

# Luma-based directional copy interpolation for color bilevel AM halftoning for printing

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**Abstract:** The interpolation of color pixel values prior to digital halftoning is discussed and a new color interpolation scheme is presented by a directional copy of color values in the gradient field of luma. Error diffusion quantization is combined with clustered-dot ordered dithering to prevent from contouring. Experimental results demonstrate that sharp and false color-free interpolation is obtained to produce color bilevel AM halftones with weak rosettes and no contouring artifacts.

**Keywords:** interpolation, halftoning, AM halftoning, printing

**Classification:** Science and engineering for electronics

## References

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## 1 Introduction

Bilevel halftones are used for printing color digital images [1, 2]. In printing applications including electro-photographic printers, one of major halftoning methods is amplitude-modulated (AM) halftoning such as clustered-dot ordered dithering (CDOD) where continuous-tone pixels are quantized into bilevel dots. Prior to the quantization, the density of continuous-tone dots is increased much more than the pixel density so that the fine spatial resolution in a dot image may compensate the poor tone-scale resolution of quantized dots in a bilevel halftone. To avoid confusion, the increased samples produced by up-sampling are referred to as dots instead of pixels.

The zero-order, bicubic, and nearest neighbor interpolations [3] are popular in printing applications. The first method produces jaggy business along diagonal object boundaries. The second one can excessively smooth local details and the third destroys them, if the interpolation factor is high in both methods. Recently a gradient-based interpolation [4] has been presented in consideration of the admissibility condition for wavelets to avoid jaggy artifacts in grayscale images. The authors have found that its simple application to color images results in strong false colors [5]. Since the method can be interpreted as a kind of the nearest neighbor interpolation, a combination of a slight modification of the gradient-based nearest neighbor interpolation and its effective application to color images is presented in this work.

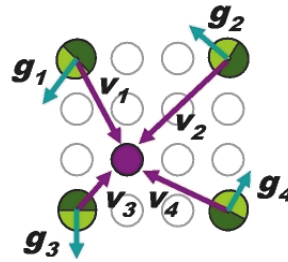
## 2 Interpolation for AM halftoning in printing applications

One of the final goals in printing is visually-pleasing hardcopies of color digital images. Halftones are generated to make it possible. The smoothing effect is unavoidable in AM halftoning at the expense of a pseudo multi-level resolution in the tone scale. In addition, since a set of screen cells with different orientations for individual color components is applied to a continuous-tone dot image to make a bilevel quantization of dots, a resulting halftone is strongly affected by the screen cells. Particular sorts of undesirable nonlinear artifacts are thus created in a bilevel halftone.

Typical artifacts [1, 2] include the color moire effect, rosettes, both of which are caused by the periodic patterns in screens, false color, and contouring that is probable to appear due to a bilevel quantization of smooth variations over uniform areas such as highlights and shadows. It is hence significant to make an interpolation that underlies better color bilevel AM halftoning. Specific issues to be considered for such an interpolation are visual sharpness in appearance, preservation of spatial details, and suppression of undesirable artifacts such as false color, moire patterning, rosettes, and contouring.

## 3 Luma-based directional copy interpolation for color bilevel AM halftoning

The first step in the directional copy interpolation is to make a color component transform to exploit the correlation among color components instead



**Fig. 1.** Four pairs of the gradient vector  $g_i$  and the orientation vector  $v_i$ , where  $i = 1, 2, 3$ , and 4. The case of 3-times interpolation is illustrated.

of allowing their independent behaviors and to fit it to the human visual system [1, 2]. A given RGB image is transformed into LMN color space [6], since it is one of perceptually-uniform color spaces [7]. In this work, only the luma [7] component is used, because the human eye is most sensitive to it. The luma of a color value triplet  $(R, G, B)$  of a pixel is given by  $L = (R + 2G + B)/4$ .

The next step is to compute the gradient vector field of the luma. A gradient operator such as Sobel filter [3] is applied to the luma that has been computed over the entire pixel locations. Note that the gradient vector is modified (that is, normalized) into a unit gradient vector so as to be insensitive against insignificant variations.

The third step is up-sampling of pixels to increase the sample density so that vacant dots are generated between original pixels.

The fourth step is to find a reference pixel to be copied onto a vacant dot. Four orientation vectors going to a target dot in the up-sampled dot image are defined at four neighboring pixel locations, respectively. Figure 1 illustrates the case of three-times interpolation. Assume that the target dot is located at the 3rd row and the 2nd column. Blank circles represent the other dots created by up-sampling, and painted disks at 4 corners are the original pixels. The reference pixel location is selected among those four original pixels, if the orientation vector  $v_i$  is orthogonal to the unit gradient vector  $g_i$  as exactly as possible, and if the distance between the reference pixel and the target dot is short. The first condition means that the interpolation along edges is more preferred than that across edges. The second condition reflects a well-known fact that, if two pixels (or dots) are spatially close, they are probable to strongly correlate with each other. These two selection conditions are simultaneously checked by a single computation. Exactly, the reference pixel labeled by  $k$  is found as  $k = \arg \min_{i \in [1,4]} \{|g_i \cdot v_i|\}$ , where  $\cdot$  stands for the inner product. In the case illustrated in Fig. 1, the 4th pixel will be selected.

Finally, a set of  $R$ ,  $G$ , and  $B$  values of the reference pixel is copied to the color values of the target dot. Hence no false color can appear.

All of the dots created by up-sampling are interpolated in the same way.

## 4 Experiments and inspections

Four images produced by different 8-times interpolations along the horizontal and vertical directions are shown in Fig. 2 as well as their original image in part (a). Note that the original image can be too small for visual inspections, but it must be accepted because enlargement is impossible without interpolation. The zero-order interpolation results in a jaggy image as seen in (b). The image (c) produced by the bicubic interpolation is acceptable and yet slightly sleepy to the eye. When the gradient-based copy interpolation is independently applied to individual  $R$ ,  $G$ , and  $B$  components, objectionable false colors appear as observed in (d). Part (e) shows a result of the luma-based directional copy interpolation, where a sharp and jaggy-free appearance is visually inspected and no false colors are present.

Color reproduction is investigated by means of CIE 1931  $xy$ -chromaticity [8], as shown in parts (f) to (h) also in Fig. 2, where the white point and three primary colors obey ITU-R Recommendation BT.709 [9]. The chromaticity distribution in the proposed interpolation is identical to that of the original image, and they are shown in part (f). In contrast, as seen in part (g), the bicubic interpolation results in a larger spread of chromaticities, which represents false colors. Part (h) shows the chromaticity distribution in the image produced by the gradient-based independent copy of different color components. Its chromaticity spread is evidently beyond an acceptable level.

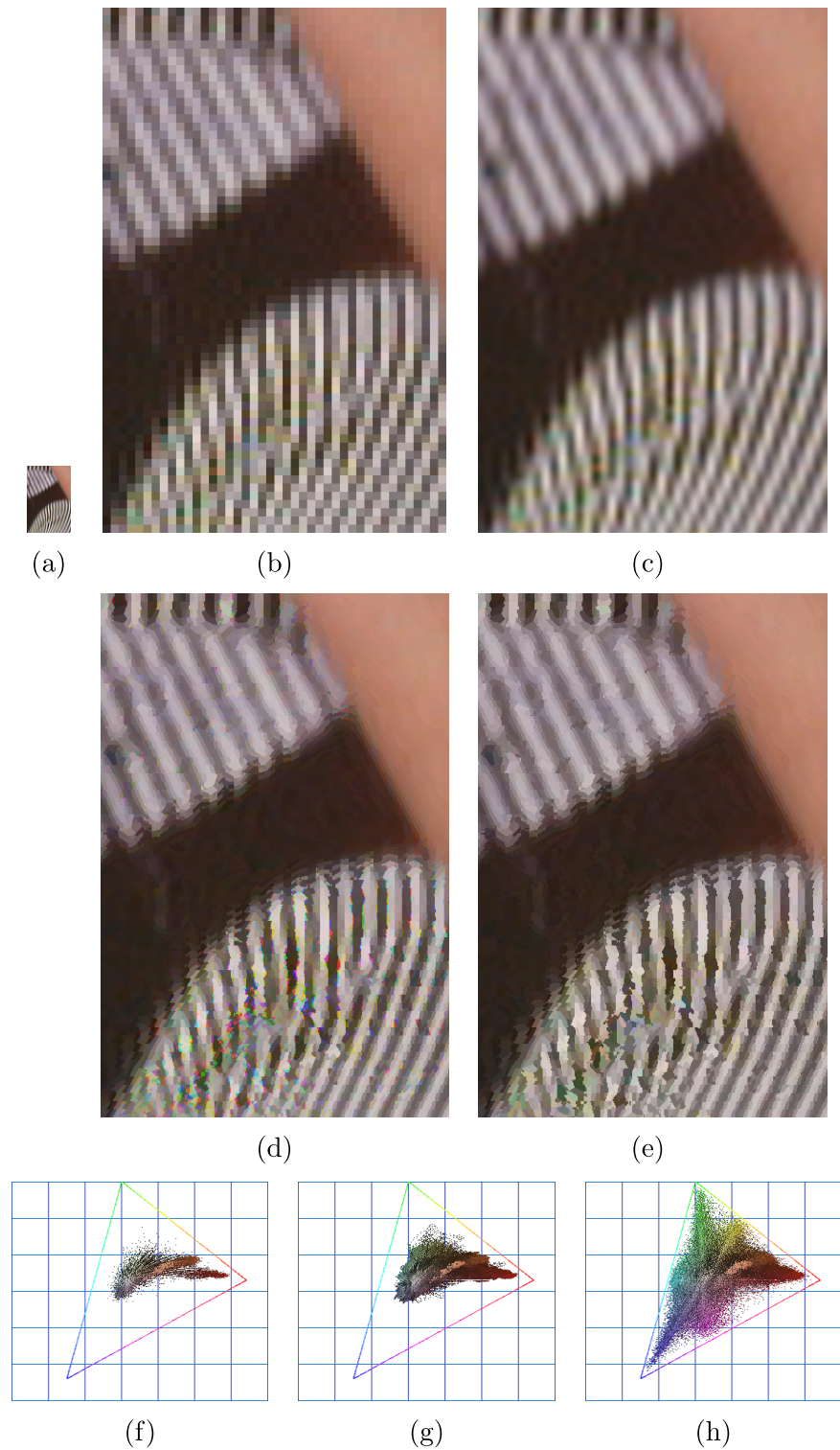
An advantageous application of the proposed interpolation to CDOD is demonstrated in Fig. 3 where halftoned bilevel dot images are shown in RGB color space for a displaying purpose. CDOD has been implemented with a 20-dot/27-degree orthogonal CMY screen set [1] after the proposed interpolation by 4 times. Parts (a) and (b) are the color bilevel halftones produced by traditional CDOD and modified CDOD [5] incorporated with error diffusion quantization by Fan's diffusion filter [1], respectively. Contouring artifacts are evident in part (a). In contrast, they are absent from part (b) where rosette patterns are also attenuated, while spatial details are well preserved.

## 5 Conclusions

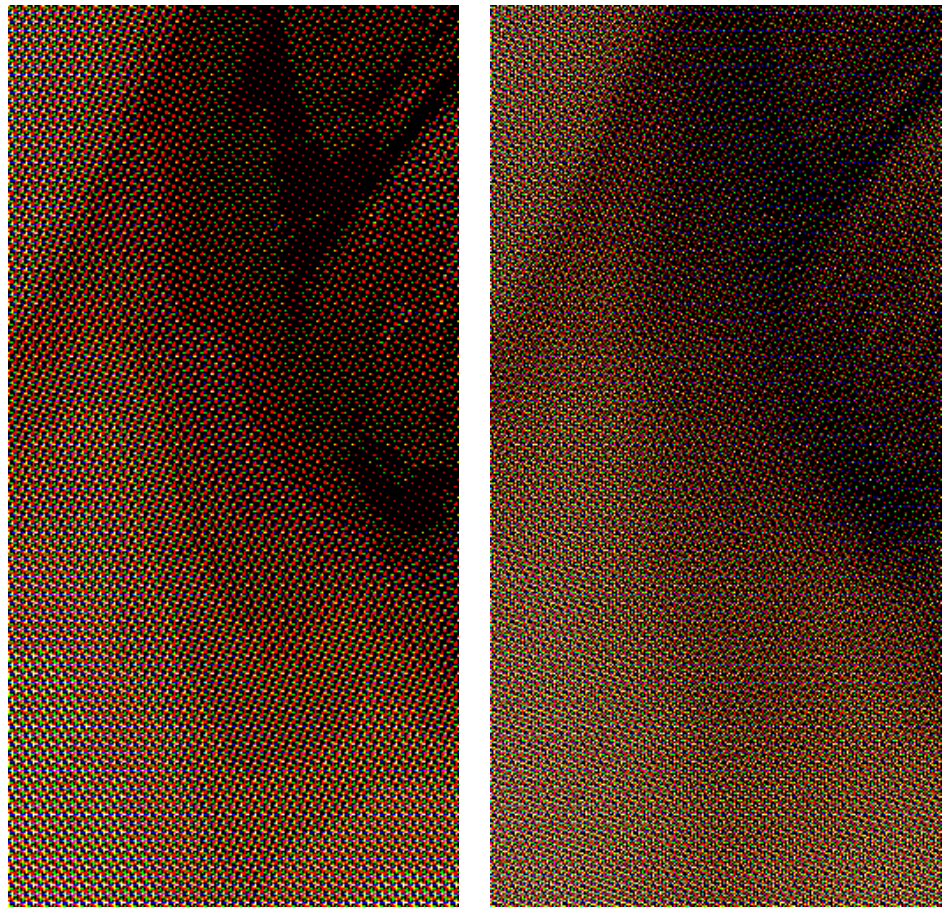
A luma-based directional copy interpolation has been presented for color bilevel AM halftoning such as clustered-dot ordered dithering for printing. The proposed method performs a sharp and detail-preserving interpolation without false colors. In spite of its simplicity, it is effective to suppress color artifacts including contouring artifacts and rosettes caused by ordered dithering, when error diffusion quantization is incorporated with CDOD.

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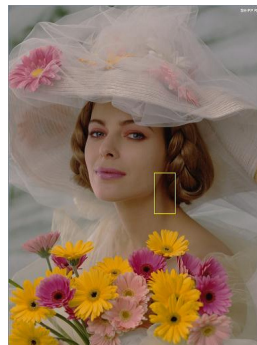


**Fig. 2.** Inspections of the images interpolated by 8 times. The test image is a part of *barbara*. (a) original, (b) zero-order, (c) bicubic, (d) gradient-based component-wise copy, and (e) proposed. Remaining three plots are the  $xy$ -chromaticity diagrams. The origin of the  $xy$  coordinate system is at the bottom-left corner and the grid spacing is equal to 0.1. (f) original and proposed, (g) bicubic, and (h) component-wise gradient-based.



(a)

(b)



(c)

**Fig. 3.** Visual appearances of different halftones. (a) traditional CDOD and (b) modified CDOD with error diffusion quantization. Part (c) is supplemented to indicate the area for (a) and (b). The test image is one of SHIPP images available at Institute of Image Electronics Engineers of Japan.