Correcting for Short-Range Spatial Non-Linearities of CRT-based Output Devices

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ABSTRACT

Most graphical output devices exhibit what has been termed spatial non-linearity: the effect of setting two adjacent pixels to a given value is not the same as the sum of the effects of setting those two pixels to the same value in isolation: checkerboards of different frequencies do not have the same apparent luminance. We present a method applicable to bit-mapped devices for compensating for short-range spatial non-linearity in error-diffused images. The modification to error diffusion is such that it can be used with any error diffusion technique. In essence, it consists of finding the influence of the neighbouring (output) pixels when making the decision of whether to turn on a given pixel, and passing errors computed accordingly.

CR Descriptors: B.4.2 [**Input/Output and Data Communications**]: Input/Output Devices — *Image display;* I.3.1 [**Computer Graphics**]: Hardware Architecture — *Raster display devices* I.3.3 [**Computer Graphics**]: Picture/image generation — *Display algorithms;* I.3.6 [**Computer Graphics**]: Methodology and Techniques; I.4.3 [**Image Processing**]: enhancement.

1 Introduction

While the full-colour display is becoming more and more common, bit-mapped CRTs remain commonplace as well. These have advantages in terms of speed, resolution, and cost that cannot be matched by colour displays. Occasionally it is necessary to display an image on such a device. Moreover, certain colour-table animation techniques rely on the use of single bit-planes of a full-colour display. Here the full colour display is being used to simulate a bit-mapped display with a very fast frame update rate. A common method of converting from full-colour continuous tone to black and white binary is to error diffuse the luminance component. Various forms of error diffusion have been suggested[7, 15, 6, 8, 3, 16, 14]; the particular choice of error diffusion technique has relatively little effect on the appearance of an image when it is displayed on a sufficiently high-resolution monitor.

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The value of gamma-correction of colour displays (or better still instrumented compensation)[2, 4], is well known. On a bit-mapped display the concept of gamma-correction is meaningless. As Naiman has noted, CRTs exhibit spatial non-linearities [11], , as can be easily seen by displaying a checkerboard of period two pixels adjacent to a checkerboard of twice that period. When viewed from a sufficient distance to cause the coarser checkerboard to appear smooth, these two images should ideally appear the same intensity. On most output devices they do not. (An LCD display may be an exception).

Much has been said about correcting for neighbourhood effects in prints. Commonly, it is based on a simple model of circular pixels with greater than unit area [13, 1, 12, 5]. For the SIGGRAPH audience, two more important display devices are the CRT and the film recorder. We begin with the simplest example: the bit-mapped CRT. Bit-mapped CRTs are so common that most readers of this paper are likely to have one. The improvement can be quite striking, as shown by figures 1 and 2. A linearity assumption (ie. that the phosphors are not saturated) allows the extension to greyscale and colour monitors, and to film recorders.

2 SIMPLE CRT CORRECTION

The general idea behind neighbourhood-based compensation is that the intensity generated at a pixel depends not only on the setting of that pixel but also on the intensity of the neighbouring pixels. The CRT is a special case. Here the non-linearities are primarily in the amplifiers driving the electron gun(s), so it is sufficient to consider only the left and right neighbours (whichever have been visited). An isolated pixel does not contribute as much intensity as it would with its neighbour on. . Neighbours in adjacent scanlines have no effect under this assumption (valid for CRTs [10]).

To test the assumption of independent scanlines, display four images: with a) alternate scanlines b) alternate columns c) alternate pairs of scanlines, and d) alternate pairs of columns intensified. If scanlines are independent, a) and c) should have the same intensity. In the unlikely event that b) and d) appear the same, the monitor has excellent high frequency response, and no correction is necessary. If flicker causes a problem with interlaced displays when displaying single scanlines it can be alleviated by using a checkerboard and changing only the vertical frequency.

The second assumption is one of single neighbours contributing. This can be tested using a pattern of decreasing frequency vertical lines. For the (SONY) monitors we tested, the difference between single and double pixel lines was much greater than that between double and triple pixel width lines, so the assumption appears safe.

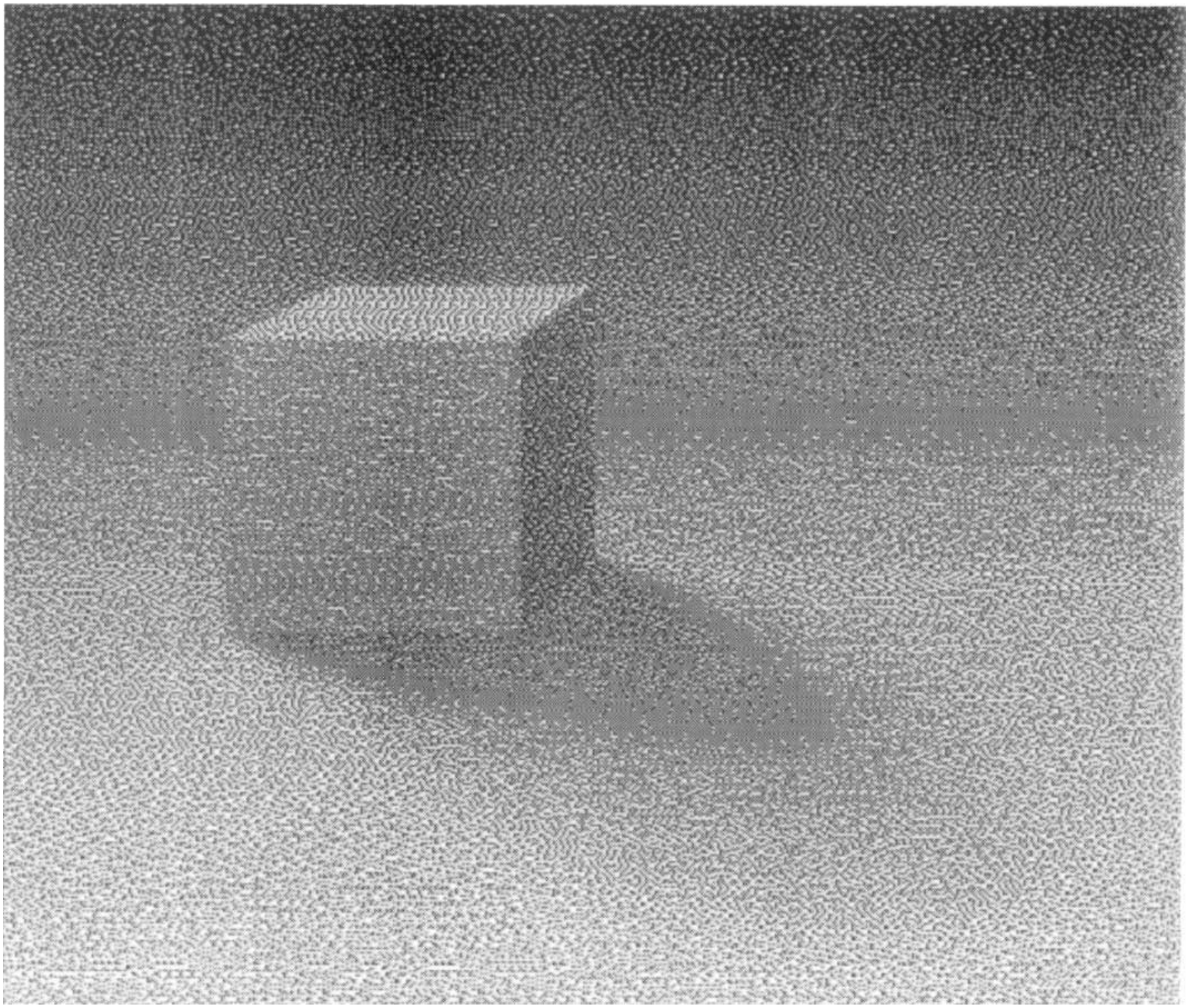

Figure 1 A radiosity-like scene, error diffused without correction. Note the dark band in the shadow. (The image was enlarged to 150% actual size to improve reproduction. It is best viewed from 2m/6–7 feet.)

To correct for the presence or absence of a neighbouring pixel, the algorithm in the CRT case is as follows:

for each pixel
  if no neighbouring output pixel is on (white)
    if value (including errors passed in) > threshold $-\ \delta$
      set the pixel
      quantization error $=$ value $-$ (1 $-$ δ)
    else *value ≤ threshold* $-\ \delta$
      quantization error $=$ value
  else *a neighbouring output pixel is on*
    if value (including errors passed in) > threshold
      set the pixel
      quantization error $=$ value $-$ 1
    else *value ≤ threshold*
      quantization error $=$ value
  Diffuse quantization error in the normal way

If there is no neighbouring pixel on, the effect of turning the current pixel on is reduced. This is reflected both in the turn-on decision, and in the calculation of the quantization error.

The specification deliberately leaves open the choice of error diffusion algorithm, including the order in which pixels are visited. Left and right neighbours are treated equally, although in reality pixels are only affected by the state of their left neighbours. The result of processing some pixels in right to left order, rather than left to right, results in the same average intensity overall, with a slight phase shift.

The value of δ must be determined experimentally: to do so, display a checkerboard containing 2×2 squares adjacent to a region of mid-grey that has been error diffused using the modified error diffusion algorithm. Vary δ across the error diffused region (Figure 3), and find the point where the two regions have the same luminance. We have found values in the 5–30% range apply to the monitors we tried. Figure 4 is a photograph of a screen with the pattern of Figure 3 displayed on the screen. The crossover point on the screen photographed is about midway across the

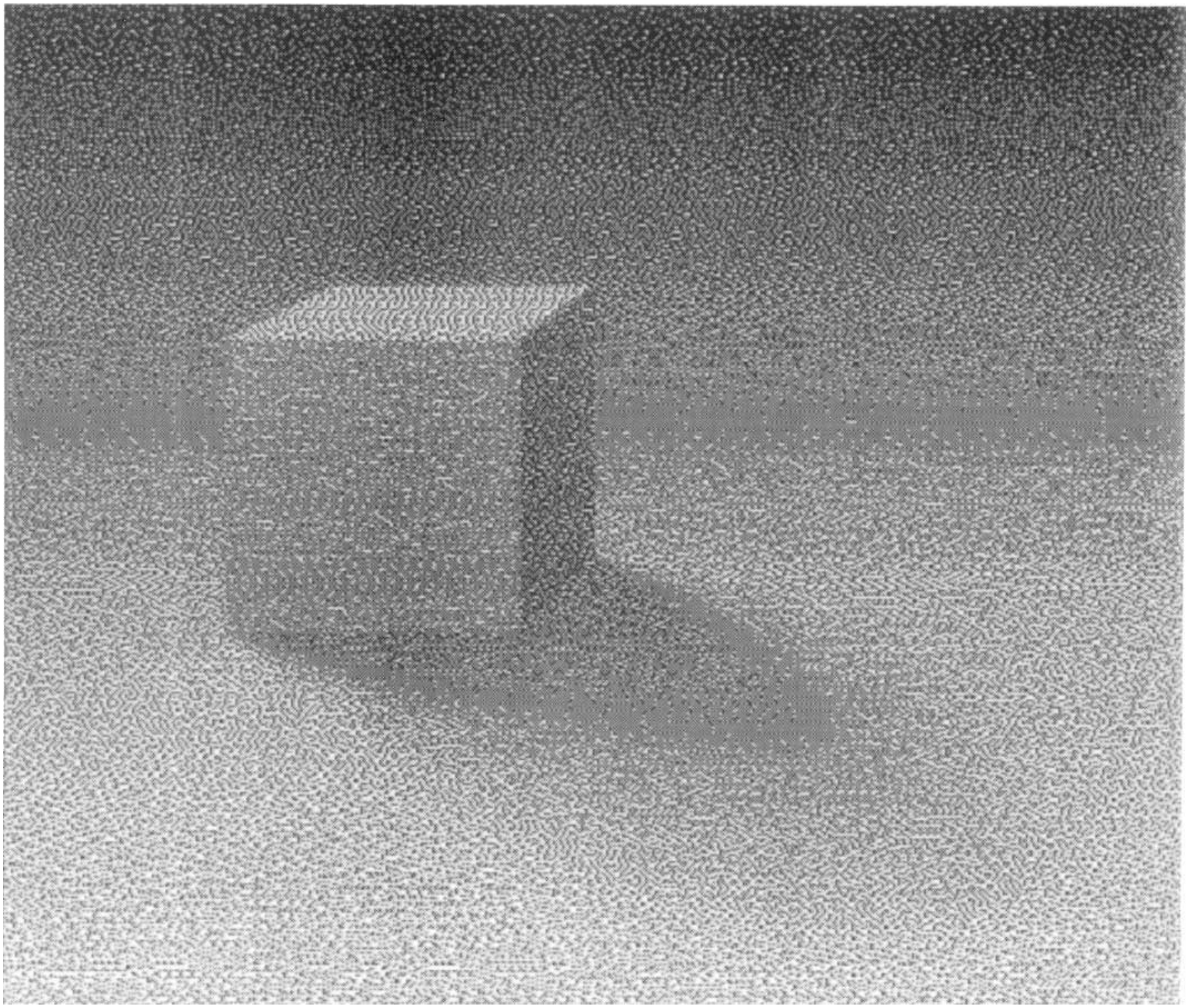

Figure 2 After correction the shadow fades smoothly through its penumbral region.

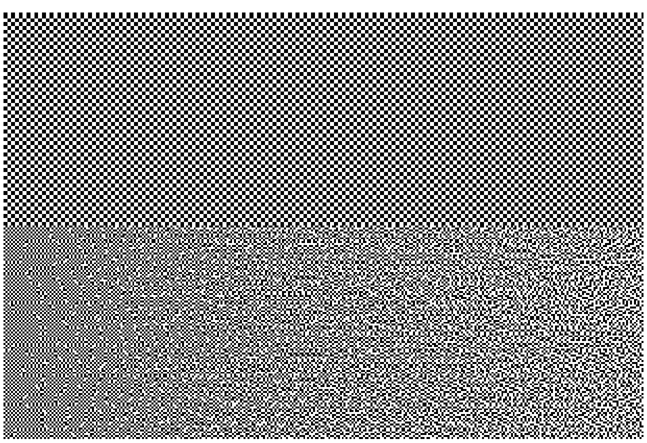

Figure 3 Finding the value of δ. The checkerboard has period two pixels. Below is an error diffused version of a 50% grey with δ varying from 0 (at the left) to 20%. Figure 4 shows the result of displaying this pattern on a CRT.

figure (the process of photographing and printing the image may have changed the crossover point in the picture).

3 GREY SCALE MONITOR OR FILM RECORDER

The difference between a bit-mapped monitor and a greyscale one is the frame buffer behind it. Both employ an electron beam directed at phosphors; the spatial non-linearity effects are identical. As long as images displayed on greyscale monitors do not have high frequency information in them, their spatial non-linearities will be hidden. Where high contrast edges appear, the non-linearities can affect image quality. Fortunately, spatial non-linearities due to gun amplifier non-linearity are close enough to intensity invariant that the methods above can be safely generalized.

Before proceeding to correct for spatial non-linearities, it should be ascertained that the monitor is corrected for gun non-linearities. Given an otherwise corrected monitor, the value of δ can be determined as above, using patterns of full-on, full-off.

It is not normal to error diffuse images unless the display is operating from a low depth frame buffer (eg. 8 bits for all

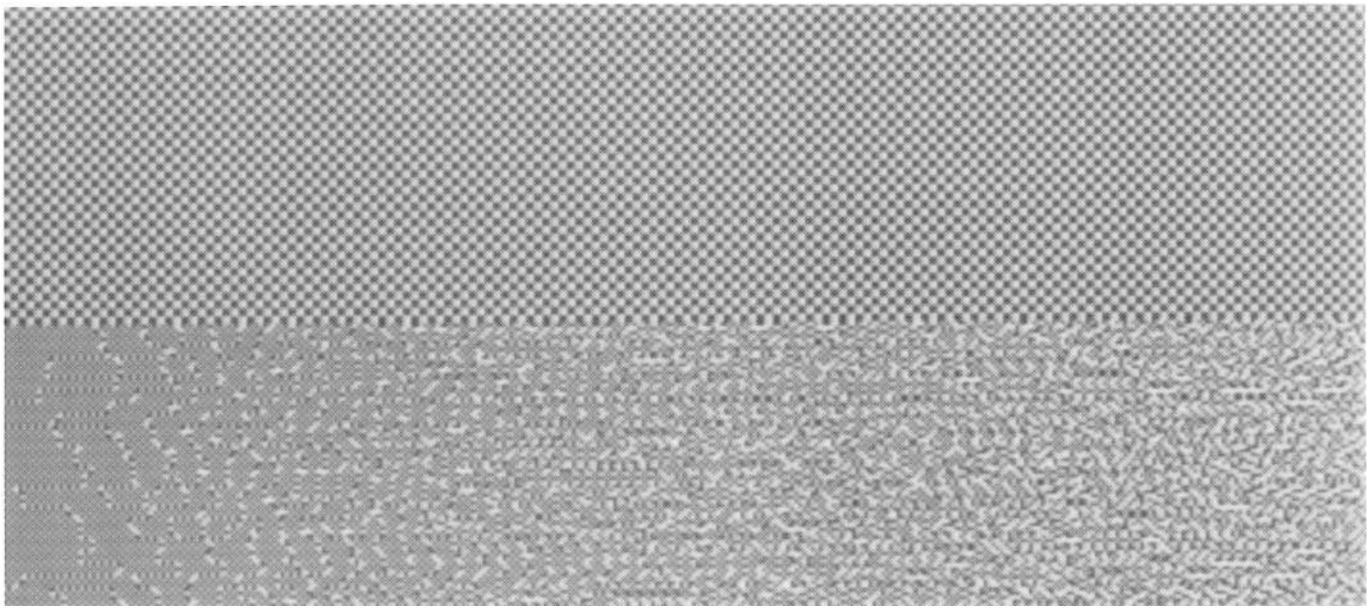

Figure 4 The result of displaying a pattern similar to that shown in Figure 3.

three components). If it is, the error diffusion algorithm can be adjusted in the same way as described above. In the typical case of a 24 (or higher) bit frame buffer, error diffusion can still be applied, without the quantization step. Normally there would be no error generated, but the alteration to the input values can still be applied, possibly generating out-of-gamut values. For example, a white pixel immediately followed by a black pixel would lead to a request for a negative pixel value for the second one. A remapping of the input (reducing the contrast) can prevent such negative pixel values entirely. A partial contrast reduction can make such negative pixel values infrequent. This is similar to eliminating phosphor trails in temporally varying displays, as described in [9]

4 SUMMARY & CAVEAT

We have described a simple technique for improving the tonal reproduction accuracy of CRTs. For bit-mapped displays, it serves the usual function of gamma correction. For regular CRTs it performs in image regions of high spatial frequency what gamma correction or instrumented compensation does in image regions of low spatial frequency. The method involves very little extra computation over that required for conventional error diffusion, and is simple to implement and calibrate. It should be noted that the generalization to print is complicated by the larger neighbourhoods affecting pixels, two (spatial) dimensional interactions, and non-linear colour mixing in the case of coloured printing.

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