Digital Halftoning Using Optimum Pattern Selection in Human Visual System

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Abstract

This paper proposes a new approach to the problem of producing high quality halftone images. In order to reproduce continuous-tone images on bilevel output devices such as non-impact printers, various halftoning techniques have been developed. Ordered dither and error diffusion (or minimum average error) are the typical methods widely used for the purpose. In these methods, decision of bilevel is made on each pixel bases. In this paper, a new method named "Optimum Pattern Selection " is proposed. In the proposed system, each non-overlapping block of n × n pixels is taken up from the original continuous-tone image. On the other hand, all the possible binary patterns of the same size, i.e. n × n pixels, are generated mathematically. Each of the binary patterns is then transformed to a reproduced continuous-tone image block by a lowpass filter, which is a simplified model of HVS (Human Visual System). The reproduced images are then compared to the original image block. The optimum binary pattern, which brings about the reproduced image most similar to the original image block, is selected. For the purpose of improving the halftone image quality further, the optional filter switching algorithm is introduced.

Introduction

Halftoning[1,2] is a process of converting a continuous-tone image to a visually similar binary dot pattern. Halftone images are used in conventional printing, electronic printing, facsimile, and in other applications. Since halftoning has tremendous practical value, many algorithms have been studied and proposed. The two most common conventional algorithms of digital halftoning are ordered dither[3] and error diffusion.[4]

However, the following limitations have been pointed out. In ordered dither, it is difficult to achieve both high resolution and high fidelity gray-level reproduction at the same time, because dither matrix of the fixed position is used. Moreover, peculiar texture, the origin of which is its dither matrix, is noticeable. In error diffusion, correlated artifacts, a little similar to contour lines and sometimes called "serpentine raster", are visible. In addition, transient behavior appears near edges or boundaries. They are because a binary decision is made at each pixel respectively.

Basic System

A basic system is considered first. In the Figure 1, both the original image and the halftone image consist of N × N picture elements. Although a halftone image is obviously binary, it is perceived to our visual system as if it were a continuous-tone image, on condition that it is seen from a position of certain distance from the image. This phenomenon can be explained by the fact that HVS averages fine texture, and it is modeled by a lowpass filter. The next fact turns out. There are no more than finite number, in this case $2^{N \times N}$, of halftone images. If the lowpass filter is given, there is one or more optimum halftone image among them. It is optimum because its score is the best under a given evaluation criteria. What we have to do is to choose the best among no more than finite number of halftone images.

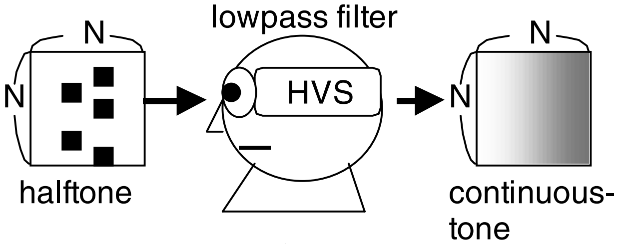

Figure 1. HVS

However, even if the image is small and N=256, $2^{N \times N}$ is a huge number, and it takes very long time to try all of them, even if the fastest supercomputer is used. How can we reduce the computation time? Kobayashi and Saito[5] divided an original continuous-tone image into non-overlapping square blocks, the typical size of which is 16 × 16 pixels. Moreover, they proposed to use GA (Generic Algorithm) to reduce the computation further. In their algorithm, candidates of the binary pattern corresponding to a block are regarded to be genes. Fitness value of each gene is the sum of two terms. The first term is the mean absolute error between the original image and Gaussian filtered halftone image, and the second is the contrast evaluation value. Tanaka[6] used SA (Simulated Annealing) instead of GA to remove the block boundary effect and to improve the picture quality.

Our approach is simpler. First, we also divide the original image to n × n pixel blocks, but the size is smaller. The value of n is four. Therefore, all the possible binary patterns of n × n pixel blocks can be evaluated. Second, we used a single criterion, namely the MSE (mean square error). The key is to design such a good filter that can generate high quality halftone images.

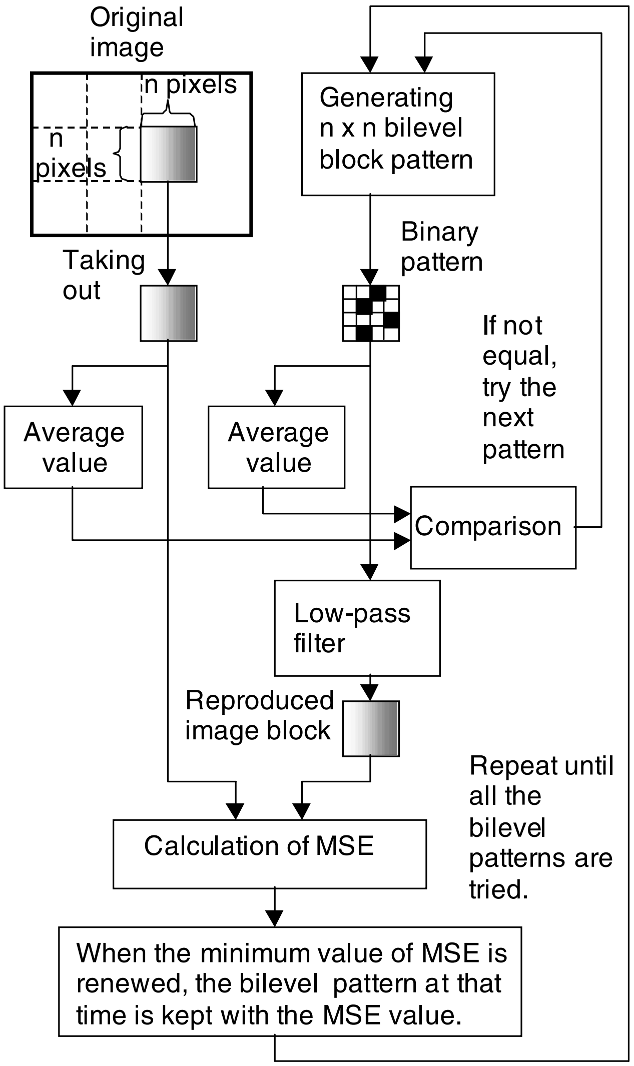

Figure 2. Block diagram of the proposed system

Proposed System

In the proposed system, the binary decision is done for every n × n block. Figure 2 shows the case in which a monochrome image, whose pixel is represented by 8 bit, is transformed to a halftone image, whose pixel is binary. First, the original image is divided into blocks of n × n pixels. In this paper, n is four. Second, pattern generator generates all the binary patterns of n × n pixels. The number of the patterns is $2^{n\times n} = 2^{4\times 4} = 65536$. These patterns are then transferred to a lowpass filter, and transformed to a continuous-tone image blocks of the same size. The lowpass filter can be regarded as an imitation of a human visual system. Each resulting continuous-tone image blocks is compared to the original image block, and the MSE between the blocks is calculated. The best pattern, which shows the smallest MSE, is selected.

Filter Design

The basic design conditions of the filters are as follows.

(A) The filter must be a linear phase filter. In other words, it must be a FIR (Finite Impulse Response) filter with symmetric coefficients.

(B) The filter must have unit gain at DC, in order to reproduce gray scale properly.

(C) The filter should have zero gain at the highest spatial frequency. Though this is not a necessary condition, we thought it is desirable for a smoothing filter.

For the purpose of simplification, we designed a one-dimensional five-tap filter first. From (A) the coefficients of the original five-tap filter can be described as a following vector.

$$\mathbf{v}=[c\ b\ a\ b\ c] \qquad (1)$$

The filter gain g is

$$g=a + 2b \cos 2\pi f + 2c \cos 4\pi f \qquad (2)$$

where f is the spatial frequency normalized by the sampling frequency. The highest spatial frequency included in the image signal corresponds to f=0.5, which means that one dark dot and one bright dot appear alternately. If f=0, it means that the brightness is constant.

From (B), g must be one if f=0. Therefore,

$$a + 2b + 2c = 1 \qquad (3)$$

From (C), g must be zero if f=0.5. Therefore,

$$a - 2b + 2c = 0 \qquad (4)$$

From (3) and (4) , b=0.25 and a=0.5 – 2c.

Namely, the degree of freedom left for us is only one. By changing the value of c, we can change the characteristics of the filter, which are shown in Figure 3. We produced many halftone images using various values of c.

The quality of halftone images is very sensitive to the value of c. By subjective evaluation we concluded that the optimum value of c is between zero and 1/16. In the case c=1/16, the coefficients of the filter is as follows.

$$\mathbf{v}=[1/16\quad 4/16\quad 6/16\quad 4/16\quad 1/16] \qquad (5)$$

Since image signals are two-dimensional by nature, we need a two-dimensional filter. We got the two-dimensional filter simply by multiplying vertical and horizontal filters, i.e.

1/256	4/256	6/256	4/256	1/256
4/256	16/256	24/256	16/256	4/256
6/256	24/256	36/256	24/256	6/256
4/256	16/256	24/256	16/256	4/256
1/256	4/256	6/256	4/256	1/256

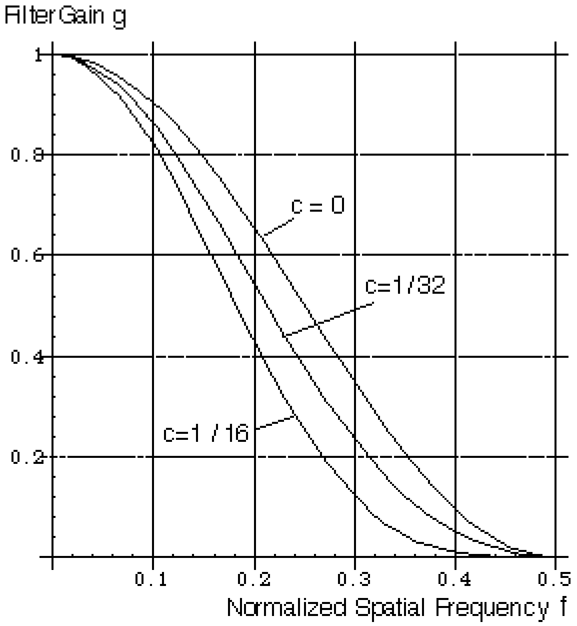

Figure 3. Filter characteristics

The filter refers to pixels not only inside the block, but also outside the block as shown in Figure 4. As for the pixels outside the block, halftone image data is used for already halftoned area, and original continuous-tone image data is used for other area.

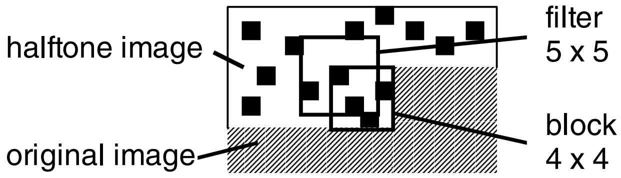

Figure 4. Referring pixels outside the block

Simulation Results

Figure 5 is a halftone image produced by the proposed algorithm. The original image is a part of an ISO/JIS SCID image titled"wine and tableware", the size of which is 256 × 256 pixels. Color information has been removed beforehand for our purpose. Artifacts, which are offence to the eyes in error diffusion, are substantially reduced. The quality of the halftone picture considerably depends on the filter characteristics. Filters with small c, for example c=0, produce halftone images with smoother texture, but their contour lines are not very clear. Filters with large c, for example c=1/16, generate halftone images with enhanced contours, which are comfortable to our eyes, though peculiar texture pattern is sometimes visible especially in flat areas. Anyway, the proposed algorithm seems to be a hopeful choice for those who require halftone technologies.

Figure 5. Halftone image produced by the proposed system (Basic algorithm)

Filter Switching

Figure 6 is a halftone image of an artificially generated gradation pattern. The texture is dense enough in almost all brightness levels between 0 (black) and 255 (white), but special unpleasant pattern is visible at specific brightness levels. In the case of Figure 5, coarse stripes or geometrical patterns can be seen at the range from 82 to 86. Probably, it is because of chaotic behavior of the system, since halftoning is a process which is located on the borderline between linear and nonlinear worlds.

A complete solution would be to find such a perfect single filter that can cover all the dynamic range. We are now trying to look for the filter, but it seems to be a tough problem. The other approach, which seems to be more practical, is to use multiple filters, and to switch them based on the average brightness level of the block. Figure 6 shows a halftone image generated by the filter switching approach. In this case two filters, corresponding to c=1/16 and c=0 respectively, are used. The latter filter is used only for such blocks that the average brightness level is between 82 and 86, and the former filter for the rest of the blocks. In Figure

7, Uncomfortable patterns on the background area have been disappeared.

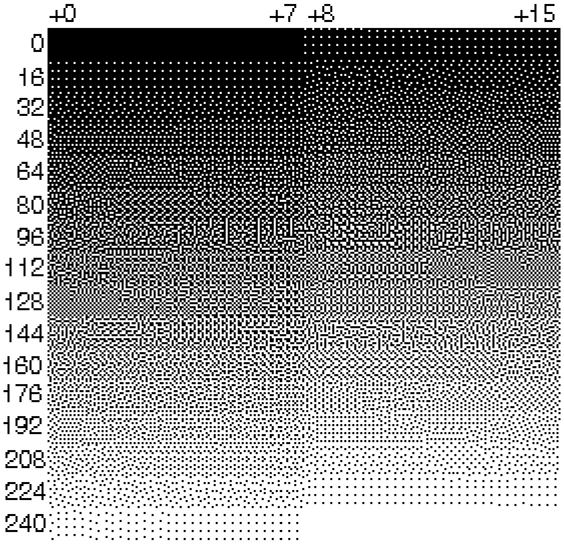

Figure 6. Halftone image of artificially generated gradation pattern

Figure 7. Halftone image produced by the proposed system (Filter switching algorithm)

Conclusion

A new technique for converting continuous-tone images to its halftoned versions has been proposed. In our algorithm, all the possible binary block patterns are generated and their low frequency component is compared to the original image, and the optimum pattern, which gives the least MSE between reproduced image block and the original image block is selected. By switching filters based on the average brightness value of the block, the quality of the resultant halftone images can be improved further. Optimization of various parameters, extension to color images, and reduction of computation, are left as future subjects.

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Biography

Kazuhisa Yanaka is a professor of Kanagawa Institute of Technology, Japan. He gained Bs., Ms. and Dr. degrees from the University of Tokyo, in 1977, 1979, and 1982 respectively. He joined Electrical Communication Laboratories of NTT in 1982 and developed videotex terminals, teleconferencing systems, and image coding algorithms. He moved to Kanagawa Institute of Technology in 1997.

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