Optimization of Cartridge Life Using JND Sampling Without Compromising the Visual Quality of Printed Images

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Abstract

This paper presents an innovative pre-dithering or pre-halftoning approach of sampling CMY color space using non-linear sampling of RGB space, under physiological limitations of human color vision. The certified sound color vision human eye color intensity thresholds have been computed in terms of Just Noticeable Differences (JNDs) in each basic color and then used for sampling the color images to be printed. From our findings of color image sampling work, we propose that the existing 22 level quantized ink injection system is inadequate to represent color images with minimum loss of visual information. So we propose an injection system with 24, 26 and 28 levels in Cyan, Magenta and Yellow respectively. The proposed system minimizes the utilization of color inks without affecting visual quality of printed color images on white background. The proposed scheme is effective for printing the dark colors, on the other hand it generates false contours while printing the light colors, as already discussed in published literature. Experimentation has been carried out to estimate the 'Threshold of Lightness' of colors in RGB space. Using the decided threshold of lightness, if the proposed scheme is applied only to dark colors, considerable saving of color ink can be achieved. This technique considerably reduces the consumption of expensive color inks for printing color images on white background and enhances the cartridge life, reducing the cost of inkjet printing.

1. Introduction

Effective and efficient algorithms for printing of color images has been an area of academic and commercial interests to many researchers. The procedure of printing RGB color images is presented in [1] and is used for color Image printing on white background. An adaptive error diffusion method for color images is presented in [2]. Digital color halftoning is the process of transforming continuous-tone color images into images with a limited number of colors for printing [3]. The contouring problem in halftoning process at the lowest density levels can be solved using a variation of error diffusion or dithering algorithms [1]. A new method for color image quantization based on the principles pertaining to the sigma-delta modulators is used in analogue-to-digital conversion and is extended to the two-dimensional image space by filtering the quantization noise using a noise shaping filter [4]. In a drop-on-demand thermal ink-jet printer the dot size of an ink droplet expelled from a printer head MEM valve depends on the absorption ratio of the substrate. This causes color differences between output images on different printing materials. A color consistency algorithm for different papers is proposed in [5]. To eliminate the damage from the dot gain effect in printed halftone images, Jing-Ming Guo [6] proposed a printer model that cooperates with error diffusion and totally solves the dot gain problem in just one processing pass for all kinds of printed dot radii. With this modified printer model, it also offers an additional benefit of saving the cartridge expenditure with average cartridge saving around 38.58% with natural images. Another method for color halftoning for improving the quality of image to be printed is Block color quantization presented in [7], which exploits the higher spatial resolution of the printing process and yields constrained local color optimality. The application of perceptual models to the watermarking of still images can be found in many literatures [8]. Most of these methods use a luminance based model and do not take into account the effect of the output process on image quality on different papers. In [8] Color image appearance model is applied to printing of watermarked images. Most color imaging devices exhibit color distortions due to nonlinear component and is corrected by the most popular technique of printer characterization. Printer modeling and printer controller are two parts of printer characterization using neural network. The work in [9] presents a method of printer modeling with spectral reflectance values using error back propagation. The quality of halftone prints produced by inkjet (IJ) printers can be limited by random dot-placement errors [10]. A model-based approach to both iterative least-squares halftoning, direct binary search (DBS), and tone-dependent error diffusion (TDED) are presented in [10]. An efficient method to improve the display quality of a quantized image is error diffusion which works by distributing the previous quantization errors to neighboring pixels exploiting the averaging of colors in human eye in the neighborhood of the point of interest. Many times this creates the illusion of more colors. An error diffusion method is presented in [11] which uses the adaptive recursive least squares (RLS) algorithm and is used instead of the deterministic approaches in literature. A model with a fuzzy set of quality factors is introduced in [12] and a numerical quality value of the same is calculated and compared to an experimentally established acceptable quality value for particular customers and printing processes. The developed model reduces the amount of rework.

In section 2, the basic framework of the non-linear sampling theory and the related experiment for computation of the R,G and B cones (human retinal color sensor) models have been discussed using Bauchsbaum's predictions[13,14]. Physiologically, human eye cannot discriminate between more than 17000 colors without saturation [18]. Section 3 presents the nonlinear sampling technique in brief, based on the discussions in section 2. Section 4 presents the proposed measure of Redundancy in color images as a measure of color ink wastage during the printing of color images. Section 5 describes the experiments carried out using the proposed sampling and printing techniques along with the estimation of the lightness threshold and subsequent printing of the images using the same. Section 6 presents the results of printing experiments and the obtained % average saving in printing different color images without any compromise on the visual quality of the printed images. Section 7 briefs the conclusion.

2. Buchsbaum's Non-linearity of Color Vision

The incremental behavior of human retina has been modeled by Buchsbaum using a differential equation as presented in [13,14]. The non-linearity on R, G and B axes was proposed by Buchsbaum [13] as in eq. (1).

$$y(I) = \frac{K}{4q - p^2}\left[\tan^{-1}\frac{2qI + p}{\sqrt{4q - p^2}}\right]^2 + C \qquad (1)$$

where, *K* represents gain, p and q represent illumination constant in the two directions, *I* input intensity, C represents saturation of the eye and *y(I)* is output of the system which can be expressed in terms of JND colors on R, G and B axis respectively. These quantization levels (JNDs) can be calculated solving eq. (1) as in eq. (2).

$$I = \frac{\sqrt{4q - p^2}}{2q} * \tan\sqrt{\frac{(y - C)\sqrt{4q + p^2}}{K}} - \frac{p}{2q} \qquad (2)$$

An experiment has been carried out to model the just noticeable different color response of a certified sound color normal eye to the varying color intensities in the three basic colors using 64 color palettes of each basic color under daylight illumination conditions over an average gray background [15]. This response is further used to evaluate the parameters p, q, K and C of the visual non-linearity using a neural network curve fitting procedure with an error of less than one JND. A similar experiment was carried to provide a linear fit to their non-linear equation by E. Boldrin [17]. The computed values of these parameters are presented in Table 1.

Table 1: Parameters of the RGB non-linearity

Col.	w_1	w_2	w_3	w_4	Max (y-d)	MSE
Red	89.13	210.07	9288.88	-22781.5	0.43	0.056
Green	46.74	149.5	9334.13	-22836.4	0.40	0.037
Blue	41.59	143.55	9339.37	-22843.1	0.52	0.48

3. Sampling of Color Images

In the proposed approach of sampling of color images, using the parameters of eq.(1), the y(I) levels on each axis have been computed and every pixel color in the image has been reduced to its nearest lower y(I) level. Thus every image selected for printing has been sampled according to the proposed approach. A set of 100 real life color images has been selected but only two of them are shown in figure 1 and 2. The image set has been selected in such a way that a lot of color variations are observed amongst them. Figure 1(a) and 2(a) show the respective sampled color images using this approach. It may be noted that it is hardly possible to mark any difference between the original images and the sampled images indicating that the visual quality of each image has been maintained. Moreover every sampled image has now been displayed using only 24x26x28=17,472 colors instead of 16M colors, without any compromise on the visual quality.

4. Redundancy in Color Images

As discussed above the redundancy in the real life color image data is minimized and the original data is reduced to its respective nearest just noticeable lower color co-ordinates or quantization levels. Figure 3 shows original clown image while figure 3(b), (c) and (d) show the reduced color images by 5%, 10% and 20%. It may be noted that the 5% reduction in colors of original image is hardly noticeable. While 10% and 15% color differences are comparatively noticeable. This means that the original image definitely has some redundancy in it.

Figure 1 *Clown*

Figure 1(a) *Sampled Clown*

Figure 2 *Stones*

Figure 2(a) *Sampled Stones*

Figure 3 *Clown*

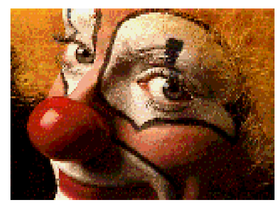

Figure 3(a) *Colors Reduced by 5%*

Figure 3(b) *Colors Reduced by 10%*

Figure 3(c) *Colors Reduced by 20%*

Thus a qualitative definition for redundancy in color image data, for color vision applications may be proposed as follows.

Definition: Redundancy in the color image data can be defined as an average allowable change in the image data without causing any human perceivable change in the color image quality.

The measure of redundancy as defined above with special reference to the proposed approach is presented in eq. (3).

$$R_c = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left(I_{(i,j,c)} - I'_{(i,j,c)}\right)}{\sum_{i=1}^{m}\sum_{j=1}^{n} I_{(i,j,c)}} \qquad (3)$$

Here, Rc is redundancy for color c (c=1 for Red, 2 for Green and 3 for blue). Here I and I' represent the original and sampled image data, while m and n represent the rows and columns of the image. The overall redundancy is represented by average of the three color redundancies. Initially, redundancy in colors in each of these images has been calculated by subtracting the sampled image from the original image. Further the average redundancy has been calculated. The redundancy values for a few images have been tabulated in Table 2 as presented below.

Table 2: Redundancy in the color images

Para→ meters	Extra Color intensities (approx)			%Redundancy (Rd)			% Avg.
Image↓	R	G	B	R	G	B	Redu.
Clown	8.8×10^4	5.7×10^4	2.3×10^4	4.4	4.8	3.9	4.4
Stones	4.8×10^6	4.7×10^6	3.9×10^6	3.6	3.0	3.4	3.4
Pears	1.8×10^6	1.5×10^6	1.6×10^6	3.2	2.9	4.9	3.7
Concord.	8.3×10^8	6.0×10^8	6.5×10^8	3.5	4.1	4.1	3.9

5. Printing Experiment

For verifying the proposed approach, the quantization levels on each axis R, G and B have been computed and every pixel in the image has been reduced to its nearest lower quantization level. Hence the sampled image using 24, 26 & 28 quantization levels of R, B and G colors respectively has been obtained. It may be noted from figure 1(a) and 2(a) that it is hardly possible to mark any difference between the original and sampled image as far as the image contains dark color shades. But in the images having lighter color shades, contours are observed in the sampled image as shown in figure 2 (a) as already predicted in [20]. To avoid such contours, some additional light color inks i.e. light cyan, Lc, and light magenta, Lm, have been used [20]. The additional light color cartridges add to recurring cost of printing in addition to the driving hardware and programming overhead. In this paper, we have proposed a new approach to solve this problem without adding any hardware. The ultimate aim of this approach is to define a Lightness Threshold in RGB space. If a color is a light color, the proposed sampling scheme for minimizing colors cannot be applied as it introduces contours. So the color satisfying the lightness threshold will be left unchanged while the dark colors will be sampled using the proposed approach. Also the light colors do not require much ink for printing, so the saving of the ink while printing of light colors will also be nominal. Here we are sacrificing that nominal saving for solving the problem of contouring during printing of light colors.

In the available 8-bit graphics true color system, the [R G B] triplet [0 0 0] is black color while [255 255 255] is white color. In the RGB color space, obviously the colors around white color i.e. [255 255 255] will be considered light colors. We have carried out an experiment on color palettes with [R G B] intensities greater than [128 128 128]. The color palettes with the intensities in the step of four in each basic color were shown to 100 certified normal vision observers in the normal daylight. They were asked whether the shown color palette is a light color or not, and light color threshold of every observer is noted and sample observations of 20 observers are shown in Table 3. Minimum of this threshold (intensity-wise or maximum Euclidian distance-wise from reference white) is selected as a 'Lightness Threshold'. Based on this, [224 224 224] is considered Direct Lightness Threshold (DLT) for all the colors i.e. DLT = 224, which is

Table 3: Observations for Lightness Threshold

Obs. S. N.	Threshold R	G	B	Obs S. N.	Threshold R	G	B
1	224	228	232	11	228	228	228
2	228	232	228	12	232	228	232
3	228	228	228	13	232	232	232
4	232	228	232	14	228	228	228
5	224	232	228	15	228	232	228
6	224	228	232	16	228	232	232
7	232	232	228	17	224	224	228
8	228	228	232	18	224	228	228
9	228	228	228	19	224	232	232
10	224	232	228	20	228	228	228
				Min	**224**	**228**	**228**

approximately 12% less of 255. It is to be noted here that if any of the three color intensities is 224, it may be treated as light color. Thus all the colors which are closer to reference white as compared to the DLT [224 224 224] using the Euclidian distance will be termed light. The proposed sampling approach will not be applied to such light colors.

A test image pattern was designed by us in such a way that the test image requires equal quantity of ink colors C, M and Y so that the printer should not stop printing due to lack of any one of the three ink colors. The test image shown in figure 4 has been used for the printing experimentation. Figure 4(a) is a test image sampled in CMY domain using the proposed sampling technique.

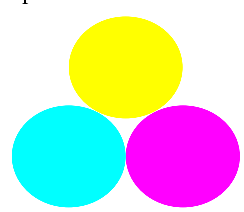

Figure: 4 *Test Image*

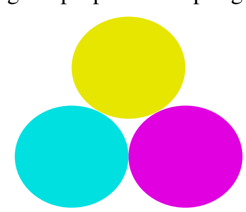

Figure: 4(a) *Test Image at Direct Lightness* threshold

6. Result

The images are printed on HP D3325 ink-jet printer with new precisely equal weighed color cartridges. It is found that in the successive trials the printer has printed 85-90 original images. While around 95 to 100 sampled images have been printed using the proposed approach. However the exact saving of ink can vary depending upon the real images to be printed, which color they contain and to what extent. The printing experimentation has been performed on a set of 100 real life images. Only a few results of our experiment which repetitively prints the same image till the cartridge is finished have been presented here. Figure 5 and 6 present the images printed with and without proposed approach and the analytical results are presented in Table 4.

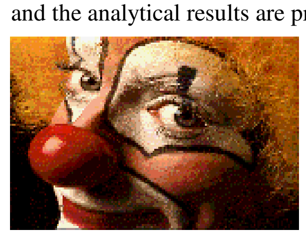

Figure 5 *Clown Printed with 4% reduced colors*

Figure 6 *Stones Printed with 3% reduced colors*

Table 4: Redundancy & Number of Printouts

Images	% Avg. Saving	Printout w/o Sampling	Printouts With Sampling
Clown	4.4	92	99
Stones	3.4	92	98
Pears	3.7	105	109
Cocordaerial	3.9	95	102

Figure 7 and 8 show the images sampled and printed using the proposed sampling and the lightness threshold approach. It may be noted that it is hardly possible to mark any difference between the original and sampled images when both are viewed at the same size.

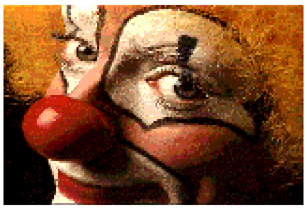

Figure 7 *Clown sampled and printed using the proposed approach and DLT*

Figure 8 *Stones sampled and printed using the proposed approach and DLT*

7. Conclusion

The results show that the original and sampled images are visually similar. It may also be noted that the quality of sampled and printed images also depends on their original sizes and the resolution of photography. That means if the viewing size of the original and sampled image are different, the quality of sampled and printed image would not match with the original image. On an average the experiment was reported to save 4% to 5% ink i.e. in around 5% more prints of the images of a set of around 100 real life images repetitively till the cartridge ends.

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