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Stable Reproduction of Highlight Density for Dye Sublimation Printers

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Abstract. *The dye sublimation transfer process, which allows continuous density gradation, is a process by which an image quality close to that of silver halide photographs can be obtained. However, deviations in process characteristics lead to deterioration in gradation characteristics in the highlight area and degradation in the image quality, such as color saturation and tone jumping in the highlight area. This paper describes a highlight error diffusion method for improving the gradation characteristics of highlight areas and stabilizing the microdensity, which will become an issue when implementing the method in a dye sublimation process. This method involves an algorithm that corrects the amount of heat applied to pixels based on the average density near those pixels. The proposed method improves gradation characteristics of the highlight area without visually recognizable granularity. © 2006 Society for Imaging Science and Technology.*
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INTRODUCTION

With the increase in the popularity and use of digital cameras, the importance of printing digital photographs has also increased. The sublimation transfer process is suitable for printing digital photographs and is widely used in devices such as compact photoprinters for home use and print engines for commercial establishments offering photolab services.

The principle of printing, as shown in Fig. 1, is the passage of electricity through heating elements of a thermal head and the production of color by transferring or diffusing some amount of dye from an ink film onto the dye receiving layer of the image receiving paper surface, in accordance with the heat generated. Unlike other processes, this process can be used to achieve continuous density gradation using individual pixels by varying the time for which electricity is passed to the heating element. Thus, by this process, a uniform image quality with no granularity is theoretically obtained.

However, the control of the highlight density is difficult in both thermal printing, which is a type of analog processing using the heat amount, and ink jet printing, which the image is reproduced using the smallest dot size.

The factors inhibiting a stable reproduction of the density can be generally categorized into two types:

(1) changes in ambient temperature and effects of heat accumulation in the thermal head; and
(2) individual differences in the principal parts of the printing process.

The factors in category (1) cause degradation in the image quality, namely, (a) degradation in the tone/color reproduction due to density deviation and changes in gamma characteristics and (b) degradation in the modulation transfer function in individual pixels. A technique termed temperature compensation has been established to overcome these problems; a practical level of degradation with regard to (a) that is particularly important for photo image quality has been ensured.[1–6]

On the other hand, the issues below are considered to be factors of category (2), although these issues were previously deemed to be theoretically unavoidable:

(a) deviation in characteristics of print media (ink film and image receiving paper) due to differences in manufacturing lots and changes in terms of storage over time; and
(b) deviation in characteristics of the thermal head, i.e., differences in characteristics of reference thermal heads with measured gamma characteristics and those of heads of mass-produced products, and deviations primarily in the glazing thickness and thermal conductivity.

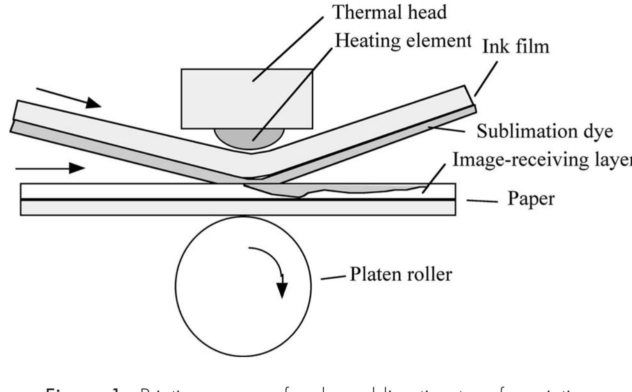

Figure 1. Printing process for dye sublimation transfer printing.

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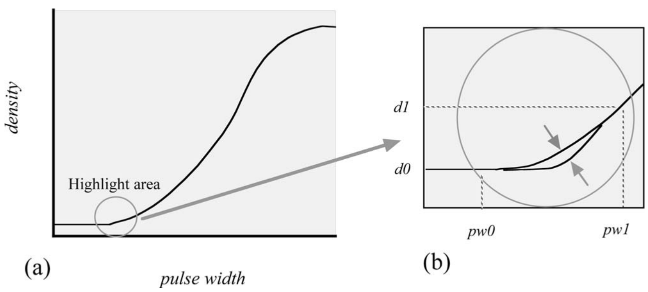


Figure 2. Density-tone curve of a dye sublimation transfer printing process.

These issues are presently handled by inspection and screening at manufacturing sites in the case of both printer and print media. In addition, the characteristics are individually measured for expensive commercial products, and correction values are also changed. Nonetheless, some deviation must unfortunately be allowed for lower priced products that place priority on cost. In any case, this is an issue that not only affects the production and running costs but also occurs in the market in the form of degradation in the print image quality.

Figure 2 shows an example of gamma characteristics in the dye sublimation process. The horizontal axis represents the electrical pulse width and the vertical axis represents the reflection density; the reflection density is given by a continuous function of the electrical pulse width. A feature of the gamma characteristic is that the transfer of the dye ink does not occur at a small pulse width; rather, the density of the image is equal to the density of the paper surface. The transfer of the dye begins when the pulse width exceeds a certain level and the density begins to increase.

The area before and just after the commencement of transfer of dye is termed the highlight area. This area involves an amount of heat just sufficient for the dye transfer; hence, the density of the highlight area changes, as shown in Fig. 2(b), due to the slight deviation in characteristics mentioned previously. Printing with different levels of gradation results in abrupt changes in places that should have densities that gradually approach the paper surface density near the highlight area. Such a degradation in the tone is linked to a marked degradation in the image quality, such as blooming of the image, false contouring, and color saturation.

In order to develop photoprinting by a dye sublimation process, techniques must be developed from the perspectives of both image quality and cost (hardware and running costs) so as to fundamentally resolve the problem of degradation in the image quality due to the previously mentioned deviation.

This paper describes a highlight error diffusion method to improve the gradation characteristics of highlight areas, which tend to be unstable, and a technique for compensating the amount of heat per pixel to stabilize the microdensity, which will become an issue when this method is implemented in a dye sublimation process.

Figure 3. Highlight error diffusion method.

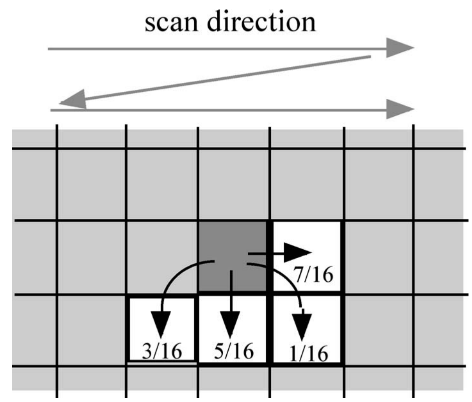


Figure 4. Floyd and Steinberg type error diffusion matrix.

METHODS

Highlight Error Diffusion Method

This paper focuses on limiting areas with a high level of sensitivity with respect to process deviation to the highlight area. Moreover, as shown in Fig. 3, the paper proposes a highlight error diffusion method for the stable reproduction of the highlight area by area coverage modulation using only the stabilized density preceding and following the area, without using the area density near an unstable highlight area. The error diffusion method[7–10] that is used in this study for area coverage modulation is a method of diffusing the difference in density between the original image and output image to unprocessed pixels around the concerned areas in accordance with a previously set matrix. This method performs very well with regard to the compatibility of the resolution and tone in comparison to halftoning screen and dithering,[11] and it is used when rendering the tone with a binary printer such as an ink jet printer. One of the problems in the error diffusion method is the generation of a "wormy" pattern of dots. Some improved error diffusion methods[9,10] have been proposed to ensure that such a pattern of dots is not generated. To demonstrate the features of our method, a simple Floyd and Steinberg error diffusion matrix,[7] as shown in Fig. 4, was first employed.

It is absolutely essential to incorporate area coverage modulation of only the highlight area in a dye sublimation printer, whose noteworthy feature is a continuous tone, having defects particular to area coverage modulation, such as texture and granularity, at a level where they are completely invisible.

There are few differences with regard to the resolution used in a normal dye sublimation process due to the various

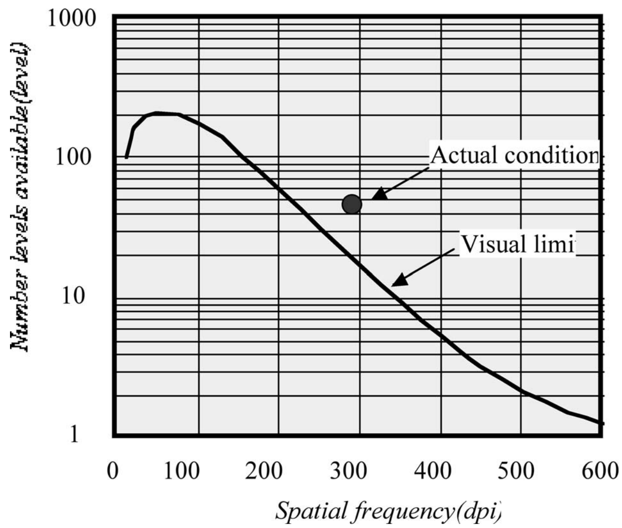


Figure 5. Spatial frequency response of human visual system by Roetling.

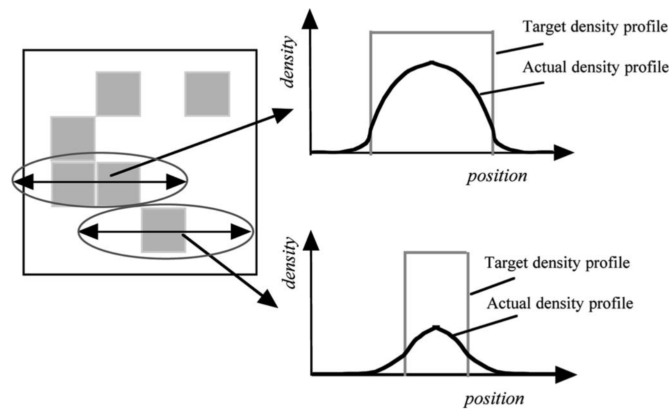


Figure 6. Microdensity profile.

manufacturers and prices of the device—the resolution generally falls in the range of 250–400 dpi. This is because it is not necessary to ensure that the number of tones for a printer such as an ink jet printer is at a certain level and to increase the resolution for resolving the problem of granularity; hence, a resolution of the order of 300 dpi that is actually needed for photo printing is sufficient.

The upper limit of the pulse width at the paper surface density $d0$, where color is not consistently produced, is $pw0$ in the areas preceding and following an unstable highlight area, as shown in Fig. 2(b). The pulse width that reproduces the density $d1$, where stable production of color is observed, is $pw1$. Here, an extremely small difference of 0.05 in the density between $d1$ and $d0$ corresponds to 1/44 of the maximum density of 2.2. Even with a resolution of the order of 300 dpi, identification of 44 tones is difficult in terms of the characteristics for the number of tones[12] that can be visually identified at each spatial frequency, as shown in Fig. 5. The texture and granularity resulting from such an extremely small difference in density exceed the limits of visual perception; therefore, they can be expected to be invisible.

Thus, if this highlight error diffusion method can actually be incorporated in the dye sublimation process, a stable reproduction near the highlight area will be possible without losing the advantages of the conventional dye sublimation process.

Issues in the Highlight Error Diffusion Method

However, when considering incorporation of the error diffusion technique in the dye sublimation process, a problem particular to analog thermal printing arises, namely, the reverse dot gain. The pulse width $pw1$ and print density $d1$ can be stably reproduced over a certain area, i.e., patches where the same amount of heat is supplied are printed for neighboring pixels as well; this does not indicate stable reproduction by individual pixels.

Figure 6 shows a conceptual diagram of the microdensity profile for surrounding pixels. The diffusion of heat to the surroundings changes when the target pixel is adjacent to "on" pixels or isolated. In this instance, an offset, i.e., a transfer threshold temperature,[1,2] is required to transfer the dye; hence, the microdensity in the pixel decreases abruptly with just a slight drop in temperature.

From the perspective of the variation in the macrodensity due to the dot arrangement, the direction of the change itself is the reverse; although this phenomenon resembles dot gain, it is a problem in area coverage modulation for a binary printer. Dot gain is a phenomenon in which the dots for individual points expand and macrodensity increases, and it can be corrected by decreasing the number of dots in the region where the density increases by means of a correction table using a Yule-Nielsen n value[13] or its equivalent. However, in the case of the highlight error diffusion method for dye sublimation, a decrease in the microdensity occurs due to heat diffusion at isolated points, and the macrodensity also decreases subsequently. This reduced microdensity is easily affected by deviation and is unstable. Hence, a correction of the increasing reflection density by increasing the number of dots (dot density) corresponds to forced correction by a gamma correction of unstable gradation characteristics; thus, the highlight density decreases abruptly and stable reproduction is not attained, which is a goal of the current research.

Hence, a new approach different from the correction of the dot gain is needed to correct the amount of heat in accordance with conditions for the diffusion of heat. In this paper, the following are discussed: a method to reproduce the microdensity using individual pixels and thus reproduce the macrodensity, and a method to correct the microdensity so that the macrodensity becomes equal to the target density.

Correction of the Amount of Heat via Microdensity

In order to stabilize the macrodensity by error diffusion, only the microdensity of individual pixels needs to be stably reproduced regardless of the arrangement of adjacent pixels.

The diffusion of heat has a qualitative effect, observed as blurring of the image; therefore, this problem can be resolved by enhancing the pulse width after error diffusion by differentiation, as indicated in Eq. (1). The direction of sub-

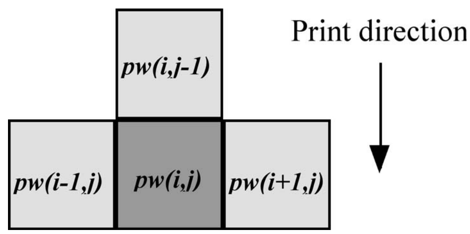


Figure 7. Pixels used for differential processing.

scanning is the first order differentiation for asymmetric blurring and the direction of scanning is the secondary directive with differential correction of the pulse width $pw(ij)$ in the case of the pixel concerned, based on the pulse width data for three adjacent pixels, as shown in Fig. 7,

$$pw'(i,j) = pw(i,j) + k1[2pw(i,j) - pw(i-1,j) - pw(i+1,j)] + k2[pw(i,j) - pw(i,j-1)]. \quad (1)$$

The method of correcting thermal diffusion by differentiation is qualitatively a correct approach, although the following considerations are insufficient:

(a) the relationship between the temperature and density of pixels, both of which decrease due to thermal diffusion, is not linear; and
(b) the effects of thermal diffusion are not limited to the three adjacent pixels; an even broader area is affected.

Thus, it was determined whether the above-mentioned effects are negligible, i.e., to verify the extent to which precise correction is needed, in the actual dye sublimation process.

The error diffusion is calculated using the pulse width that represents the amount of heat; the density above $d1$ in Fig. 2 is reproduced by density gradation with the normal pulse width, while the density below $d1$ is reproduced by error diffusion using the two values of the pulse width, $pw1$ and $pw0$.

The experimental conditions were a resolution of 259 dpi and line period of 10 ms; the pulse width signal is represented by a numerical value with the line period divided by 12 bits (4096); $d0$ was set to 0.07, and $d1$ was set to 0.12 on the basis of a preliminary investigation with the previously mentioned printing conditions. The pulse width values $pw0$ and $pw1$ were 640 and 1014, respectively.

Tone A in Fig. 8 represents the gradation characteristics obtained without correction for thermal diffusion. As expected, the highlight density decreased to the paper surface density without any increase due to the reverse dot gain. Along with the decrease in dot density, the pixels shrank and the microdensity decreased; isolated dots generally did not produce color. In addition, small values of $k1$ and $k2$ and a small amount of correction in the amount of heat by differential processing in Eq. (1) led to a value approaching tone A, and increasing the amount of correction led to tone reversal indicated by tones B and C in Fig. 8. From Eq. (1), it was determined that there is no optimum solution for correction. Thus, more precise correction is needed using a model considering points (a) and (b), as previously discussed.

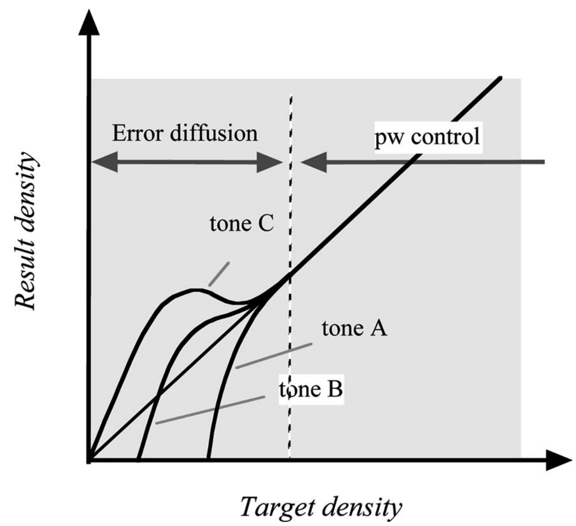


Figure 8. Result from a trial of highlight error diffusion method in a dye sublimation transfer printing process.

Therefore, seeking precise correction considering points (a) and (b) as discussed through the approach in this section, i.e., stably reproducing the microdensity using individual pixels and thereby stabilizing the macrodensity, will lead to the development of new temperature compensation techniques (based on thermal history correction techniques)[5,6] with respect to the microdensity; moreover, the differential processing will become more intensive.

Correction of the Amount of Heat by Macrodensity

The goal of the current research is to stably reproduce the tone near the highlight area using an error diffusion technique that involves only a correct reproduction of the intended macrodensity by error diffusion, even if the microdensity for single dots varies considerably due to the dot arrangement. Thus, an approach to obtain the correct pulse width per pixel so that the macrodensity coincides with the target density was studied.

Algorithm

The basis for this algorithm is the unique determination of differences in the thermal diffusion per pixel that change due to the arrangement, based on the average area ratio for on pixels.

This approach has the following merits:

(a) if the average area ratio is known, correction values can be determined by testing; and
(b) the average area ratio can be uniquely estimated based on the pulse width before error diffusion.

This is the solution with regard to points (a) and (b) in the preceding section. The nonlinearity in (a) can be resolved by estimation with the required precision via testing

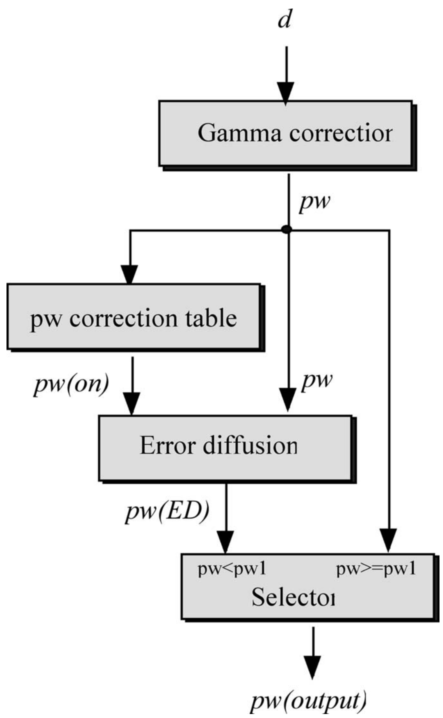


Figure 9. Proposed highlight error diffusion method.

and by using the correction table; the reference range in (b) will be an area ratio with a sufficiently broad range, based on the nature of error diffusion.

In addition, intensive processing, i.e., examining the arrangement of surrounding pixels, is unnecessary from the algorithmic perspective and can be achieved with a simple flow, as shown in Fig. 9. The input density d is converted to the pulse width pw by gamma correction, as shown in Fig. 10(a); when pw is greater than $pw1$, the result will be a continuous tone with the original pulse width. A highlight area with a pulse width value between $pw0$ and $pw1$ is binarized by error diffusion. The area ratio α for on pixels in this instance is given by Eq. (2), as shown in Fig. 10(b),

$$\alpha = \frac{pw - pw0}{pw1 - pw0}. \tag{2}$$

In the case of ideal error diffusion, the assumptions that on pixels correspond to the value of $pw1$ and "off" pixels correspond to the value of $pw0$ imply that an intermediate density will definitely be reproduced by area coverage modulation via the area ratio α. Although the heat diffusion along with the decrease in the area ratio is indicative of the actual dye sublimation process, the average microdensity $d1$ cannot be obtained with a pulse width of $pw1$ for on pixels, and the macrodensity also decreases. Thus, the current algorithm reproduces the target macrodensity regardless of thermal diffusion by performing error diffusion with the values of $pw(on)$ and $pw0$ as determined by the correction table.

The function shown in Fig. 10(c) is stored in the correction table. This function determines the average area ratio α for on pixels when error diffusion is performed based on the pulse width for the target density d originally desired in the concerned pixels; this pulse width represents the output of correction values $pw(on)$ for the pulse width of on pixels in accordance with the area ratio α.

Here, $\alpha=1$, i.e., it is equivalent to density gradation when the area ratio is 100%; therefore, $pw(on)$ coincides with $pw1$, producing a curve that rises in accordance with the decrease in α.

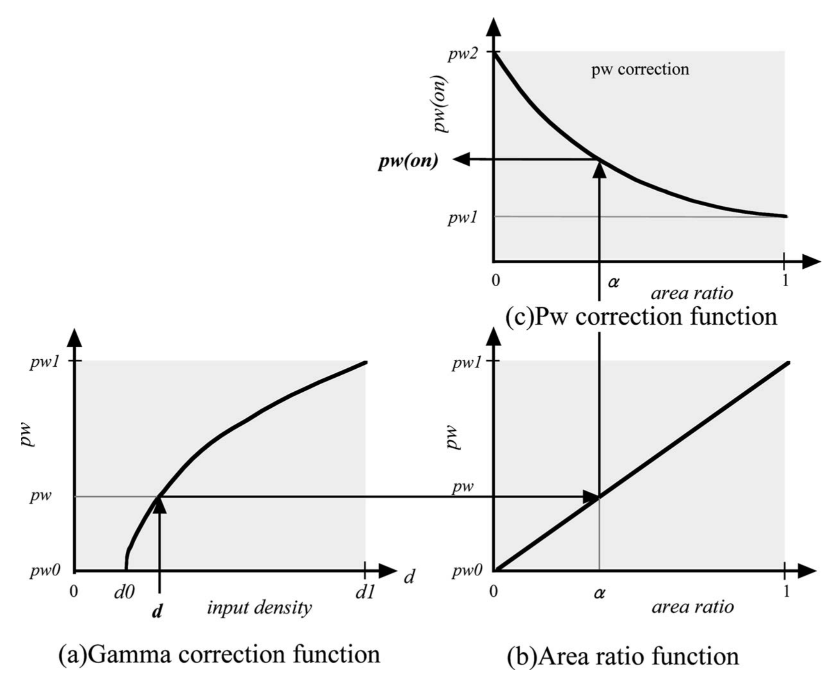
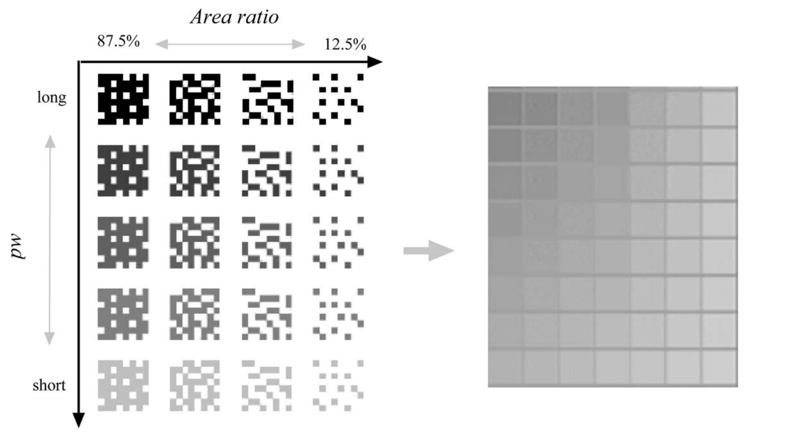


Figure 10. (a) Gamma correction function, (b) area ratio function, and (c) pw correction function.



(a) Patches in which the pulse width of a pixel and the area ratio were changed.

(b) Photograph of an actual test pattern.

Figure 11. The printed test pattern. (a) Patches in which the pulse width of a pixel and the area ratio were changed. (b) Photograph of an actual test pattern.

Determination of the Amount of Correction

If the correction function in Fig. 10 can be precisely obtained, the density stabilized by the highlight error diffusion method can be printed. In order to quantitatively obtain this function, a test pattern was developed to create the correction table, as shown in Fig. 11. Parameters can be uniquely determined by printing this pattern and solving the equation as described below with actual measurements of the density.

With regard to the test image, patches for the density measurement are arranged in two dimensions. In the horizontal direction, the area ratio for error diffusion from right to left changes from 12.5% to 87.5% in units of 12.5%. The vertical direction indicates an increase of pulse width in eight stages from a pulse width of $pw1$ for on pixels from bottom to top. The actual printed image is shown in Fig. 11(b).

The patch at the bottom right of Fig. 11(b) is a pulse with a width of $pw1$; since the area ratio is low and heat is diffused, color is not produced for the most part. The top left region, in contrast, has a high area ratio although there is a large amount of correction to the pulse width, resulting in a high density that cannot be considered to be a highlight area. The significant observation in this case is that the arrangement of patches is from the bottom left region to the top right one.

A graph showing the measurement of the test pattern is provided in Fig. 12. The horizontal axis denotes $pw(on)$ per area ratio and the vertical axis represents the density of the patch. When the pulse width pw corresponding to the target density is determined, the area ratio is determined by Eq. (2). The curve for the area ratio is also depicted in Fig. 12. From this curve, the pulse width that coincides with the target density is determined as $pw(on)$. By repeating this step, a function can be calculated to uniquely specify the on pulse width $pw(on)$ where the macrodensity reproduced by

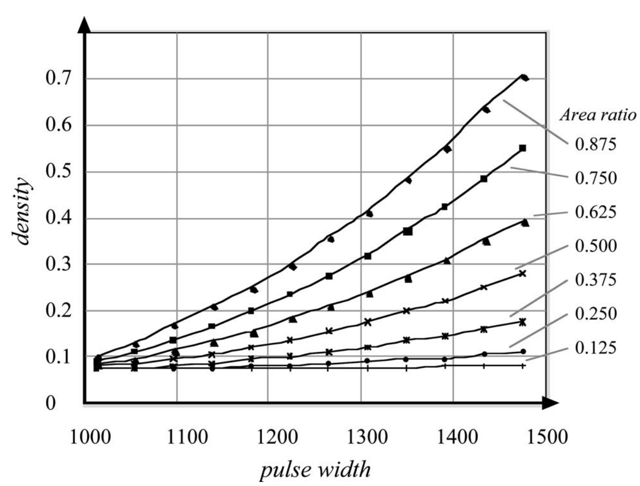


Figure 12. Density of test pattern.

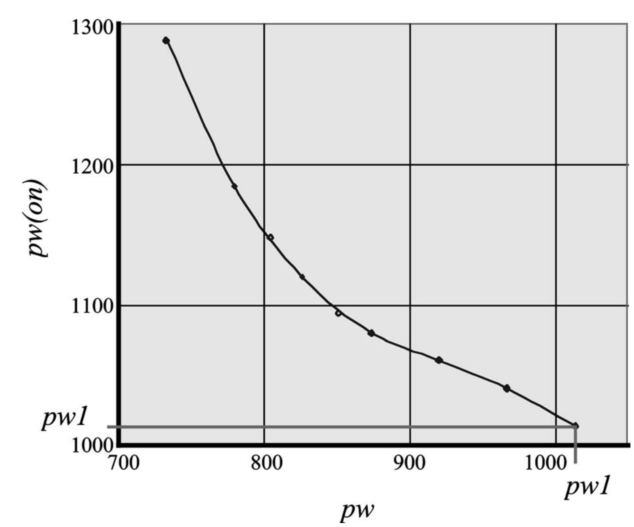


Figure 13. *pw* correction table.

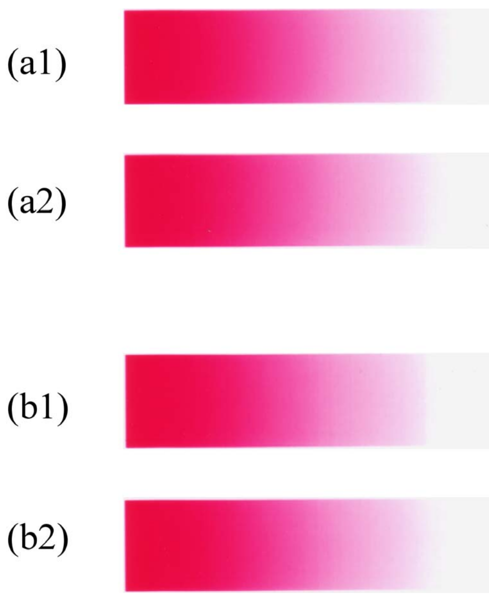


Figure 14. Printed gradation images. (a) Standard ink film: (a1) conventional density gradation method and (a2) highlight error diffusion method. (b) Nonstandard ink film: (b1) conventional density gradation method and (b2) highlight error diffusion method.

error diffusion coincides with the target density. Figure 13 contains actual measurements corresponding to the table in this figure.

EXPERIMENTAL EVALUATION AND RESULTS

In order to evaluate the effects of the proposed method, experimental evaluation was performed with the highlight error diffusion algorithm shown in Fig. 9. The factors in the image evaluation are the smoothness of the gradation, level of the tone jump, and saturation of the color in the highlight area. The printing conditions were a resolution of 259 dpi and line period of 10 ms; the table in Fig. 13 was used as the pulse width correction table for correcting the amount of heat.

Figure 14 shows a gradation image printed for evaluation in monochrome (magenta ink). Figures 14(a1) and 14(a2) are print images produced using a standard ink film whose deviations in characteristics are within standards; Figs. 14(b1) and (b2) are those produced using a nonstandard ink film. In addition, Figs. 14(a1) and 14(b1) are images with density gradation obtained only by the conventional pulse width control, and Figs. 14(a2) and 14(b2) are images obtained by the highlight error diffusion algorithm.

A graph showing the measurement of the density of gradation patches printed by magenta ink is presented in Fig. 15. The target densities of patches are set in a range below 0.3 near the paper surface density. Figures 15(a) and 15(b) show the characteristics with the standard ink film and the nonstandard ink film, respectively. Figures 14(a1) and 14(b1) show characteristic curves obtained by the conventional density gradation method using only the pulse width control; Figs. 14(a2) and 14(b2) show curves obtained by the highlight error diffusion method. The density of each patch is measured ten times using GretagMacbeth RD-19I, and the average is recorded on the graph.

DISCUSSION

The above-mentioned test data will be discussed from the following two perspectives.

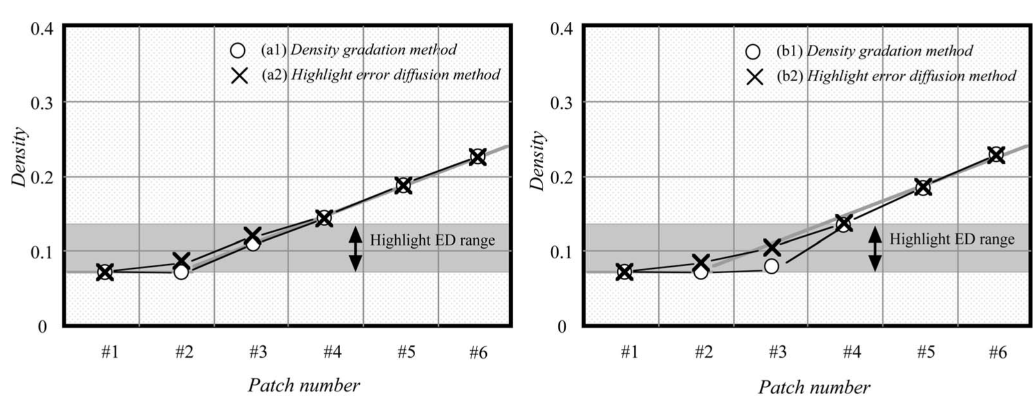
(1) Verification of the algorithm for correction of the amount of heat by the macrodensity:

The target density was directly obtained by the conventional density gradation [Fig. 14(a1)] with the standard ink film, according to Fig. 15(a).

The conditions under which the highlight error diffusion was incorporated [Fig. 14(a2)] also reproduced a density almost equal to the density gradation without degradation of gradation like tones A, B, and C shown in Fig. 10. Thus, it was verified that the macro correction of the amount of heat performed as expected.

(2) Effects of highlight error diffusion when the process varied:

Figure 15(b), which shows the result of printing using the nonstandard ink film, indicates that the density of patches near the paper surface density decreased when print-



(a) Standard ink film. (b) Non-standard ink film.

Figure 15. Measured density of patches. (a) Standard ink film. (b) Nonstandard ink film.

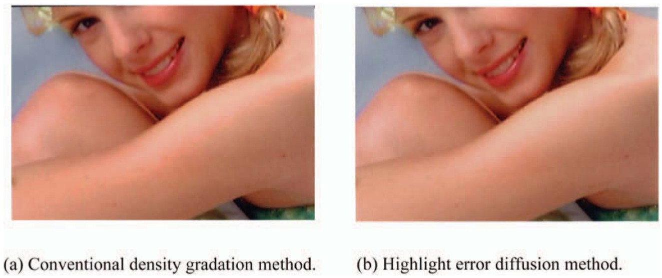


Figure 16. Printed images. (a) Conventional density gradation method. (b) Highlight error diffusion method.

ing with density gradation [Fig. 14(b1)]. The application of the proposed method, highlight error diffusion, led to the elimination of tone jumping even with ink such as that used in Fig. 15(b), as shown in the graph [Fig. 14(b2)]. Further, satisfactory gradation was ensured, similar to that with the standard ink film Fig. 15(a).

Figure 16 shows a color print of a photoimage using nonstandard ink. Figure 16(a) corresponds to printing using the conventional density gradation; Fig. 16(b), printing using the proposed method. Color saturation due to tone jumping of magenta in human skin, which was a problem as observed in Fig. 16(a), remedied at an acceptable level for practical use, as can be seen in Fig. 16(b).

With regard to the texture and granularity, which are prerequisites for the incorporation of the error diffusion technique in the dye sublimation process, current methods lead to error diffusion with a low density difference of 0.05, even if the Floyd and Steinberg error diffusion matrix that causes an anisotropic wormy pattern of dots is adopted. Hence, it was confirmed by observations that the texture and granularity cannot be visually perceived at the distance of distinct vision.

CONCLUSION

A highlight error diffusion method was studied as a technique to stabilize the tone of a highlight area resulting from process deviations in a sublimation transfer process. When error diffusion is performed in the dye sublimation process, the microdensity of pixels becomes unstable due to thermal diffusion in individual pixels. A method was developed to ensure that the macrodensity after error diffusion coincides with the target density through an approach that corrected the pulse width of on pixels via the area ratio after error diffusion and compensated for the microdensity via averaging. This method can provide simple processing of individual pixels by merely creating a table based on the input pixel level and determining the output pixel level.

The technique proposed in this paper for stable reproduction of the highlight area can be used to increase tolerances with respect to control and screening of thermal characteristics of thermal heads and reduce degradation in the image quality caused by deviations in characteristics between lots of ink film and by changes over time. Thus, this method can substantially contribute to the reduction in manufacturing and running costs for dye sublimation printers and to the production of higher quality images.

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