A Multiscale Color Error Diffusion Algorithm for Color Quantization

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ABSTRACT

This paper presents a new multiscale vector error diffusion algorithm for color quantization. This iterative algorithm selects a pixel, color-quantizes it and then diffuses the quantization error with a non-causal filter at each iteration until all pixels are color-quantized. By doing so, directional hysteresis is completely eliminated and color impulses can be reduced to a certain extent. Simulation results show that it provides better outputs in terms of S-CIELAB color difference metric as compared with conventional approaches. The subjective quality of the output is also improved.

1. INTRODUCTION

Color quantization is a process which reduces colors of an image by replacing them with some representative colors selected from a palette [1,2]. It is widely used in many multimedia applications to save transmission bandwidth, save data storage requirement and make images displayable with a display device which supports only a limited number of colors.

The reduction of colors results in artifacts such as false contour and color shift. In general, the smaller the color palette size, the more severe the defects are. Digital halftoning techniques [3,4] especially error diffusion [5-8] would be helpful to eliminate these artifacts by making use of the fact that human eyes act as spatial low-pass filters.

Most halftoning algorithms are originally proposed for binary halftoning which emulates a gray level image with a binary image[3-5]. To apply them to color quantization, the most straightforward approach is to consider each color component plane as individual gray scale image and handle them separately[6-8].

However, this approach may only work in printing applications in which the output colors are composed of 3 or 4 bi-level fixed color components (CMY or CMYK). Color quantization is actually a vector quantization instead of a bi-level uniform scalar quantization as in the case of binary halftoning. It is not a combination of several independent bi-level uniform scalar quantization processes either. In general, when a low-end display unit such as a VGA monitor is involved, the palette colors are not uniformly distributed in the color space and hence the extension of binary halftoning to color halftoning is not as straightforward as most people assume. Besides, this approach is not an effective approach as it does not take the correlation among color components into account.

Figure 1 shows the system block diagram of a conventional system for color error-diffusion halftoning [1]. An image is raster scanned during the quantization process. After a pixel is quantized, the quantization error is diffused to its neighboring pixels with a casual filter.

Since a predetermined scanning order and a casual filter are used in the system, quantization error propagates along a fixed direction, which introduces directional hysteresis. The second problem is that it produces color impulses. In a smooth region, each pixel contributes a small amount of color error and, through diffusion, the error accumulates along the direction. Eventually the accumulated error is large enough to shift the color of an input pixel a lot and causes the quantizer to quantize the color to a color visually very different from its original.

Recently, Katsavounidis proposed an error diffusion algorithm [11] which used a non-casual filter and a non-predetermined scanning order to halftone a gray-level image. In this paper, we extend Katsavounidis's work [11] to handle color quantization with error diffusion. Our proposed algorithm eliminates directional hysteresis and is able to reduce color impulse to a certain extent.

2. PROPOSED ALGORITHM

In our proposed algorithm, color quantization is performed in YIQ color space so as to reduce the correlation among different color components. Another reason for doing so is that Euclidean distance in YIQ space matches HVS response more closely as compared with that in RGB space. This allows the color quantizer to select a visually more appropriate palette color with a given input. Without lose of generality, hereafter, we assume the color palette and the input image are defined in YIQ space. If they are not, color transformation will be required to transform their colors from their original domain to YIQ domain before color quantization.

Let **X** be a 24-bit $N \times N$ true-color image each pixel of which is represented as $\vec{\mathbf{X}}_{(i,j)} = (X_{(i,j)Y}, X_{(i,j)I}, X_{(i,j)Q})$, where $X_{(i,j)c}$ for $c \in \{Y, I, Q\}$ is the intensity value of the c^{th} primary color component of the $(i,j)^{th}$ pixel of the image.

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The proposed algorithm is an iterative algorithm. Let $\mathbf{U}$ be an image which reports the current status of the image being processed at the beginning of a particular iteration. At each iteration, the algorithm first locates a pixel location based on the maximum energy guidance with an energy pyramid $\mathbf{E}$ associated with $\mathbf{U}$. The details of the pyramid will be elaborated later. The selected pixel is then color-quantized with a predefined set of colors (palette). The quantization error is diffused with a non-casual filter to neighboring pixels to update $\mathbf{U}$. These procedures are repeated until all pixels are color-quantized. At the start of the first iteration, $\mathbf{U}$ is initialized to be $\mathbf{X}$.

A. Constructing energy pyramid E

Let $\mathbf{M}$ be a mask of size $N \times N$ which defines which pixels have been color-quantized. Specifically, its element $M_{(i,j)}$ is 0 if $\vec{\mathbf{X}}_{(i,j)}$ has been color-quantized or else it is 1.

A multiscale representation of a given color image $\mathbf{U}$ is defined as a sequence of matrices $\{\mathbf{U}^0, \cdots \mathbf{U}^l, \cdots \mathbf{U}^L\}$, where $L = \log_2 N$ and $\mathbf{U}^L = \mathbf{U}$. $\mathbf{U}^l$ is of size $2^l \times 2^l$ and its $(i,j)^{th}$ element is a triplet ($U^l_{(i,j)Y}, U^l_{(i,j)I}, U^l_{(i,j)Q}$) for $i,j = 0,1,\ldots,2^l - 1$. Elements of $\mathbf{U}^l$ for l = 0, $1 \cdots L-2$ is defined as

$$U^l_{(i,j)c} = \sum_{m=0}^{1}\sum_{n=0}^{1} U^{l+1}_{(2i+m,2j+n)c} \qquad for\ c \in \{Y,I,Q\} \qquad (1)$$

while elements of $\mathbf{U}^{L-1}$ is defined as

$$U^{L-1}_{(i,j)c} = \begin{cases} \frac{1}{S}\sum_{m=0}^{1}\sum_{n=0}^{1} M_{(2i+m,2j+n)} U^L_{(2i+m,2j+n)c} & if\ S \neq 0 \\ 0 & else \end{cases}$$

$$\text{for } c \in \{Y,I,Q\} \quad (2)$$

$$\text{where } S = \sum_{m=0}^{1}\sum_{n=0}^{1} M_{(2i+m,2j+n)} \qquad (3)$$

The energy pyramid $\mathbf{E}$ associated with image $\mathbf{U}$ is then constructed with $\{ \mathbf{E}^l \mid l = 0,1,\cdots L \}$, where $\mathbf{E}^l$ is the energy plane of matrix $\mathbf{U}^l$. The $(i,j)^{th}$ element of $\mathbf{E}^l$ is defined as

$$E^l_{(i,j)} = \begin{cases} \left| U^l_{(i,j)Y} + U^l_{(i,j)I} + U^l_{(i,j)Q} \right| & if\ 0 \le l < L \\ \left| M_{(i,j)}\left(U^L_{(i,j)Y} + U^L_{(i,j)I} + U^L_{(i,j)Q}\right) \right| & if\ l = L \end{cases}$$

$$\text{for } i,j = 0,1,\ldots,2^l - 1 \quad (4)$$

B. Searching the pixel for color quantization

The location of a pixel to be color-quantized is determined via maximum energy guidance with energy pyramid $\mathbf{E}$. The location is obtained by searching the energy pyramid from the coarsest level $\mathbf{E}^0$ to the finest level $\mathbf{E}^L$. Note that $\mathbf{E}^0$ contains only one element $E^0_{(0,0)}$.

Assume that we are now at position $(l,(i,j))$ which corresponds to the $(i,j)^{th}$ element of a particular level l. We check $\{ E^{l+1}_{(2i+m,2j+n)} \mid m,n = 0,1\}$ and proceed to the position $(l+1,(2i+p,2j+q))$ such that $E^{l+1}_{(2i+p,2j+q)}$ is maximum in $\{ E^{l+1}_{(2i+m,2j+n)} \mid m,n = 0,1\}$ and $p,q \in \{0,1\}$. If more than one position satisfies the criterion, one of them will be randomly selected.

C. Color Quantization and Error Diffusion

Let $(L,(m,n))$ be the position that we finally reach at the finest level of the pyramid $\mathbf{E}$ in the search and $C = \{\hat{\mathbf{v}}_i : i = 1,2,\cdots N_c\}$ be the given color palette. $\vec{\mathbf{U}}_{(m,n)}$ =($U_{(m,n)Y}$, $U_{(m,n)I}$, $U_{(m,n)Q}$) is then color-quantized. The best-matched color in the palette, say $\hat{\mathbf{v}}_k$, is selected based on the minimum Euclidean distance criterion in YIQ color space as follows.

$$\left\| \vec{\mathbf{U}}_{(m,n)} - \hat{\mathbf{v}}_k \right\| \le \left\| \vec{\mathbf{U}}_{(m,n)} - \hat{\mathbf{v}}_l \right\| \qquad \forall\ \hat{\mathbf{v}}_l \in C \quad (5)$$

The quantization error $\vec{\varepsilon} = \hat{\mathbf{v}}_k - \vec{\mathbf{U}}_{(m,n)}$ is then diffused to $\vec{\mathbf{U}}_{(m,n)}$'s neighborhood to update image $\mathbf{U}$ with a non-causal filter. In formulation, it is given as

$$\vec{\mathbf{U}}_{(i,j)} = \vec{\mathbf{U}}_{(i,j)} - W_{(m-i,n-j)}\vec{\varepsilon}$$

$$\text{for } i = m \pm 1 \text{ and } j = n \pm 1 \quad (6)$$

where W is defined as $W = \begin{bmatrix} W_{(-1,-1)} & W_{(-1,0)} & W_{(-1,1)} \\ W_{(0,-1)} & W_{(0,0)} & W_{(0,1)} \\ W_{(1,-1)} & W_{(1,0)} & W_{(1,1)} \end{bmatrix} = \begin{bmatrix} 0.0833 & 0.1667 & 0.0833 \\ 0.1667 & -1.0000 & 0.1667 \\ 0.0833 & 0.1667 & 0.0833 \end{bmatrix}$. To handle the boundary and the corner pixels, W is modified to be $\begin{bmatrix} 0.0000 & 0.0000 & 0.0000 \\ 0.2500 & -1.0000 & 0.2500 \\ 0.1250 & 0.2500 & 0.1250 \end{bmatrix}$ and $\begin{bmatrix} 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & -1.0000 & 0.4000 \\ 0.0000 & 0.4000 & 0.2000 \end{bmatrix}$ respectively to avoid energy leakage.

3. SIMULATIONS

Simulations were carried out on a number of *de facto* standard 24-bit full-color images of size 256×256 each to evaluate the performance of the proposed algorithm. Figure 2 shows the testing images used in the simulation. These images were color-quantized with color palettes of different size. The color palettes were generated with median-cut algorithm [2].

For comparison, some other error diffusion algorithms for color quantization were also evaluated. Unlike most color halftoning algorithms which are dedicated for printing applications, these evaluated algorithms are not straightforward extension of binary halftoning and are able to handle color quantization in which any arbitrary palettes can be used.

Among them, Akarun's algorithm [9] takes the correlation among color components into account and derives an error diffusion filter adaptively with the input for achieving a better color quantization results. Breaux's algorithm [10] color-quantizes an input image without halftoning at first and then refines it by adjusting certain pixels. Orchard's algorithm [1] is the conventional approach for producing a halftoned color-quantized image. In its realization, halftoning was performed by error diffusion and Floyd-Steinberg filter [5] was used.

S-CIELab color difference ($\Delta\mathbf{E}$) metric [12] is a spatial extension of the CIELab color difference ($\Delta\mathbf{E}$) metric [13] and it is defined as the Euclidean distance between the original color pixel and its reproduction in S-CIELab color metric space. It is widely accepted and used for measuring color reproduction error when a continuous-tone color image is reproduced with halftoning. Table 1 shows the performance of different algorithms in terms of the average of the $\Delta\mathbf{E}$ values of all pixels in the color quantization outputs. The proposed algorithm is obviously superior to the others.

Figure 3 shows some color-quantized outputs of various algorithms. Noticeable color shift and false contour can be found in the middle of Figure 3d. In Figures 3b and 3c, in the sky, one can see ripple patterns that propagate from the top of the left to the middle of the right of the pictures. They are induced by directional hysteresis and composed of a number of ordered color impulses. The proposed algorithm does not generate directional hysteresis and it can significantly reduce color impulses as shown in Figure 3e.

4. Conclusions

In this paper, a multiscale color error-diffusion halftoning algorithm for color quantization is proposed. It makes use of the multiscale technique to perform color quantization in YIQ color space with error diffusion using a non-casual filter. This eliminates directional hysteresis and reduces color impulses. Simulation results demonstrated that the proposed algorithm can achieve a remarkable improvement in the quality of halftoned color-quantized images both subjectively and objectively in terms of S-CIELAB color difference ($\Delta\mathbf{E}$) metric [13] as compared with other available algorithms.

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6. References

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Palette Size	Average of S-CIELAB difference $\Delta\mathbf{E}$			
	Orchard [1]	Akarun [10]	Breaux [11]	Ours
16	34.52	33.76	33.48	32.69
32	25.89	25.83	25.10	24.36
64	19.57	19.43	18.83	18.20
128	15.74	15.54	15.01	14.34

Table 1. Average of S-CIELab difference ($\Delta\mathbf{E}$) metric of the halftoned color-quantized outputs of various algorithms

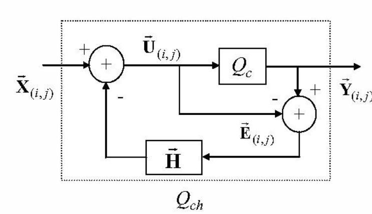


Figure 1. Color quantization with error diffusion

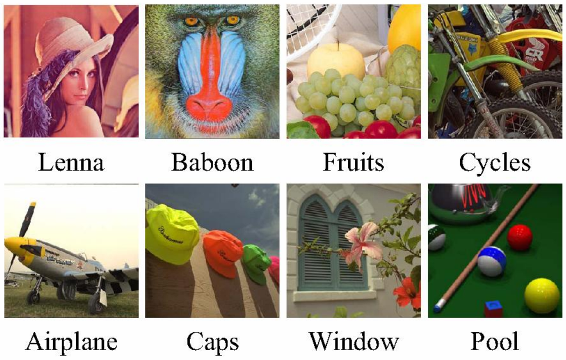
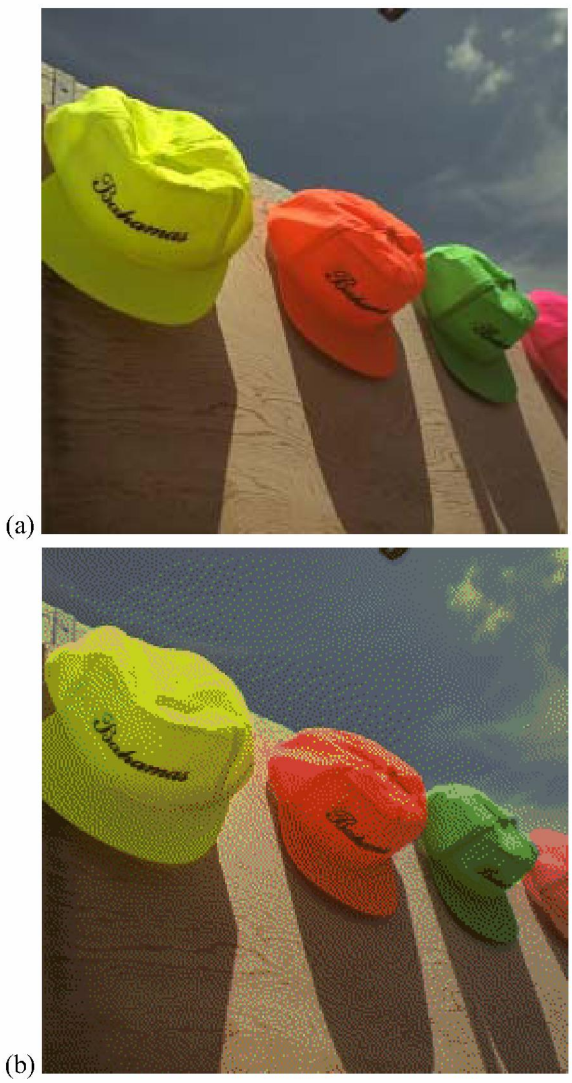


Figure 2. Testing Images



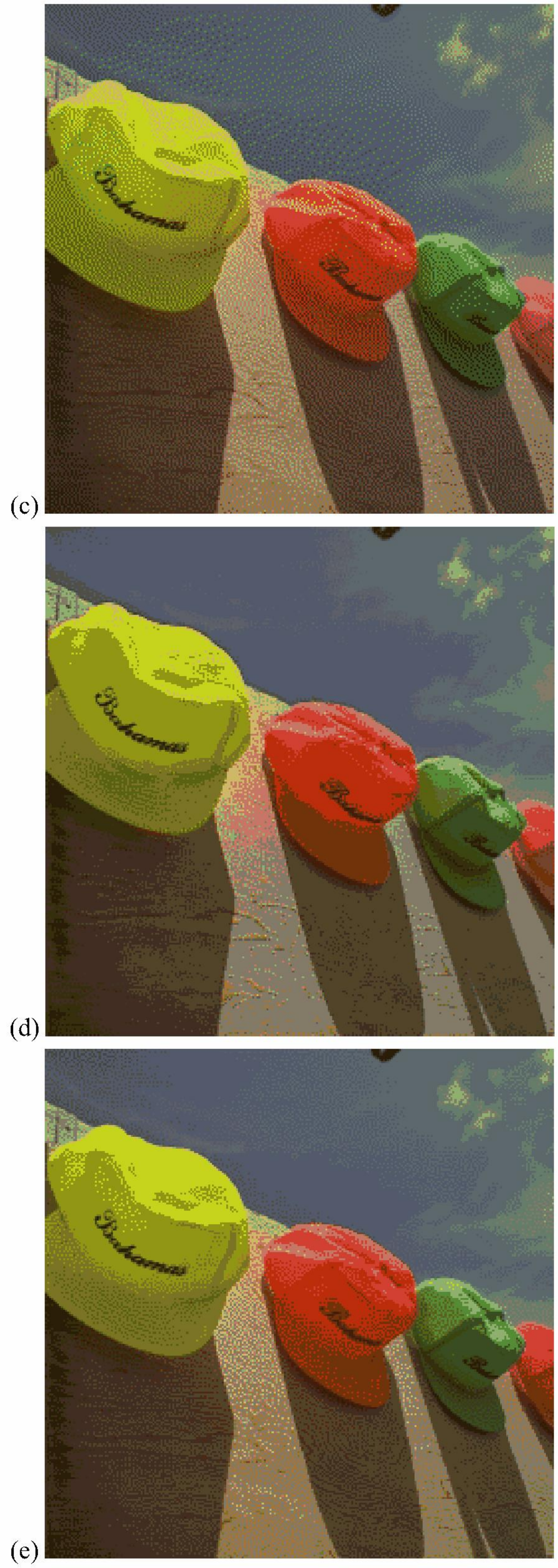


Figure 3. Color quantization results (Palette size = 32): (a) Original, (b) Orchard[1], (c) Akarun[10], (d) Breaux [11] and (e) the proposed algorithm