Structure Artifact Free Multi-Level Error Diffusion Algorithm

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Abstract

Error-diffusion is widely used to generate intensity levels between the primary levels of multi-level colour printing devices (ink-jet printers, electrophotographic printers). Standard error-diffusion algorithms produce structure artifacts at rational intensity levels such as 1/3, 1/2 and 2/3. The boundary between structure artifacts breaks the visual continuity in regions of low intensity gradients and generates undesirable false contours. These undesirable structure artifacts are also visible when error-diffusion is used to generate intermediate intensity levels between primary levels.

In this contribution, we propose to remove these structure artifacts by introducing small discontinuities in the tone correction curve, thereby avoiding reproducing the intensity levels responsible for the generation of structure artifacts. The method can not be applied to bilevel printing, since the forbidden intensity regions responsible for the structure artifacts would be too large. In multi-level colour printing however, the forbidden intensity regions are small enough and do not produce any visible intensity breaks in varying intensity wedges.

1. Introduction

During the last years, colour ink-jet printing technology has developed at a rapid pace. Printer manufacturers have been able to significantly decrease the volume of individual ink droplets while improving their spatial positioning. In addition, some printers use three- or multi-level inks rather than traditional bi-level inks. Nowadays, low-cost ink-jet printers reach a resolution of over 1000 dpi and provide almost photographic quality. In early ink-jet printers, individual ink drops were relatively large and therefore clearly visible. The inherent quality of halftoning algorithms used in these printers was one of the most important factors for achieving satisfactory printing quality. Clustered-dot dithering, popular for laser and traditional offset printing, has not been used in ink-jet printers due to the relatively coarse size of the produced screen dots. In contrast, halftones produced with error-diffusion algorithms appear much finer. This is the reason why error-diffusion was used preponderantly in first-generation colour ink-jet printers. With the advent of higher resolution (over 1000 dpi) multi-level colour ink- jet printers, the situation has changed. Dots of variable size are formed by a variable number of tiny individual ink droplets printed like small clusters. The produced variable size dots are still invisible to the human eye. Possibly combined with multi-ink technology (e.g. low- and high-density inks, for the same colour), these new printers may be considered as multi- level ink-jet printers operating at medium resolution (say 300-600 dpi), with a relatively large number of “primary” colours. By “primary” colour we understand here different permitted combinations of dot size and/or multi ink features.

The quality criteria for judging and comparing halftoning algorithms are the following:

- the visibility of individual dots or screen elements should be minimized
- the number of intensity levels should be large enough (> 64) to avoid banding effects
- structure artifacts, i.e. repetitive or semi-repetitive visible structures should be avoided
- false contours due to sharp halftone structure changes should be avoided

This paper presents an error-diffusion method for the halftoning of images on multi-level printing devices. The resulting visual effects are shown by simulating the printed dots of a multi-level inkjet printer.

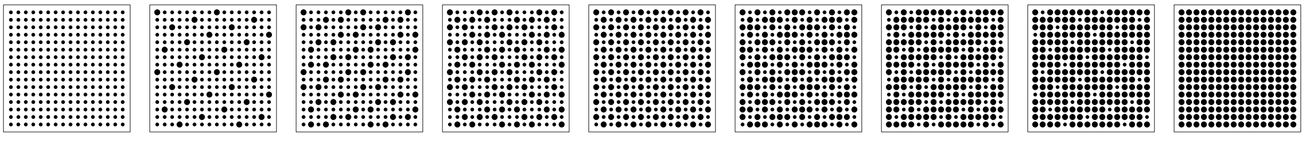

Figure 1. Intermediate darkness levels obtained by dithering between basic levels

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Zürich, May 1998,
Proceedings Europto Conf. Series, SPIE Vol. 3409.

The number of available primary colours, usually between 8 and 32, is not sufficient to avoid banding effects and to permit the faithful reproduction of high-quality images. These banding effects are generally eliminated by applying between consecutive primary colours error-diffusion methods [Ostromoukhov96a], [Yu98].

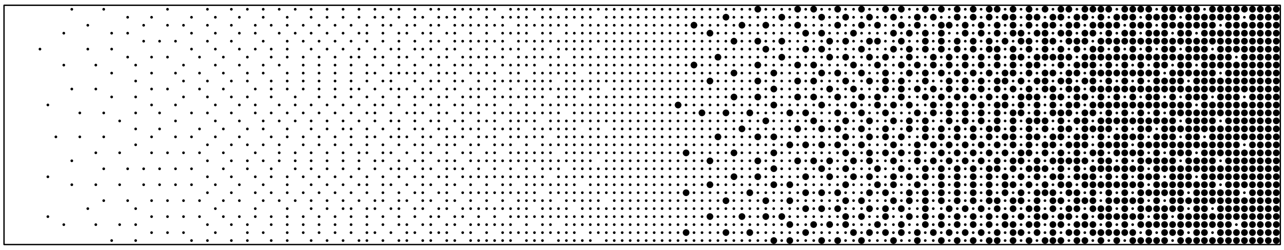

Figure 2. Simulated example of a 3 level printing process incorporating error-diffusion between the primary levels

In section 2, we show that standard error-diffusion methods yield structure artifacts at specific intensity levels. In section 3, we describe how to modify a device's tone correction curve in order to create images without structure artifacts.

2. Structure artifacts in error-diffusion

It is known that error-diffusion algorithms such as Floyd-Steinberg [Floyd76], Jarvis, Judice & Ninke [Jarvis76] as well as Stucki [Stucki81] produce undesirable artifacts in the form of structure artifacts such as checkerboard patterns at 1/2 intensity, diagonal stripes at 1/3 intensity and other repetitive structures at 1/4 intensity (Fig. 3). The boundaries between structure artifacts break the visual continuity in regions of low intensity gradients and may be therefore responsible for false contours.

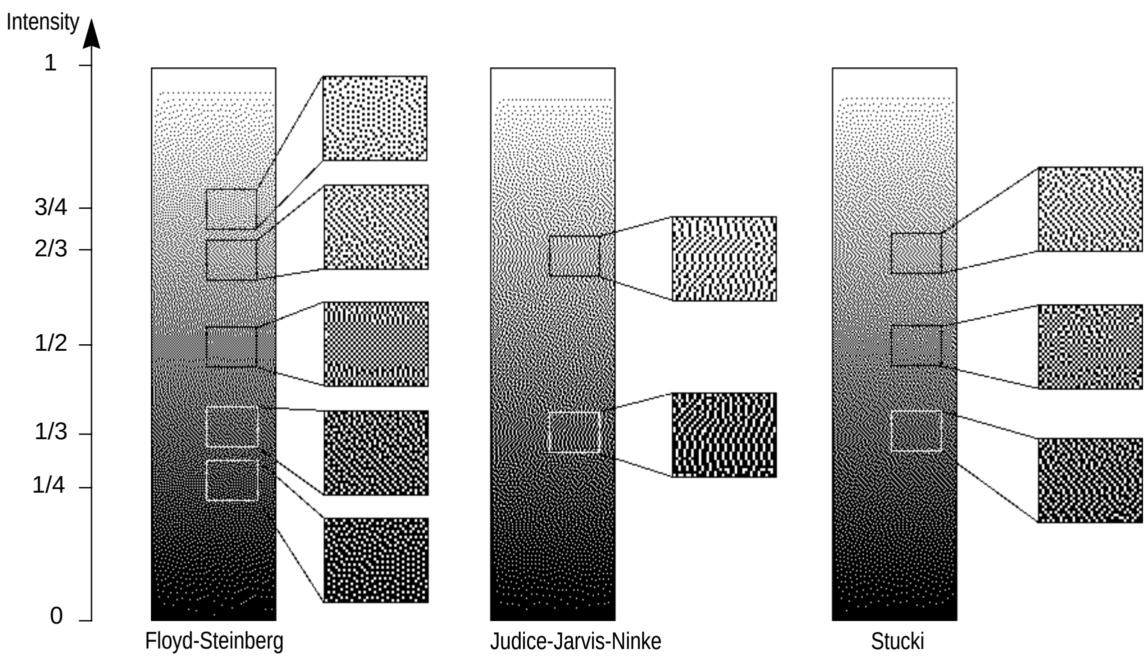

Figure 3. Error diffusion artifacts at specific intensities

In section 3, we show how to avoid producing structure artifacts by eliminating the possibility of printing at intensities inducing structure artifacts.

3. Constrained error-diffusion between successive primary colours

The structure artifacts described in section 2 are inherited by multi-level error-diffusion, which maps the range of intensity levels [I1—I2] between two consecutive intensities I1 and I2 onto the range [0—255]. The key idea of the proposed improved multi-level error-diffusion algorithm is to use for each process colour a non-linear tone reproduction curve ensuring that the corresponding two-level error-diffusion never falls into "forbidden" intensities around the dangerous values 255*i/j, where i,j are small integer values.

Since colour reproduction exhibits due to dot gain a non-linear tone reproduction curve, we can tune the behavior of the tone correction curve so as to avoid printing in the intensity areas responsible for structure artifacts, by applying a mapping which maps the tone reproduction curve on a perceptually equilibrated one.

Let us consider an error-diffusion range between 0 (black) and 1 (white). In order to avoid 1/3, 1/2 and 2/3 structure artifacts (Fig. 2), we need to avoid printing respectively in the intensity ranges (0.333-0.02)—(0.333+0.02), (0.5-0.02)—(0.5+0.02) and (0.667-0.02)—(0.667+0.02), where 0.02 represents the half-width of the forbidden zone (defined experimentally).

The same rule can be applied for example to a 3 level ink-jet reproduction process capable of producing levels 0 (black: 2 ink droplets), 60 (one ink droplet) and 255 (no droplet). The application of that rule yields the following forbidden intensity ranges on a scale 0 to 255.

We first measure the tone reproduction curve by applying error diffusion between primary intensity levels without taking into account structure artifacts. By mapping it onto the perceptually equilibrated tone reproduction curve, we obtain the tone correction curve (Fig. 3). The tone correction curve is then modified by introducing discontinuities to eliminate the forbidden intensity ranges. This step is illustrated in the next section.

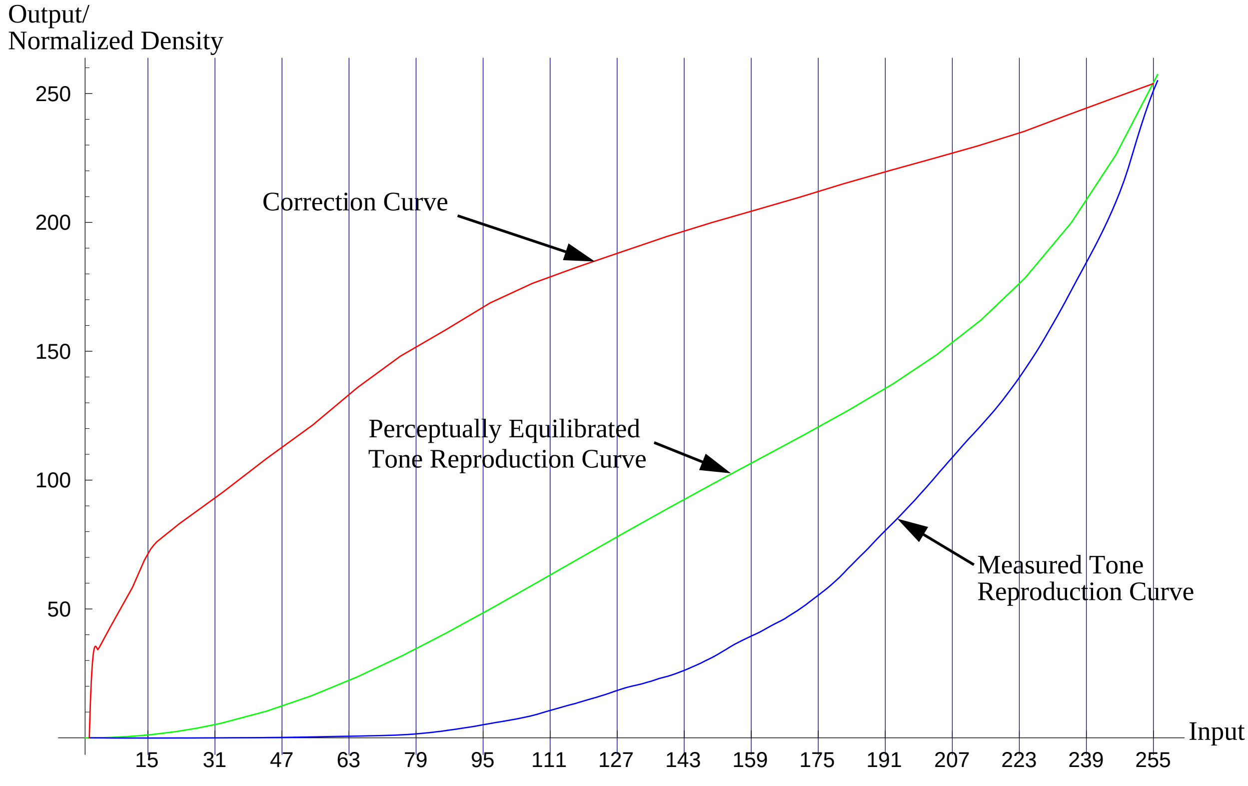

Figure 4. Measured tone reproduction curve, perceptually equilibrated tone reproduction curve and resulting tone correction curve.

4. Simulated results

The proposed method is illustrated by a set of samples, produced with our simulator which mimics the behaviour of a typical high-resolution (1440 dpi) multi- level ink-jet printer. In our simulator, the droplets corresponding to consecutive intensity levels of basic inks are obtained by putting several binary pixels together. These fixed-size groups of pixels behave as individual multi-level pixels in the simulated printing process. Algorithmically, our simulator implements dot-to-dot error diffusion as described in the literature [Fan92].

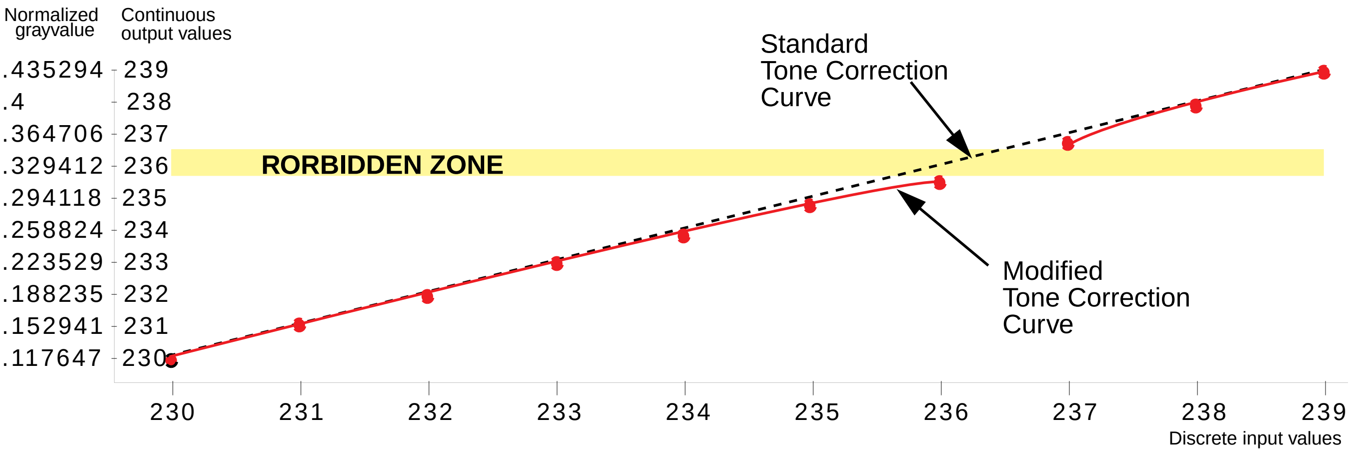

Figure 5. Standard tone correction curve (dashed line) and modified tone correction curve designed to avoid the forbidden zone around 1/3 (normalized grayvalue), near the input value 236. Figure 6 shows the achieved effect.

Let us consider the case study where 10-level error-diffusion is simulated by groups of 3x3 binary pixels. For the sake of simplicity, we assume that the standard tone correction curve is linear, as shown in Figure 5. We are particularly interested in a range of input values between 230 and 239 (highlights). As can be observed in Figure 6a, the standard algorithm shows a strong structure artifact at grayvalue 236. The reason for this phenomenon is clear: if we map the range [226.7 — 255] to the range [0—1], the input grayvalue of 236 corresponds to the normalized grayvalue of 0.3294, very close to the value 0.3333. Consequently, the input grayvalue 236 lies in the forbidden zone, where the structure artifact is strong. After modification of the tone correction curve as shown in Figure 5, all values of the considered range [230—239] fall outside forbidden zones.

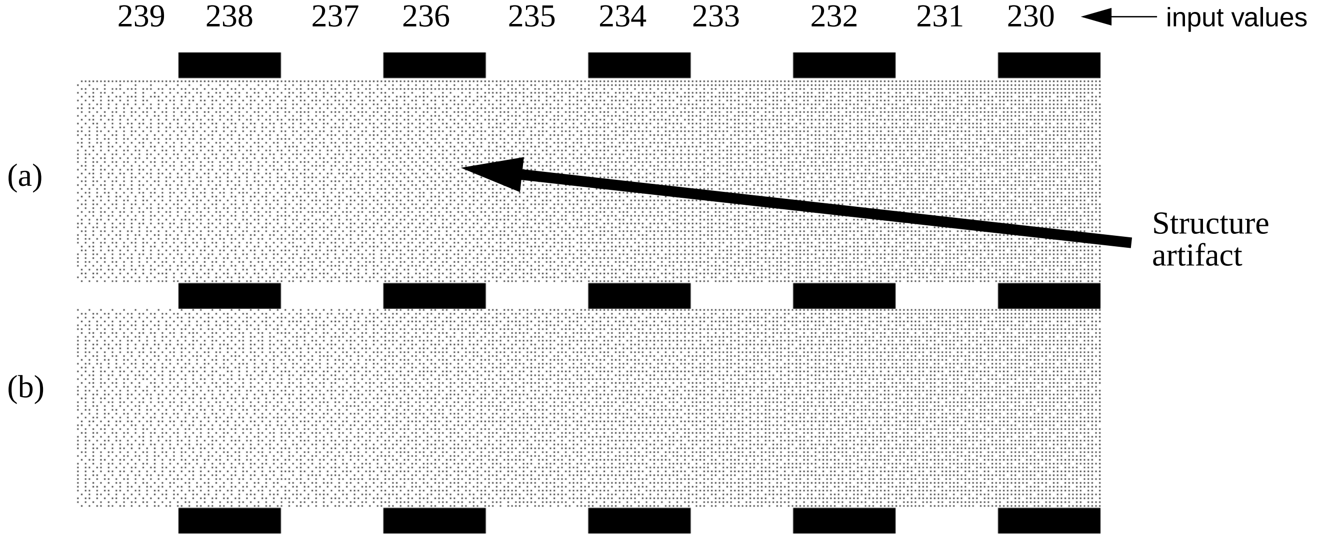

Figure 6. Simulated samples (a) without modified tone correction curve and (b) with modified tone correction curve.

The corresponding resulting halftone (Figure 6b) shows a satisfactory improvement with respect to the original, non-modified tone correction curve. This method can be extended to the whole range [0—255] of input values. Notice that the described structure artifact may be visible in some areas (typically, in highlights), and be neglectfully small in others (typically, in dark areas). Consequently, the described method should be applied selectively.

5. CONCLUSIONS

Error-diffusion is widely used to generate intensity levels between the primary levels of multi-level printing devices (ink-jet printers, electrophotographic printers). By introducing small discontinuities in the tone correction curve to avoid printing at some narrow intensity intervals we can avoid the formation of structure elements and therefore significantly improve image reproduction quality.

The method can not be applied to bi-level printing, since the forbidden intensity regions responsible for the structure artifacts would be too large. In multi-level colour printing however, the forbidden intensity regions are small enough and do not produce any visible intensity breaks in varying intensity wedges.

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