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Error diffusion on an adaptive raster

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SUMMARY

The principles of a new halftoning algorithm are presented. The idea is to use error diffusion not on a fixed raster, but to adapt the raster to the properties of the original continuous-tone image, e.g. the local intensity. Examples show the advantages of this approach.

KEY WORDS Halftoning Error diffusion

1 INTRODUCTION

Whenever a continuous-tone image has to be displayed on a bi-level medium, some kind of halftoning has to be carried out. Nowadays processing of the continuous-tone image is often done by a computer, i.e. the sampled and quantized continuous-tone image is transformed into a binary image by a halftoning algorithm. In the following we will assume the continuous-tone image to be scaled between 0 and 1. In addition, we will restrict the discussion to algorithms for output devices where the addressability of the pulse location is approximately equal to the pulse extension. In this case the binary picture can be described by a pattern of independent black and white pixels.

Depending on the properties and needs of the output device, pulse-width modulation (PWM) or pulse-density modulation (PDM) is used. A special kind of PDM is generated by the error diffusion algorithm (ED) [1]. Because of its easy implementation and its relatively high speed, this algorithm is in widespread use.

2 THE ERROR DIFFUSION ALGORITHM

In the ED algorithm the grey value at a raster point is corrected by binarization errors of already processed points and then compared with a threshold level to obtain the binarized value. Then the binarization error is weighted and distributed to unprocessed neighbour raster points. The weighting factors of this error transmission are called *diffusion weights*. Two examples are shown in Figure 1. The particular choice of diffusion weights has a decisive influence on the properties of the binary image, and many suggestions of specially chosen diffusion weights have been made. Obviously the number of diffusion weights influences the calculation time, therefore in time-critical applications it has to be kept small.

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Figure 1. Two examples of diffusion weights. (a) Original diffusion weights proposed by Floyd and Steinberg; (b) Example with two weights

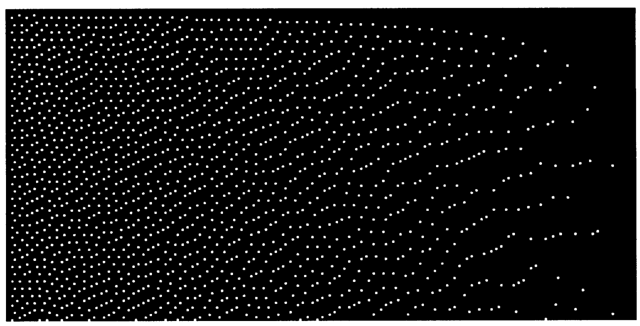

Figure 2. A grey wedge between 0.1 and 0, binarized with conventional error diffusion and the weights from Figure 1a

Using error diffusion with only a few diffusion weights leads to characteristic artefacts in the binary image, especially in regions of the continuous-tone image where the grey value is near 0 or 1. For example, Figure 2 shows the binarized version of a linear grey wedge with values between 0.1 and 0, computed with the original Floyd and Steinberg diffusion weights [1]. Near the original value of 0.1 a homogenous pulse distribution is obtained, but with decreasing intensity a special kind of low-frequency noise, the so-called 'wormy structures', becomes visible.

Many attempts have been made to overcome these artefacts. Eschbach [2] suggested a combination of ED and a PDM generated by an integration method, depending on the local grey value in the original image. Other approaches are modifications of the threshold in the ED algorithm, e.g. superposition of ordered dither [3] or random dither [4] to the threshold, modifications of sequential processing such as serpentine rasters or space-filling curves [5], and the addition of noise to the diffusion weights [4]. Another possibility is to increase the number of diffusion weights, because more weights allow a better control of texture [6]. In the following we will describe an ED algorithm that generates a more homogeneous pixel distribution, and that in addition reduces the calculation effort in those regions where 'wormy' textures can arise.

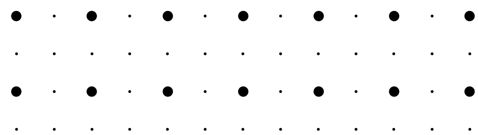

Figure 3. The raster points of the modified raster used in this paper (•) consist of a quarter of the points of the normal raster (·). In regions of the input image with grey values below Δ *and above* $1-\Delta$*, only these raster points are processed by error diffusion*

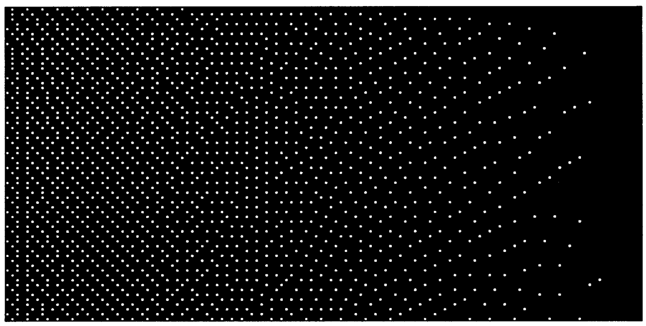

Figure 4. Binarized image of a grey wedge between 0.1 and 0.0 with error diffusion on the modified raster of Figure 3 and the weights from Figure 1a

3 ERROR DIFFUSION ON AN ADAPTIVE RASTER

For simplicity we will first restrict our discussion to the dark regions of the continuous-tone image (the discussion of the bright regions is equivalent).

In these regions the binary image consists of only a few white pixels on a black background. Our approach is to restrict the freedom of positioning of the white pixels in regions of low intensity, i.e. to choose a modified raster for the error diffusion in regions where the original grey value is below Δ, and the same modified raster in the bright regions with grey values above $1-\Delta$. The value of Δ has to be chosen accordingly.

In this paper we will discuss a modified raster that contains only a quarter of the points of the original raster (Figure 3). ED is performed only on these raster points, while the remaining points are set to 0 (or 1 in the bright regions). For correct continuous-tone reproduction, the input values of the modified raster have to be changed. In the bright regions the original grey value I is tranformed into $I' = 4(I-3/4)$, in the dark regions into $I' = 4I$.

For comparison with the conventional ED algorithm, Figure 4 shows a binarization of the same grey wedge as in Figure 2, but performed on a modified raster as described above. Although processed with the same diffusion weights as in Figure 2, the texture is different. In regions where the original grey values are below 0.05 the pixel distribution is improved.

The main problems of this approach are the choice of the diffusion weights, and the means of transferring the binarization error at the boundaries of the different rasters. We chose the weights in such a way that the resulting diffusion weights in the modified and the normal raster are the same. An error transfer scheme with four weights at a raster change

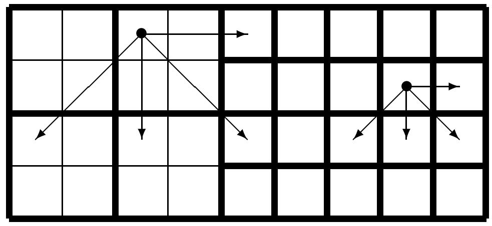

Figure 5. Realization of the error diffusion on the normal and modified rasters (with the Floyd and Steinberg diffusion weights). Independently of the raster used in the neighbourhood, the error of the modified raster is distributed to four cells of the normal raster

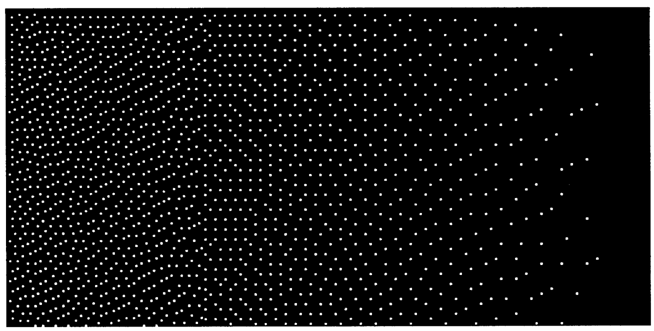

Figure 6. Binarization of a grey wedge between 0.1 and 0 with error diffusion on an adaptive raster and the weights from Figure 1a. The raster is switched at a grey value of 0.07

is shown in Figure 5. Independently of the raster used in the neighbourhood, the error of the coarse raster points is distributed among four points of the normal raster.

The result of a binarization of a grey wedge between 0.1 and 0 with raster switching at 0.07 is shown in Figure 6. It is possible to switch between the rasters without obtaining a disturbing seam between them; only a small change in texture is noticeable.

With the Floyd and Steinberg diffusion weights, the texture introduced by the modified raster is superior only over a relatively small interval of input values. As an example Figure 7 shows binarized versions of a scanned test image, in Figure 7a with the original ED algorithm and in Figure 7b with the ED on an adaptive raster and a Δ of 0.05. The improvement, especially in the reproduction of the dark hair region, is obvious, while on the other hand the two images do not differ appreciably over wide areas.

The advantages of the approach described become more visible if we restrict the number of diffusion weights to two. An acceptable binarization with two diffusion weights is difficult, for example the diffusion weights of Figure 1b lead to strong disturbing artefacts, even at input values near to 0.75 or 0.25. Fig.7c shows the binarized version of a scanned test image with these diffusion weights. In this case the switch to a modified raster is superior in larger regions of the input image. For comparison, Figure 7d shows the result of a binarization with an adaptive raster and a Δ of 0.25, i.e., more than 50% of the image was processed on the modified raster. The 'wormy' textures of Figure 7c are replaced by the more regular textures of the modified raster.

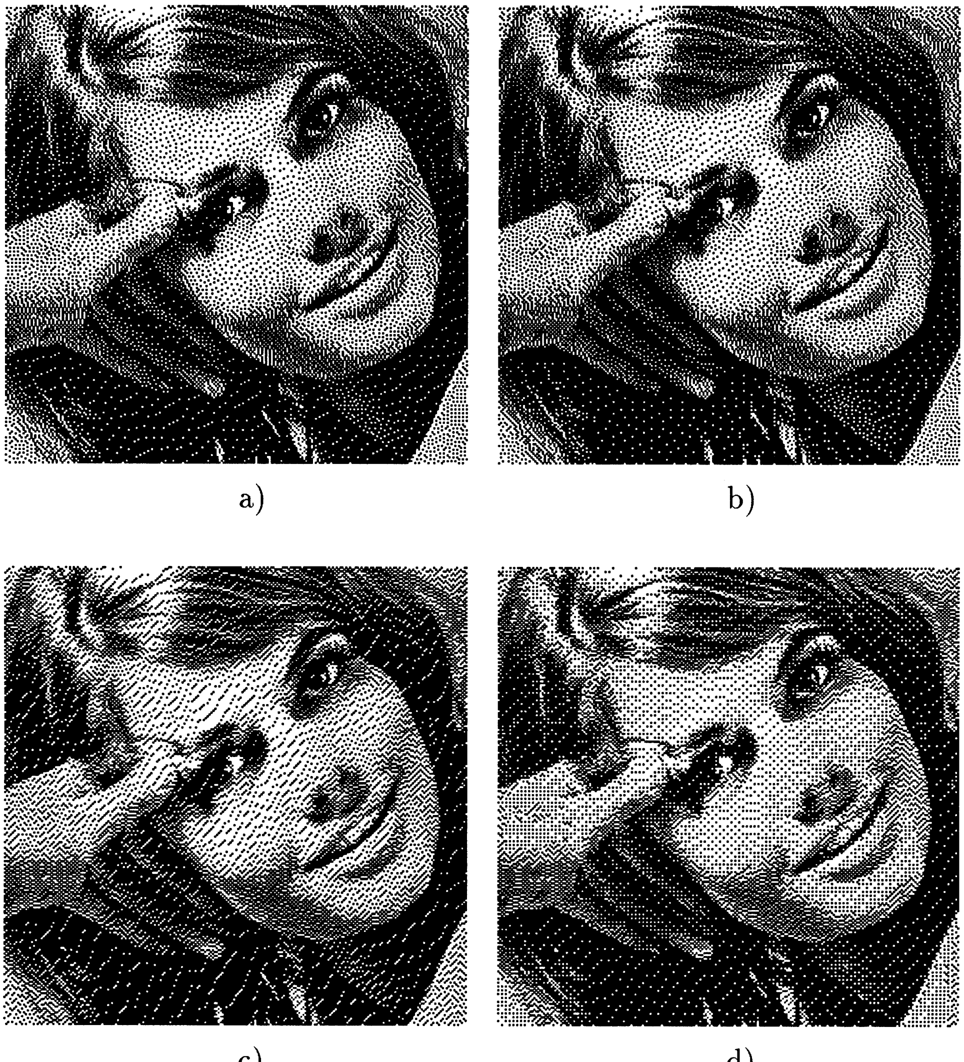

Figure 7. *Four binarized versions of a scanned test image. (a) ED on normal raster, diffusion weights of Figure 1a; (b) ED on adaptive raster,* $\Delta = 0.05$, *diffusion weights of Figure 1a; (c) ED on normal raster, diffusion weights of Figure 1b; (d) ED on adaptive raster,* $\Delta = 0.25$, *diffusion weights of Figure 1b*

4 CONCLUDING REMARKS

We propose a modification of the ED algorithm that adapts the raster on which the ED is performed to the local grey value of the image. This leads to the suppression of the low-frequency noise introduced by the conventional ED algorithm, the so-called ‘worms’.

This new approach leads to several free parameters that have to be worked out in detail. For example the geometry of the different rasters used in the algorithm can be varied. The diffusion weights in the different rasters could lead to the possibility of suppressing texture changes at raster boundaries.

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