scale "character" in the output. Assuming that such gray scale characters require at least a 4×4 array, one concludes that the already high constraints on the sampling rate for halftone input are multiplied by four in this example. The output process, therefore, must be capable of approximately 4800 samples/in to guarantee invisible moiré. Therefore, these techniques are going in the wrong direction from simplifying the reproduction process. Both high input and high output sampling rates are being required.

For the above reasons, therefore, orthographic techniques will not be evaluated, as they are least applicable for halftone reproduction.

D. Electronic Halftoning, Ordered Dither, and Random Nucleated Halftoning

1) *Definition:* In Sections V-D and V-E, the electronic halftoning and ordered dither reproduction processes were defined. In this section, we will add to those definitions that of "random nucleated" halftoning. All three may then be evaluated.

Random nucleated halftoning is the result of an attempt to alter the phase relationship of a classical electronic halftoning system so as to decrease the beat patterns (moiré) when screening a halftone input. In this technique, developed by Allebach [52], [53], a random variable determines the center of mass of the halftone cell. Thinking of the halftone cell as an area with a single dot or "nucleus," this algorithm simply shifts the center of this cell to random positions within the two-dimensional array. Fig. 33 shows a standard, electronic halftoning screen function array, along with the phase randomized thresholding patterns generated by the quasiperiodic screening process. In this case, the peak threshold, "32," may be seen to move randomly throughout the 2-D array. The other thresholds remain in phase relative to the peak, but they are "rolled" around to new locations as though the 2-D array was truly a torris.

2) *Evaluation:* All three algorithms are capable of reproducing the full tone scale visible in the input image. Even if the input scanning system has a sufficiently low sampling rate (and MTF) such that the highlight and shadow halftone detail are being "rolled off," the sample pixels will represent that average gray level and the screening processes of this section will faithfully reproduce their gray value. These processes, therefore, have the highest capability of reproducing the tone scale range for halftone input.

22	23	28	24	1	10	26	29	31	19	7	4	2	25
23	12	8	13	5	18	30	32	27	11	3	1	26	29
19	7	14	21	25	17	20	28	24	15	13	18	30	32
11	2	10	26	29	31	19	8	16	14	9	22	20	28
32	6	18	30	32	27	11	3	2	25	17	23	12	8
28	9	22	20	28	24	15	23	12	8	31	19	7	4
8	16	23	12	8	16	31	19	7	4	2	11	3	1
4	2	10	7	4	32	27	11	3	1	6	18	13	5

"STANDARD" THRESHOLD PATTERN 32 LEVELS

PHASE RANDOMIZED THRESHOLD PATTERNS

Fig. 33. Random nucleated halftoning. A 2-D subset of the thresholds used throughout an image showing a standard electronic screen function along with phase randomizations of it.

The printability for the three algorithms does vary, however. Random nucleated halftoning and ordered dither generate a considerable amount of fine detail. Both create more severe constraints on the printability of the isolated black and white pixels by the marking process than classical electronic halftoning. The output microstructure from electronic halftoning of screened input is dominated by either one of the two screen function dot patterns. In this sense, electronic halftoning may place somewhat less severe printability constraints on the output process.

All three processes utilize two-dimensional threshold arrays which have the capability of extending across the entire gray scale range or a subset of it. Thus, the "contrast" of these threshold arrays will determine the strength of their detail detection capability as compared to fixed level thresholding. In order to reproduce both highlight and shadow detail, all of these algorithms need a relatively large TRC range. The end result of this is that edge detail is serrated. The original halftoning process will utilize a "partial dot" structure to represent accurate phasing of edge detail. However, for edges with less than 100 percent contrast, even the original halftoning process will yield *serrated edges.* The algorithms in this section now further degrade the *sharpness* [8] of edge detail in the halftone input. Ordered dither manifests the sharpest edges, whereas electronic screening and random nucleated screening show near equal blurring of edge detail.

As with the first two algorithms in this section, low contrast detail is less accurately detected than high contrast detail by the three screenings in this subsection. However, none of these algorithms performs detection as well as adaptive thresholding for the same sampling rate.

The dominant artifact in electronic screening and ordered dither is the visible low frequency pattern generated by the combination of the halftone input and the "screening" process. Even ordered dither, with its spatially randomized threshold patterns, has a fixed periodicity. Distances between thresholds of equal levels are fixed throughout the image. (This is the source of the efficiency for a number of halftone data compression techniques [48]-[51].)

Random nucleated halftoning, on the other hand, alters the phase relationship between halftone thresholds of equal value. The result is that no beat frequencies (limited amplitude) are generated between the input halftone and the quasiperiodic screen function. However, the overall appearance of random nucleated halftoning contains a different form of artifact than discussed above. The pseudorandom phasing of the halftone dot structures results in a somewhat "mottled" appearance for the image. A wide variety of microstructure occurs even in image areas with uniform gray level content, and therefore the overall appearance of the image is more "noisy" than the other algorithms.

As noted in Section V, electronic screening and ordered dither require one pixel for computation of the output binary pixel. This is also the case for random nucleated halftoning; however, there is a modest additional requirement. The address of the starting pixel in the threshold array is changed from cell to cell. This is most easily performed by storing a list of precomputed random numbers, and thus in all cases the processing complexity is minimal.

E. Error Diffusion

1) *Definition:* In Section V-F, the fundamental principles behind error diffusion techniques were presented. To repeat, the process primarily is that of dynamically distributing to a local neighborhood the gray scale errors that result from coarse quantization. When binary markers are utilized, the error term can create very high as well as very low frequency structure in the image. On the other hand, there is no inherent natural frequency within the process, and therefore the output frequencies will be dominated by those of the input.

2) *Evaluation:* Provided the context for distribution of quantization errors for the error diffusion process extends over a roughly 5 pixel distance, the subjective quality of the low frequency input information will be relatively good. The input halftone dot size information will tend to be reproduced across the full tone scale range. However, the error diffusion process will heavily serrate the edge detail and yield many fine microstructural details. This will place a demand on the marking process to guarantee their reliable reproduction throughout the entire tone scale, not just the highlights or shadows. The shape and size distribution of the microstructural detail output from this process are also relatively unconstrained. Therefore, *no simple control* is provided to assure printability for any region of the tone scale.

The detail detection capability of error diffusion remains a strength even when reproducing halftone input. The main advantage of the process is its capability of detecting details throughout the entire tone scale, unlike fixed thresholding. However, as with many processes, the higher the contrast value of the detail, the more visible will be the output of this process. Also, as noted above, the printability of fine microstructural detail generated by error diffusion will often limit the visibility of detail. Therefore, error diffusion ranks above screening in its high frequency detail capabilities, but it generates additional edge blur compared with fixed thresholding.

The output from the error diffusion processes have no natural (internal) frequency. Therefore, there is limited "harmonic" artifact generated between the halftone input frequency and the processing algorithm. One will detect, however, a high frequency, "noisy" texture because the input halftone detail is being reproduced with varying detection accuracies and edge phase shifts. The additional low frequency artifact cited in Section V-F is greatly diminished for halftone input because the halftone dots are at a high frequency.

F. Alias Reduction and Image Enhancement System

1) *Definition:* Considering the problems of halftone reproduction, an image processing algorithm was developed which specifically attempted to reduce the visibility of aliased frequencies in sampled halftone input images. The technique, as described by Roetling [54], performs a low-pass filtering operation on the sum of the input image plus a screen function. The gray scale average is then distributed throughout the context utilized for the low-pass filter in such a way as to define black pixels in a *prioritized way* within the context of the low-pass filter. This is done so that fine black/white detail in the input is assigned to the same colors in the output image.

Fig. 34 outlines the flow of the ARIES algorithm. A screen function with variable contrast is incorporated within this algorithm to provide a full scale printable tone range.

2) *Evaluation:* The ARIES algorithm is capable of excellent tone scale reproduction. This follows from the fact that highlight, shadow, and midrange halftone tints are detected by the low-pass filter and output via a relatively well-constrained halftone dot structure. The quality of the gray scale results is to some extent affected by the halftone input frequency, since the ARIES algorithm will allow some of that detail to pass through to the output. The microstructural detail for this process is not as well constrained as electronically screened continuous tone input; however, it is more constrained than algorithms such as error diffusion, and hence good quality pictorials often result.

Because of the inherent prioritization of assignment to black/white colors in this algorithm, high contrast detail in the input image is most often translated to the output. The contrast of the screen within the ARIES algorithm, however, has a negative effect on such assignments since it adds a relatively high frequency detail of its own. For example, if the ARIES screen contrast is 30 percent of the tone scale, then any fine detail of lesser contrast in the input image will likely have its edges serrated in the output image. Relative to the screening algorithms in Section VI-D, however, this algorithm must be considered as having a higher level of capability for detail reproduction across the entire tone scale.

As described above, the aliased frequencies that result from the halftone input and the internal halftone frequency are reduced by this algorithm. However, they are not always reduced to a level of invisibility. Depending upon the input image, internal screen frequency, and output marker, moiré artifacts visible to an observer may be generated. The low frequency filtering capabilities of this process reduce the input halftone carrier amplitude, but the edge enhancement amplifies some of this artifact.

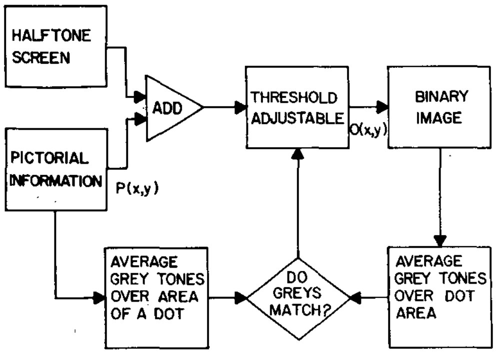


Fig. 34. Functional block diagram of ARIES signal processing capable of handling continuous tone, line copy, and halftone input.

From Fig. 34, one may note that the desired context for averaging is on the order of a halftone input cell. In this review, we may assume this average to be over something on the order of a 5 × 5 pixel array, assuming in the extreme a 65 cell/in halftone with a 250 sample/in sampling frequency. The remaining computations tend to be sequential and require a number of nonlinear branching steps. The priority assignment of white and black pixels requires an ordering of pixels by their gray value within the 2-D array. Performing this prioritization with 25 pixels is relatively complex compared with the error diffusion computation, but the remainder of the process is just a low-pass filter.

G. Selective Halftone Rescreening

1) *Definition:* As noted above, fixed and locally adaptive (line copy) thresholding are relatively good processing algorithms for low frequency halftone pictorials where low frequency refers to halftone cell frequency less than or equal to one-eighth of the scanning/sampling frequency. In cases such as this, the halftones are reproduced with minimal artifact and the inherent tone scale and detail are very well reproduced. On the other hand, for high frequency halftone input, practical scanning/sampling rates will often be such that moiré will result if fixed level thresholding is utilized.

To deal with the high frequency halftone input, it is possible to design a bandstop filter to eliminate the halftone carrier and simply pass the baseband representation of the image. The scanning system will already have performed some form of low-pass filtering via its sampling aperture, and a digital filter can be incorporated to complete the process of suppressing the halftone carrier and higher level harmonics while allowing the fundamental image signal to be captured. Also, the filter may be designed to suppress only high frequency halftone carriers and, therefore, have a relatively large bandwidth compared to that which would be required if low frequency halftones were also required to be filtered.

The end result of this filtering is a continuous tone representation of the input halftone pictorial, and this may subsequently be transformed into a binary representation via any of the techniques shown in Section V. For this review, electronic screening per Section V-D will be assumed. The opportunity of incorporating a specific screen function to match the constraints of the marking process most ideally is a positive feature of this processing technique.

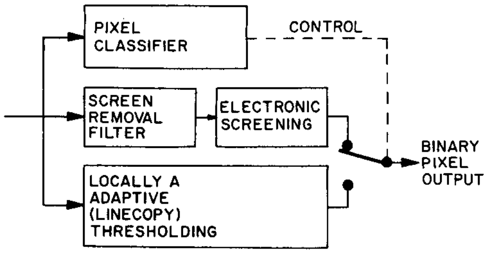


Fig. 35. Functional block diagram of relevant components of SHARE processing, if only halftone pictorial input is assumed.

Low frequency halftone pictorials will therefore be reproduced via locally adaptive (line copy) thresholding and high frequency halftones will be "rescreened." Adding a pixel discrimination circuit to select which of the two processes to use results in a simplified version of the selective halftone rescreening algorithm (SHARE) [55].

The original SHARE algorithm was a tricategory processor which enabled discrimination of 1) high frequency halftones, 2) low frequency halftones and line copy, and 3) continuous tone imagery. In that algorithm, pixels were initially classified as either being *high frequency halftone pixels* or *one of the other two classes* including low frequency halftone input. Subsequently, discrimination and processing logic reproduced the line copy and low frequency halftone input via an adaptive thresholding (line copy) process while the continuous tone input was electronically screened. For this review, it suffices to recognize the processes required for discrimination of high frequency halftone input from the other classes of pixels. Fig. 35 shows the relevant functional block diagram.

Pixel Classifier: The pixel classifier is composed of two levels of hierarchical classification logic. The first level, microdetection, is a one-dimensional classifier of single pixels or groups of pixels. The second level uses a two-dimensional context. See Fig. 36.

The *microdetection* technique utilized for discriminating high frequency pixels is based on the autocorrelation properties of the halftone signal. This is equivalent to a power spectral discrimination, and other techniques [56], [57] may be incorporated. However, the details are presented below from the space domain.

Fig. 37 gives an example of a one-dimensional autocorrelation generation process utilizing 32 pixels configured to discriminate the center 8 pixels. Fig. 38 shows a typical correlation function output for halftone input. Discrimination of high frequency halftone input is accomplished simply by noting a steep decrease in the autocorrelation function to a minimum peak followed by a rapid rise to an adjacent secondary peak. This secondary peak will be at a fixed period due to the halftone frequency, and therefore a simple spatial frequency discriminator can be enabled.

The *macrodetection* step simply looks at a larger context than the 1-D autocorrelation and makes a final decision on a group of pixels. The following outlines one of the simplest two-dimensional context discriminators.

The output from the autocorrelation is a single bit denoting high or low frequency halftone for each group of, for example, 8 pixels. The macrodiscriminator is composed of a memory

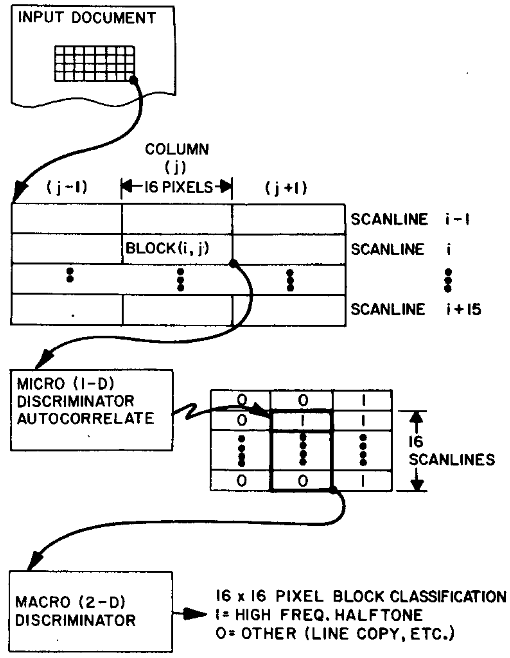


Fig. 36. Overview of pixel classifier for SHARE algorithm.

which contains a "count" (4 bits) for each group of pixels discriminated by the microdiscriminator. When a group of pixels is positively detected to be a high frequency halftone, the count is set to 15. If the group was classified as low frequency halftone pixels, then the present "count" is decremented by 1. Finally, a group of pixels is deemed to be a high frequency halftone group if its "count" or that of its immediate left or right neighbors is greater than 1.

Overall, the macrodiscriminator simply uses 2-D information to minimize false negatives. A number of variants for the details of the macrodiscriminator above are possible, but the technique described here is both simple and robust.

Screen Removal Filter: The basic approach to designing a *rescreening filter* is to allow the baseband signals to be passed for a specified high frequency halftone class. A bandstop region is created to suppress the halftone carrier and higher order harmonics which may generate low frequency aliasing artifacts. Fig. 39 shows a screen removal filter for an arbitrary class of input screen frequencies above 3 cells/mm. The simple (FIR) digital filter transforms the halftone pictorial input into a continuous tone pictorial.

Although the technique of "low-pass filtering" halftone pictorials has been a popular technique in the graphic arts world for some time, the approach utilized a defocused lens or other equivalent process which in general yielded a low detail representation of the input halftone image. Digital filtering can yield very sharp frequency cutoffs, as well as a uniform spatial frequency transfer function throughout the entire image; therefore, electronic rescreening is a very potent technique for reproducing high frequency pictorial halftones.

The remaining steps, *electronic screening* and *adaptive thresholding*, shown in Fig. 35, were described in Section V.

2) *Evaluation:*

Low Frequency Rendition: The low frequency halftone input will, as noted in Section VI-A, have the capability of

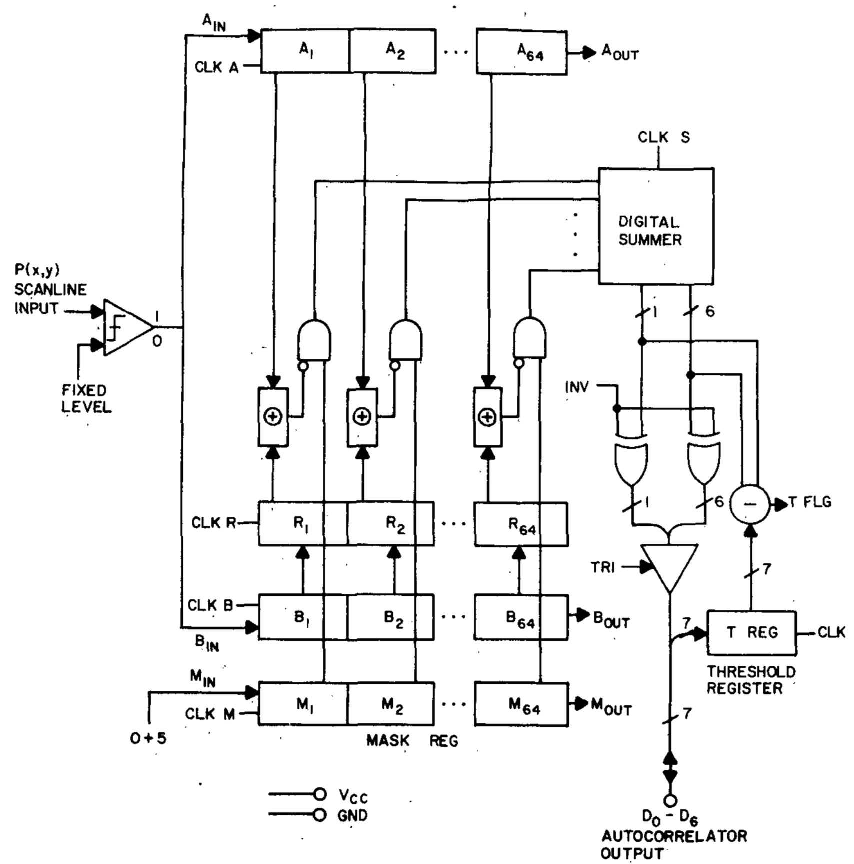


Fig. 37. Block diagram of microdetection function, 1-D autocorrelator for 32 pixels.

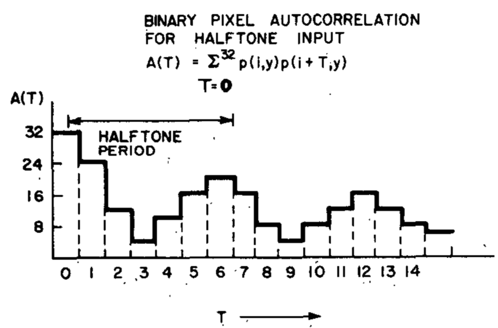


Fig. 38. Output of "binary autocorrelator" for halftone input.

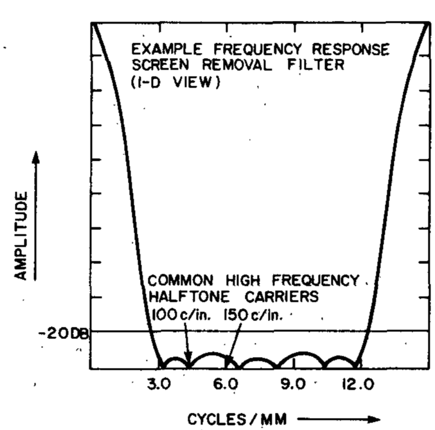


Fig. 39. Screen removal filter for SHARE algorithm.

large dynamic tone scales and a relatively accurate tone reproduction curve. The high frequency halftone process (rescreening) is also capable of reproducing the complete tone scale with high fidelity. Furthermore, the rescreened halftone input may have its TRC altered so as to match even better the output marking process. This capability, along with the opportunity to adjust the output screening process to account for marking process constraints, should enable a most high quality pictorial with a minimum of printability constraints in the marking process.

The low frequency halftone input will again have extremely good high contrast and even low contrast detail reproduction, given that the sampling rate will by definition be high relative to the input halftone frequency. For high frequency halftone input, the low contrast fine detail will likely be attenuated. Low contrast detail of the size of the halftone dots will be blurred by the rescreening filter. However, since these are only high frequency halftones, this detail is usually less frequent and less important. High contrast detail, for example, a high contrast edge, will be softened by the rescreening filter and subsequent processing.

The key source of artifacts for the SHARE algorithm is the misclassification of pixels. Some regions of high frequency halftones may be misclassified as low frequency pixels, and thus that region of the image is adaptively thresholded. This results in a mixture of halftone dot structures in one image and, thus, a potentially visible artifact. Misclassifications of the low frequency pixels will also result in artifacts; therefore, accurate discrimination is important.

TABLE II
SUMMARY OF ALGORITHM PERFORMANCE–HALFTONE REPRODUCTION

	LOW FREQUENCY RENDITION (PRINTABILITY)	HIGH FREQUENCY RENDITION	ARTIFACT	PROCESSING COMPLEXITY
THRESHOLDING (GLOBALLY FIXED)	• LIMITED TONE SCALE VS VERY HIGH SAMPLE RATES. • NO TRC CONTROL AND REQUIREMENT FOR RELIABLE ISOLATED PIXEL PRINTING.	• EXCELLENT HIGH CONTRAST AND MIDTONE DETAIL REPRODUCTION. • LIMITED HIGHLIGHT AND SHADOW DETAIL DETECTION. • GOOD EDGE LOCATION (PHASE).	• SAMPLING MOIRE.	• 1 PIXEL CONTEXT.
THRESHOLDING (LOCALLY ADAPTIVE "CONSTRAINED AVERAGE")	• LIMITED TONE SCALE BUT LARGER THAN "FIXED LEVEL". • NO TRC CONTROL AND ISOLATED PIXEL REQUIREMENTS AS IN FIXED LEVEL.	• BETTER THAN FIXED LEVEL AT NONMAXIMAL CONTRAST DETAIL DETECTION. • GOOD EDGE LOCATION (PHASE).	• SAMPLING MOIRE MORE VISIBLE THAN FIXED LEVEL THRESHOLDING.	• 9 PIXEL CONTEXT, (2-D). • WEIGHTED AVERAGE PIXEL SUMMATION.
ARIES	• FULL TONE SCALE CAPABILITY. • TRC CONTROL ENABLED, SOME CONTROL OF OUTPUT MICROSTRUCTURE.	o GOOD, HIGH-CONTRAST DETECTION, BETTER THAN ELECTRONIC HALFTONING, ORDERED DITHER, AND QP SCREENING. • SOME BLUR DUE TO PRESENCE OF SCREEN FUNCTION.	• SOME MOIRE VISIBILITY BUT BELOW THAT OF ALL OTHER ALGORITHMS OTHER THAN ERROR DIFFUSION AND SHARE.	• 25 PIXEL CONTEXT (2-D), PRIORITY RANKING OF PIXELS AND "COLOR" ASSIGNMENT LOGIC.
SHARE	• FULL TONE SCALE. • TRC CONTROL AND OUTPUT MICROSTRUCTURE CONTROL ENABLING THE BEST FIT OF "SCREEN FUNCTION" TO MARKING PROCESS.	• HIGH CONTRAST EDGES DETECTED AND LOCATED ACCURATELY. • LESSER CONTRAST, HIGH FREQUENCY HALFTONE DETAIL "BLURRED".	• MINIMAL MOIRE. • SOME FALSE TEXTURE CONTOURS FROM LOGIC ERRORS.	• 35 PIXEL CONTEXT (2-D) (SCREEN REMOVAL FILTER), SCREEN STORE, AUTO-CORRELATOR, CONTEXT BUFFER MACROLOGIC,
ELECTRONIC SCREENING, ORDERED DITHER, QUASI PERIODIC SCREENING (QP)	• FULL TONE SCALE CAPABILITY FOR ALL. • TRC CONTROL BUT LIMITED PRINTABILITY GUARANTEES SINCE ORIGINAL MICROSTRUCTURE PASSES THROUGH. ORDERED DITHER AND QP SCREENING ARE MORE DEMANDING.	• RANKED: ORDERED DITHER, ELECTRONIC SCREENING, QP SCREENING. • HIGH CONTRAST DETAIL DETECTED, BUT LESSER CONTRAST DETAIL BLURRED MORE THAN ADAPTIVE THRESHOLDING.	• PROCESSING MOIRE RANKED: QP SCREENING ORDERED DITHER, HALFTONE SCREENING. • QP SCREENING GENERATES MORE "NOISE".	• 1 PIXEL CONTEXT, STORED THRESHOLD MATRIX. QP SCREENING REQUIRES ADDITIONAL PN SEQUENCING.
ERROR DIFFUSION	• FULL TONE SCALE. • NO TRC CONTROL, NO CONTROL OF OUTPUT MICROSTRUCTURE.	• BEST OVERALL DETAIL DETECTION WITHIN FULL TONE RANGE, CONTEXT DEPENDANT. • EDGES STILL "BLURRED".	• LESSENS SAMPLING MOIRE TO NEAR INVISIBLE LEVEL. • "NOISY" TEXTURE.	• 12 PIXEL CONTEXT, (2-D).

It should be noted that, for a given scanning system, the halftones with the greatest misclassification rate and therefore the most artifacts are those with halftone frequencies nearest to the boundary separating low frequency from high frequency halftones.

The SHARE algorithm is the most complex of any of the algorithms in this section. A 4 × 8 pixel context is needed for the rescreening filter, i.e., 4 scan lines. Also, the autocorrelator utilizes a 32 × 1 binary pixel context, and the macrodiscriminator incorporates *storage* of a "count" for each group of, for example, 8 pixels in a scan line. For comparison purposes, the context can be assumed to be the 32 pixels used for the rescreening filter, provided one does not lose sight of all the additional processing done in parallel.

H. Summary–Halftone Reproduction

In Section VI, a number of algorithms were reviewed to evaluate their capability of reproducing halftone pictorial input. Table II summarizes the reviewed algorithms along with their characteristic strengths and weaknesses.

To view the results of applying the most unique of the algorithms above, a 150 cell/in halftone version of Fig. 23 was scanned at 250 samples/in, processed by the selected algorithms, and printed on a Versatec plotter with a 200 sample/in resolution. This manuscript is reduced for publication to 75 percent of the original size, so the "journal imagery" have an apparent output resolution of 266 samples/in. See Figs. 40-47.

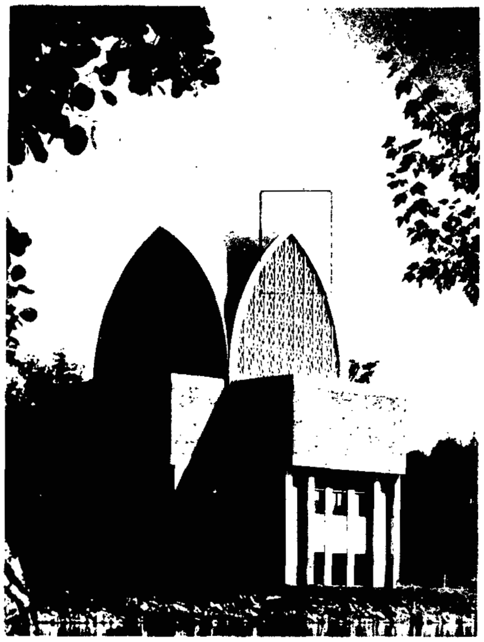
VII. CONCLUSIONS

Electronic manipulation of pictorial imagery for document creation, storage, communication, and reproduction will often utilize "binary" marking/display processes for cost effectiveness. This is not due to the predominance of digital electronics, but to the practical constraints that have resulted in virtually all printed pictorials (gravure, letterpress, and lithography) being generated in the "binary mode."

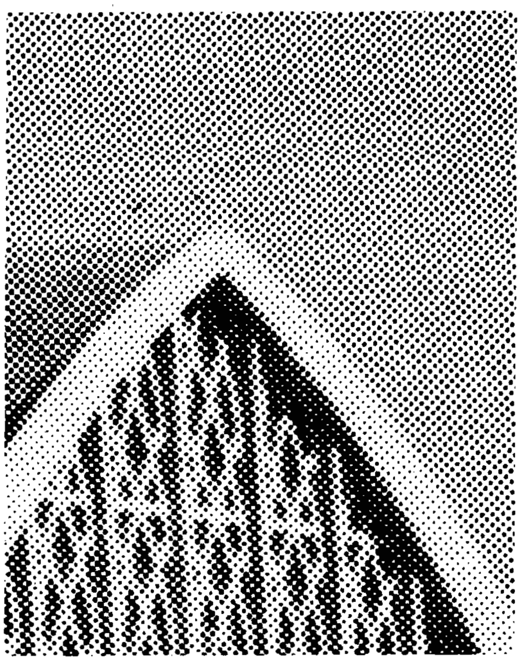
There are two classes of pictorial input, continuous tone and halftone, which have very different properties and therefore require unique reproduction processes. This survey makes the assumption that both classes of imagery are captured by an electronic scanning system and then examines algorithms which are capable of generating a binary pixel representation of the input.

For continuous tone imagery, there is a small difference in processing complexity amongst the algorithms. However, there are major tradeoffs in tone scale range, fine detail reproduction capabilities, and false contours that must be evaluated for each application.

With regard to halftone input, there are unique power spectral properties that motivate greater processing complexity in some of the surveyed algorithms. In this case, the sampling resolution for a specific application will have a profound effect

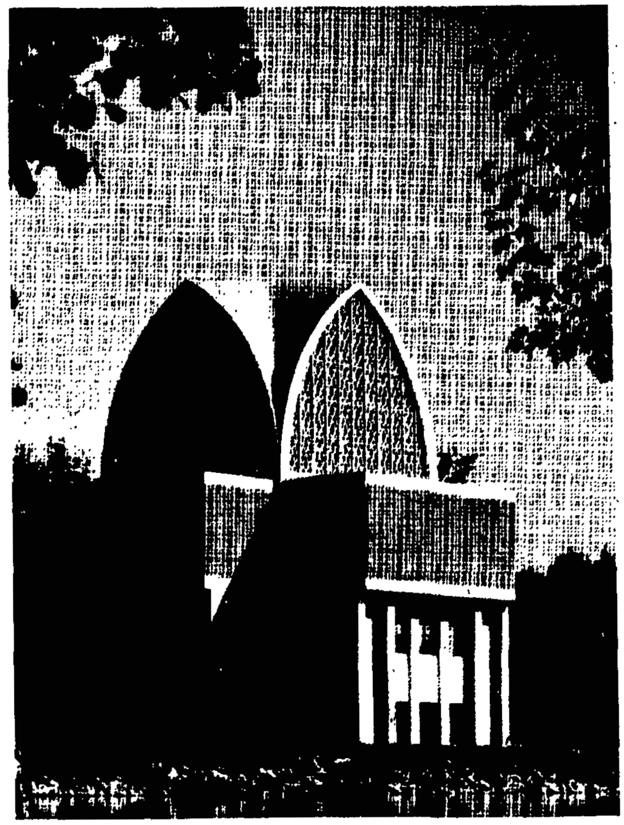


(a)

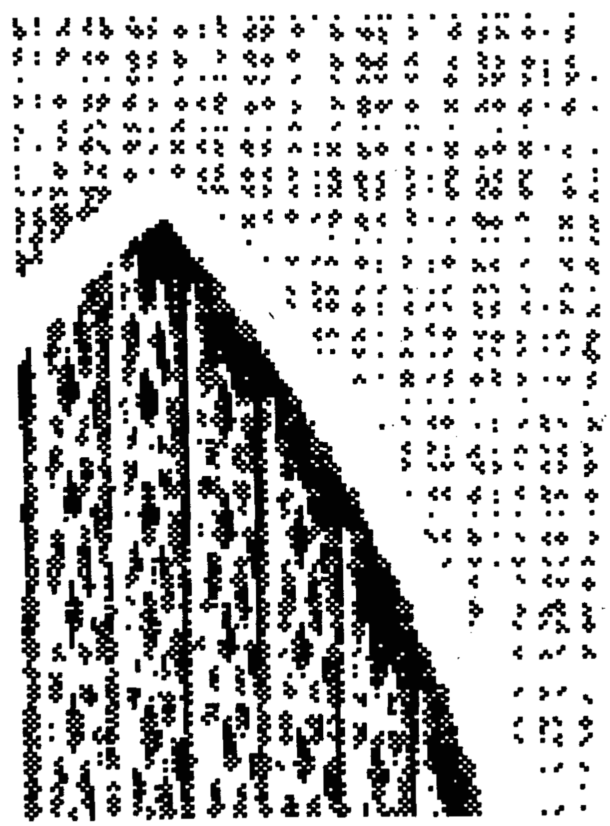


(b)

Fig. 40. Original halftone input (150 cells/in). (b) Magnified subimage of (a).

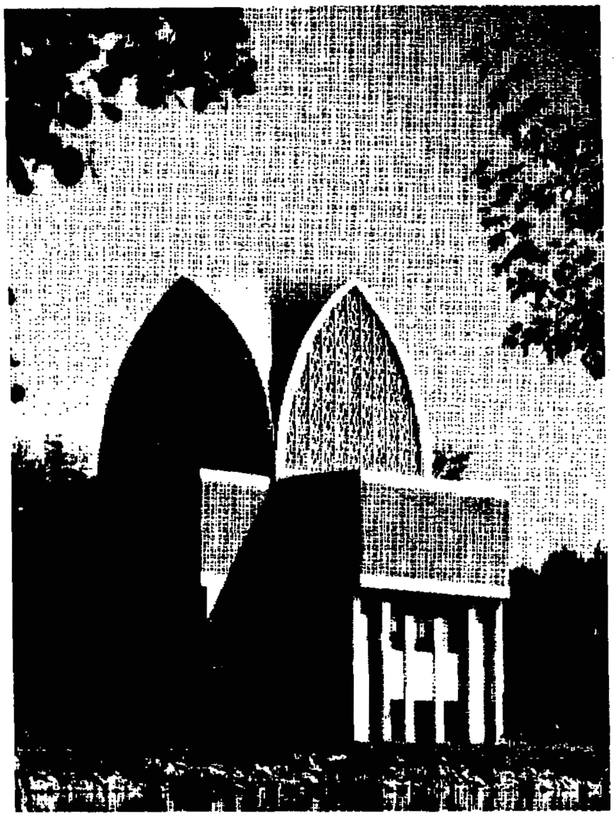


(a)

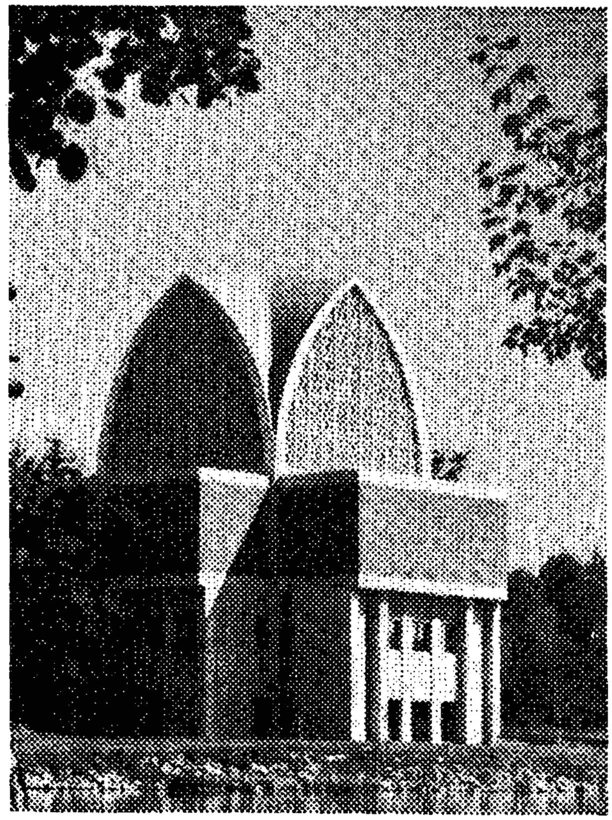


(b)

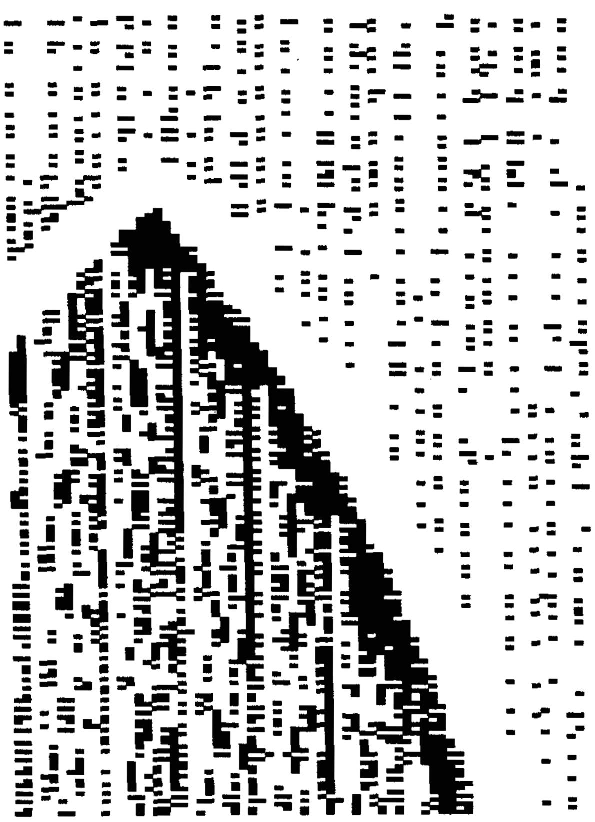
Fig. 41. Fixed threshold output. (b) Magnified subimage of (a).



(a)

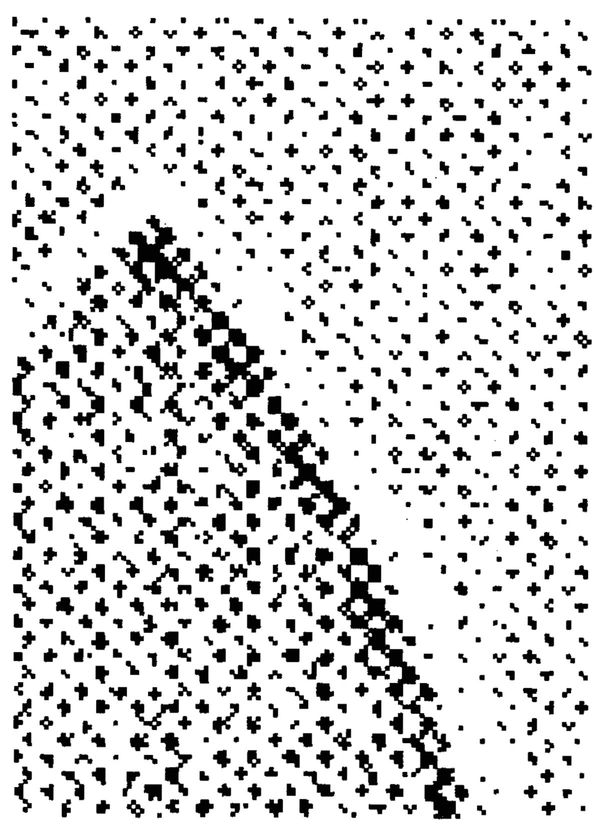


(a)



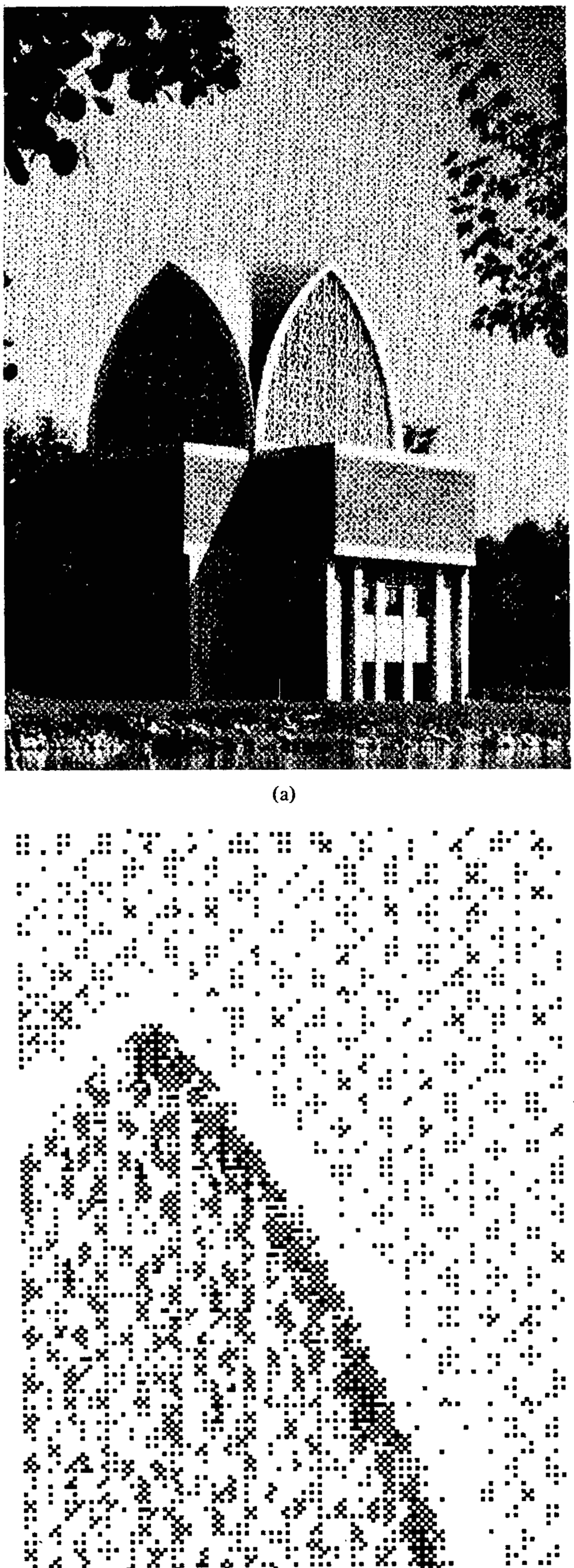
(b)

Fig. 42. Constrained average output. (b) Magnified subimage of (a).



(b)

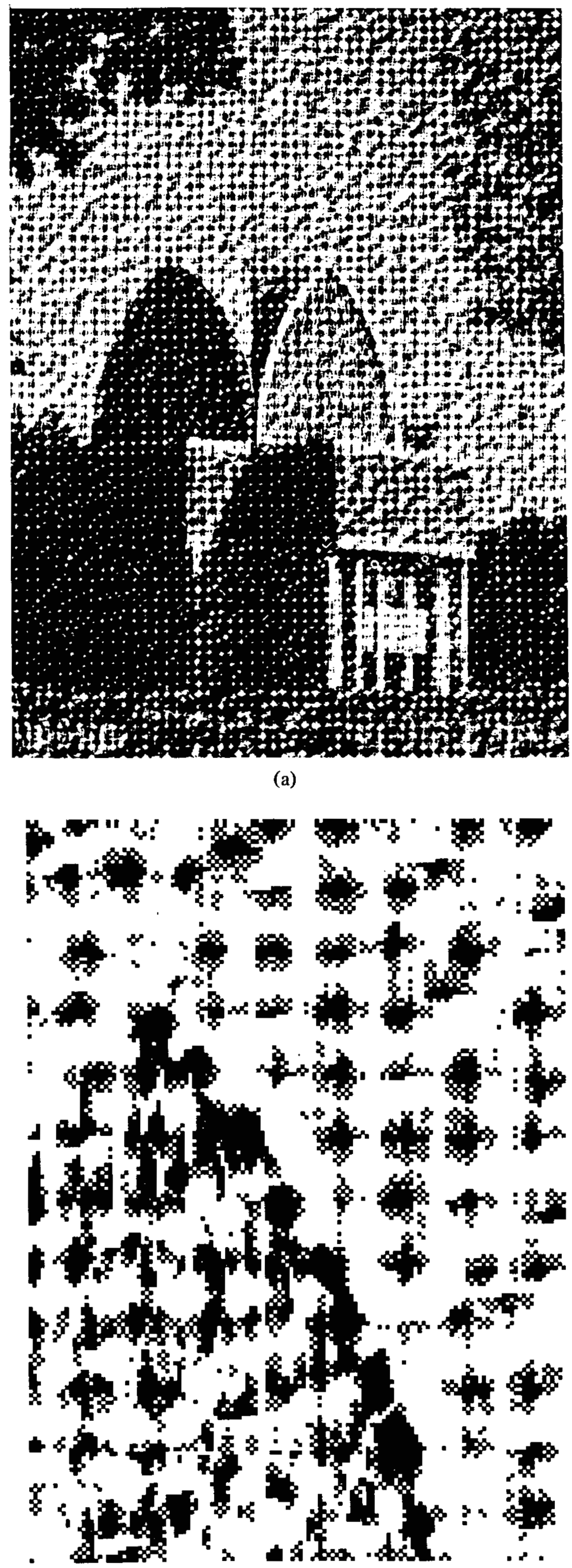
Fig. 43. Electronic screening output. (b) Magnified subimage of (a).



(a)

(b)

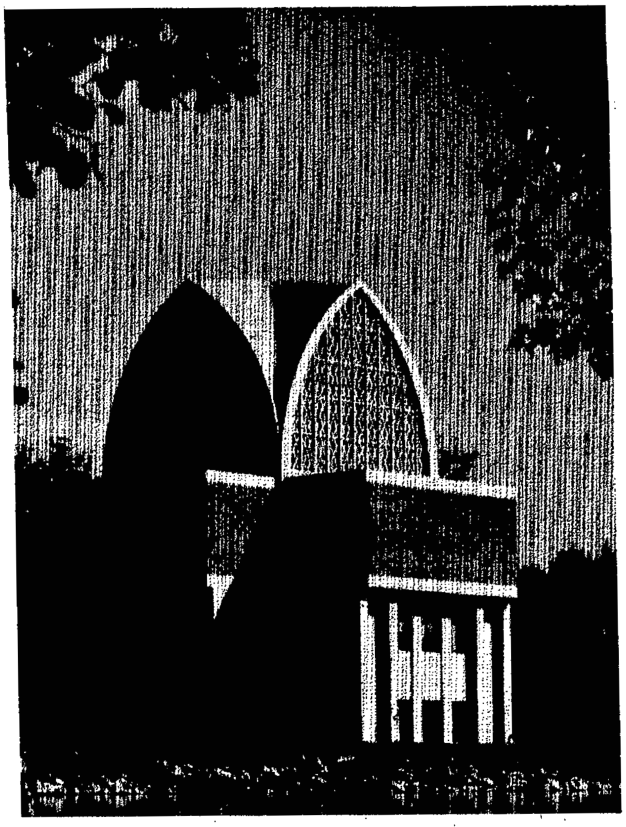
Fig. 44. Ordered dither output (Bayer's). (b) Magnified subimage of (a).



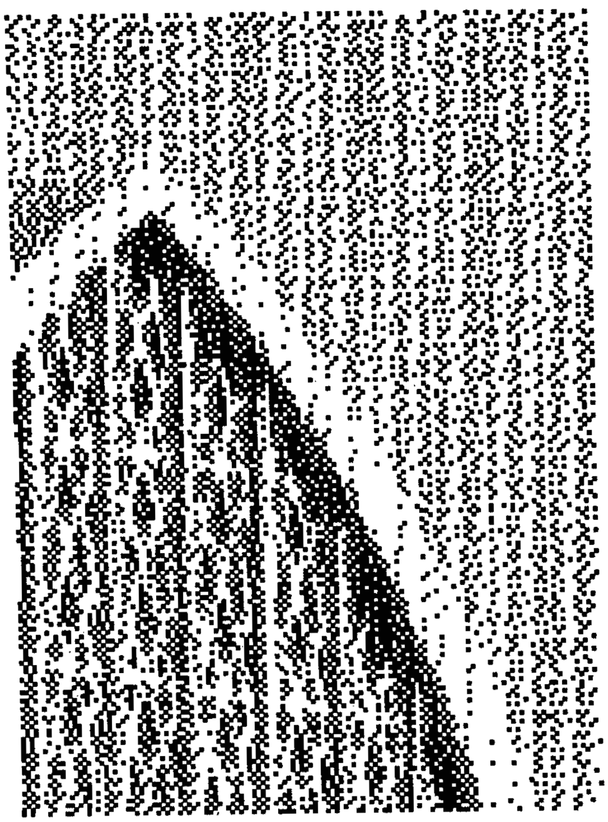
(a)

(b)

Fig. 45. Random nucleated halftoning output. (b) Magnified subimage of (a).

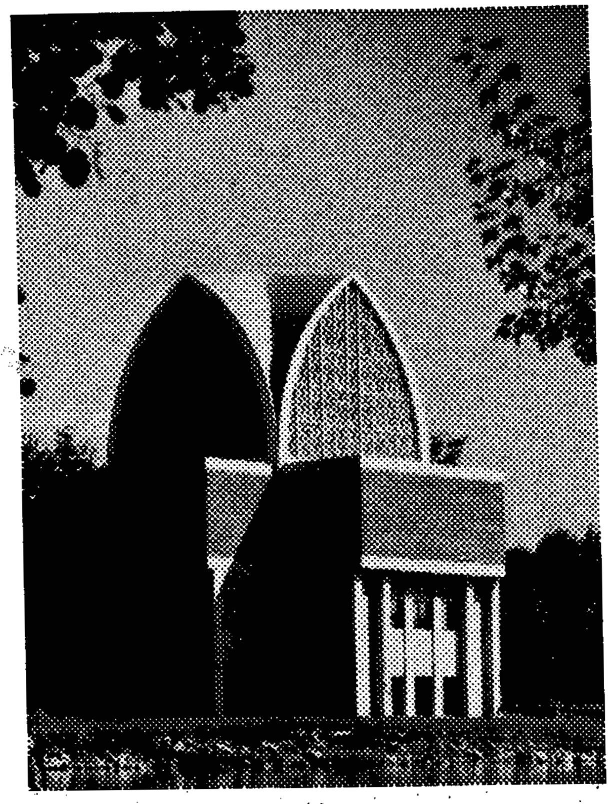


(a)

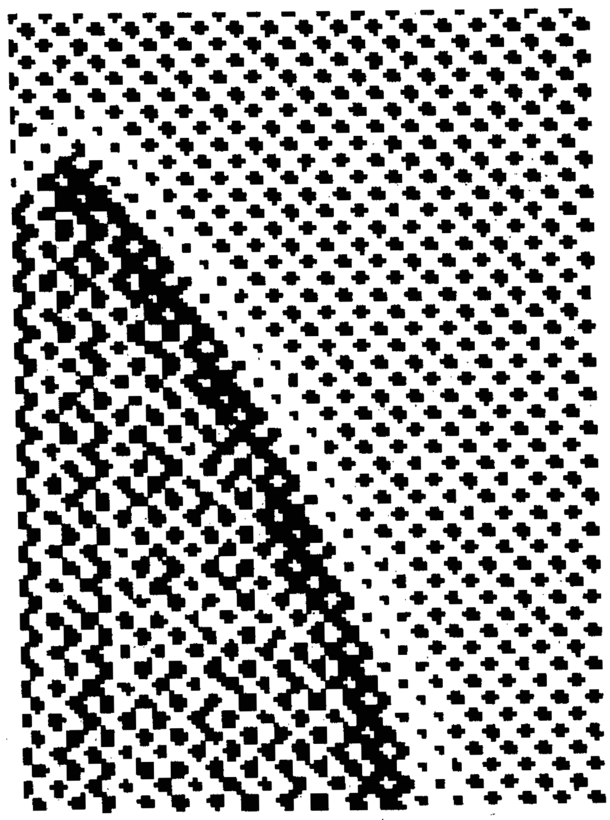


(b)

Fig. 46. Error diffusion output. (b) Magnified subimage of (a).



(a)



(b)

Fig. 47. SHARE (rescreening) output. (b) Magnified subimage of (a).

on the selection of a desired technique. Furthermore, artifact minimization will be a dominant issue when selecting a desired process.

Overall, the pictorial features of low and high frequency rendition along with minimization of artifacts are important for both classes of pictorials; however, they are unique input classes and each application should be addressed individually.

ACKNOWLEDGMENT

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Adaptive Block/Location Coding of Facsimile Signals Using Subsampling and Interpolation for Pre- and Postprocessing

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***Abstract*—In this paper, an information lossy preprocessing technique using subsampling is described. Notches and pinholes in the original image are first removed using a set of masks, after which single element runs are doubled to preserve connectivity. The image is then subsampled by taking alternate picture elements (pels) horizontally and vertically. Enlargement of the subsampled image is carried out at the receiver where replication, bilinear, and cubic B-spline interpolation techniques are investigated. The edges of the interpolated images are "smoothed out" by a set of restoration masks, producing a visually acceptable result. A formal subjective experiment is also conducted to determine the order of subjective preference of the resulting restored images. Finally, adaptive block/location coding (ABLC), with respect to a numerical measure of complexity, is used to code the subsampled image. Compression ratios achieved for the CCITT documents range from 13.31:1 to 63.77:1, a reduction, on average, by about 40 percent when one-dimensional run-length coding using the modified Huffman code (MHC) is applied to the subsampled image and by about 73 percent when MHC is applied to the original data.**

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I. INTRODUCTION

THE growing need to transmit black and white documents quickly has prompted researchers to resort to an information lossy approach to facsimile coding. Preprocessing [1]-[2] prior to coding is one such approach which enables the compression ratios (CR's) of existing coding methods to be significantly enhanced. Signal modification [3], a thinning process [4], and the notchless bilevel quantizer with logical feedback [5] are some of the more important techniques. Preprocessing to clean up noisy originals, to ensure that the CR's remain high, has been extensively studied by Ting and Prasada [6]. The combined symbol matching (CSM) technique [7] is another approach where extremely high CR's are obtained for alphanumeric documents which are efficiently coded by symbol recognition techniques. However, CSM has the disadvantage of not maintaining its superior performance for graphics-type documents and it is relatively complex to implement.

This paper describes another information lossy approach to facsimile coding using a subsampling technique. The coding scheme, known as adaptive block/location coding (ABLC), is an area coding algorithm which takes a square block of pic-

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