HALF-TONING USING INK-JET: PART 2. TAILORING ALGORITHM TO A PRINTER

Yigal Gur* and F.X.D. O'Donnell*

Abstract: Given a particular algorithm, such as error diffusion, the print produced by it may be enhanced by consideration of the printing system. This is especially true for ink-jet printing. The quality of a print is very strongly dependent upon the combination of ink and paper used. A useful first step is to print a series of grey levels. These levels may be measured instrumentally and converted to a form which correlates well with visual perception. From these measurements an adjustment is made that equal differences in grey level are also perceived as being nearly equal. The final check on the algorithm should be several pictures. These should be rated visually by a reasonably large number of observers.

Visual Grey Scales

The relationship between the visual perception of lightness and its physically measurable quantity reflectance has been thoroughly studied and found to be non-linear. The most widely used lightness scale is the Munsell Neutral Value Scale (A.E.O. Munsell et.al. 1933, I.H. Godlove 1933). This is a set of samples which varies from black to white through various shades of grey. They have been visually scaled so that samples with equal number differences on the scale will appear visually to have equal lightness differences. For example, if samples with values 3, 5 and 7 were examined, sample 5 would appear to be equally lighter than sample 3 and darker than sample 7. However, the percent reflectance of these are 6.5% for value 3, 18.0% for value 5 and 42.0% for value 7. This means that equal changes in the visual perception of lightness are not equally spaced in reflectance.

The relationship between reflectance and perceived lightness was investigated in 1933 (A.E.O. Munsell, I.H. Godlove). A fifth power polynomial was obtained relating percent reflectance and Munsell Value, the most recent form of which is:

$$Y = 1.1913V - 0.22532V^2 + 0.23351V^3 - 0.020483V^4 + 0.00081935V^5 \quad (1)$$

where Y is the percent reflectance, V is the Munsell Value.

This equation relates a perceived quantity to a measurable one. It is often more useful to relate the measurable value to the perceived value. In 1978, the Commission Internationale de l'Eclairage (CIE, 1978) published a recommendation for the use of an equation of this form:

$$L^* = 116\,(Y/Y_n)^{1/3} - 16 \quad (2)$$

---

*Diconix, a Kodak Company

In this equation Y/Y_n must be greater than 0.01 and Y_n is the Y value of the light source. L* is CIE 1976 lightness.

This equation is not a perfect fit to the Munsell Value function as at 0% reflectance L* is −16 when it should be 0. For values of Y between 1% and 100% it corresponds extremely well to the Munsell Value function. Printed samples will seldom have a reflectance less than 1%. This would correspond to a density value greater than 2.0. The CIE 1976 lightness function is important as it relates the measurable function, the percent reflectance, to the perceived function, which is the Munsell Neutral Value Scale.

In any reproduction system, the ability to produce a uniform visual grey scale is almost a necessity. When this is done, it allows adjustment of the system for increased sensitivity in the most visually important regions and for decreased sensitivity in the visually less important regions of a picture. That is, those regions which carry most of the pictorial information can be enhanced. Those regions which carry little information, such as shadow areas, need not be enhanced and even can suffer some loss without degrading the overall appearance of the picture.

Error Diffused Grey Levels

From a literature survey and a knowledge of ink-jet printers available, it was obvious that the error diffusion technique of binarization of images was the best method to use for ink-jet printing. The algorithm produces very little unwanted texture in images and as Gur (1985) in the first part of this paper has pointed out, even this may be removed. The image scanner we were using collects data at 256 levels including zero. It is for this reason we decided to use error diffusion to produce a set of 256 grey levels. The squares were generated by assigning a block of pixels a fixed numerical value. The first square was assigned a value zero, the second the one and so on up to 255. This is shown in Figure 3 in Part 1 of this paper.

The 256 levels were measured using a spectrophotometer and also a densitometer. The spectrophotometer gave CIE 1976 lightness readings directly. The density and lightness values were both plotted against the printed levels. Figure 1 shows the plot of density versus print level for three different ink-jet grade papers. These papers differ in the size of the dots produced and in the contrast between the paper and the printed dot. Figure 2 shows the plot of CIE 1976 lightness versus print level for these different papers. It is obvious from these graphs that if the print level is made linear in density, it will be non-linear for lightness and vice versa. We decided for the different papers to make them linear in lightness. The reason for this is the large amount of research into the relationship between the visual perception and the measurement of lightness.

For the purpose of measurement it was easier to measure a larger square rather than a smaller one. We experimented with this by printing only 16 levels from zero to 255 in increments of 17. When the 16 levels were plotted and compared to the 256 levels, there was no difference in the shape of the curve obtained. We decided that for future work, 16 levels were enough for adjustment of the grey levels. Figure 3 shows these 16 levels.

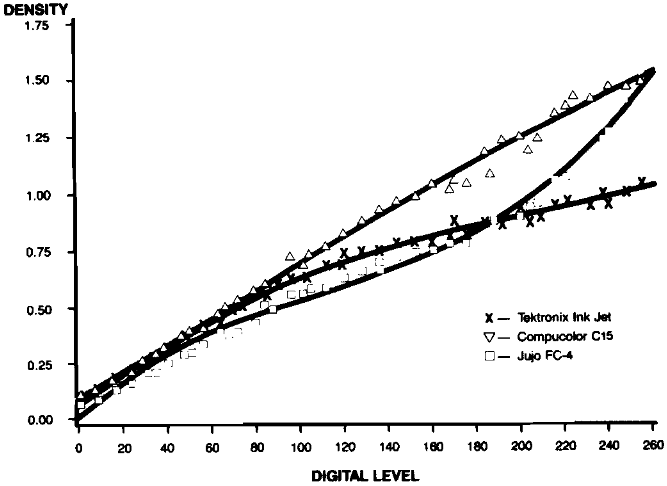

Figure 1. Density versus print level

Tailoring the Algorithm to the Ink/Paper System

We wanted to develop a technique for binarization of images that was, as far as possible, device independent. The final stage, however, requires that consideration be given to the particular reproduction system. We used the same ink in all experiments and that was the standard ink for the printer. The only variable was the paper. Five different ink-jet grade papers were used. These papers differed by the amount of spreading of the dots on the paper. The spread factor affects the blackness of the image. If the dots do not overlap, an area of solid fill will appear lighter than the blackness of the individual dot. The smaller the dot, the higher the resolution. Thus, in any ink-jet printing system, there is a trade off between obtaining maximum coverage and maximum resolution.

The sixteen levels were printed on each of the different papers. For each paper, a conversion was found between the printed levels and lightness levels. To understand the procedure for the correction of lightness for a particular paper, a plot can be made of the measured lightness for the sixteen squares versus the print level. Equal spacing in lightness would be perceived as equally spaced grey levels. This is what would be required to balance the grey levels. If the system performed ideally, a line connecting the 0 level and the 255 level would produce equally spaced distances on the lightness axis for the sixteen print levels. For all combinations of ink and paper this did not happen. The plot of lightness versus print level was curved as shown in Figure 4. To balance the grey levels, this

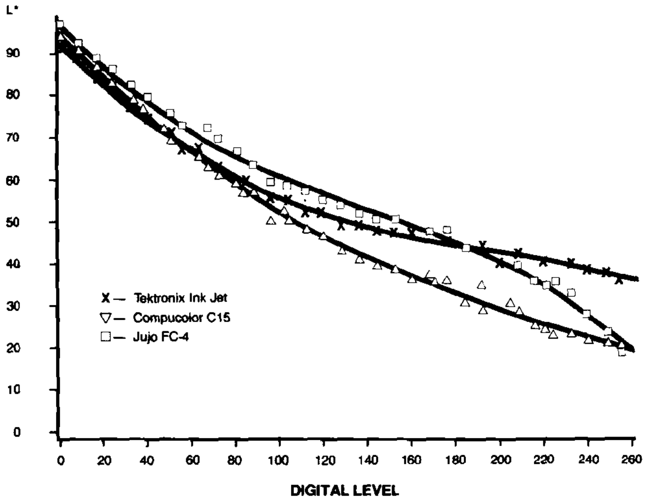

Figure 2. CIE 1976 lightness versus print level

curved line must be straightened. To do this, a straight line is drawn between the 0 level and the 255 level. For any particular input level, for instance 90 in Figure 4, a line is drawn to the straight line connecting the 0 and 255 levels. The required lightness may be read by drawing a horizontal line to the lightness axis. The required signal for the print level with this lightness is where this horizontal line intercepts the curved line. In this example that level is 60. Figure 3 shows the 16 grey levels after correction for lightness. This may be compared with Figure 5 in Part 1 of this paper which shows the 16 grey levels before lightness correction.

It is important to realize that the error diffusion algorithm has no restriction with regards to print levels. Thus a fractional level such as 204.756 is just as valid as an integer level such as 205. That is, with error diffusion fractions have meaning as opposed to a dither method in which whole numbers only are valid. The reason for this lies in the way that the error diffusion algorithm works. A full explanation of this may be found in the first part of this paper. It must be pointed out that while there is almost an infinite number of grey levels theoretically possible, there are physical restrictions preventing the realization of all these levels. The first restriction is in the eye's ability to detect differences in the various levels produced. For instance, one dot difference in 10,000 pixels would not be noticeable. The second restriction is in the ink/paper system. Some papers spread the dot so much that even at a modest 255 levels the last 20 levels are visually indistinguishable. They all are solid coverage even though the number of drops of ink used are different. A third restriction is the size of the area covered. If a

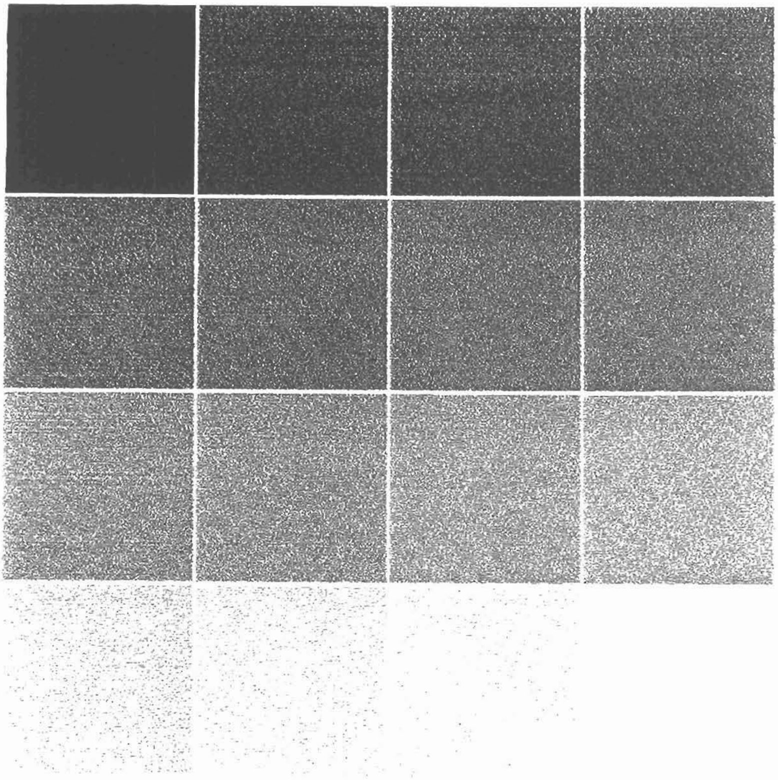

Figure 3. Grey levels error diffused with random threshold and lightness corrected

square of only four pixels is to be printed, then only sixteen different combinations are possible. This restriction became very obvious when we compared the quarter inch squares to the one inch squares of the same print level. A "herring bone" pattern that was not present in the small squares began to appear in some of the larger squares. This is shown in Figures 3 and 4 in Part 1 of this paper.

It is thus possible to derive a look up table that will convert the 256 input levels to 256 values that will appear equally spaced visually when printed on a particular ink-paper combination. The 256 levels were used because of the sensitivity of our scanner. There is no reason the method would not work for a scanner with smaller or larger sensitivity than this.

Figure 5 shows the plot of the original print levels against lightness. Also plotted in Figure 5 are the adjusted levels that were produced by the table look up for this particular ink-paper interaction. This shows an almost perfect linearization of print levels to lightness. The image we have been working with is a picture of climbing materials. It is a complex scene with a wide range of contrast and tones. Figure 5 shows the original print, and Figures 6 and 7 show the image before and after grey level adjustment for the paper.

It is interesting to note that this same method of lightness adjustment may be used for transparencies with equally good results.

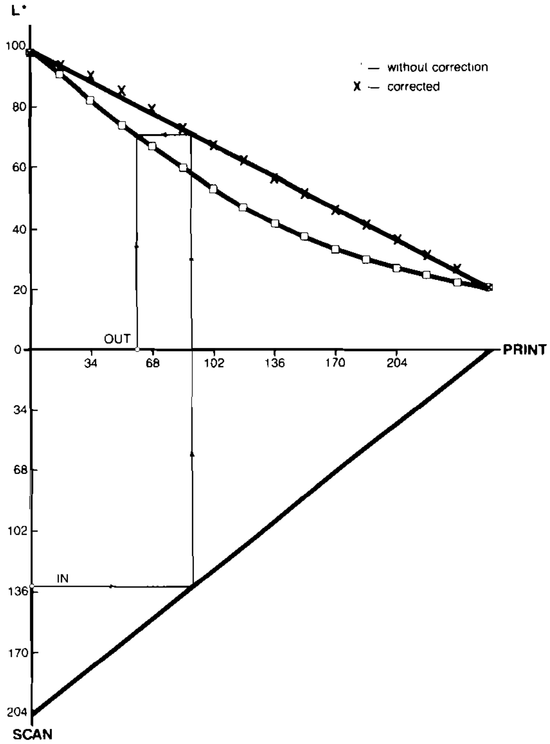

Figure 4. Illustration of lightness correction for a particular ink-paper combination

Fine Tuning the Grey Levels

The Munsell Neutral Value Scale, which is the basis for our grey level corrections, is only strictly valid for a background of Neutral 5. For a complex scene, the Munsell Neutral Value Scale may not be perfectly visually spaced. A good summary of how background effects may be accounted for is found in a paper by Dom (1981). The equations given in this article are taken directly from the work of Bartleson and Brenneman (1967). They are very similar to the CIE 1976 lighteners function, but allow for three different types of background; namely, light, dim and dark. For this correction to be worthwhile, the equations should be applied specifically for each individual picture. We considered this fine tuning as unnecessary for most purposes.

Figure 5. Original print of climbing materials

A more useful fine tuning is to examine a histogram of the scanned picture. From this histogram, it is possible to detect the part of the image which contains the pictorial information and the part which contains just noise. In our case, most images contained useful information to only 208 levels. The other 48 levels were unused. The scanner was "tuned" so that density 3 would give a value of 255. An adjustment was made so that only the levels containing pictorial information were used. This was done at the same time the table look up was generated for a particular ink-paper system. Since this adjustment was constant for all of our scanned pictures, it was worthwhile. If, however, a different adjustment for each picture was required, serious consideration would have to be given to its usefulness. A more useful approach in this case would be to try to obtain an "average" range for a large number of "typical" pictorial scenes. A constant correction would then be used which in most instances would be acceptable and probably better than no correction at all.

Conclusion

A method of grey level adjustment has been developed based on experimentation with ink-jet printers. This method is generally applicable to systems requiring binarization of an image for reproduction. It is made specific for a particular system when the grey levels are physically measured and a look up table is generated. This table is then used to convert the scanned levels to levels of equally perceived lightness. These new values are then error diffused to obtain a binarized image

Figure 6. Error diffused ink-jet reproduction of climbing materials print

for printing. This grey level adjustment is based on the Munsell Neutral Value Scale. This scale is the standard for perceived lightness.

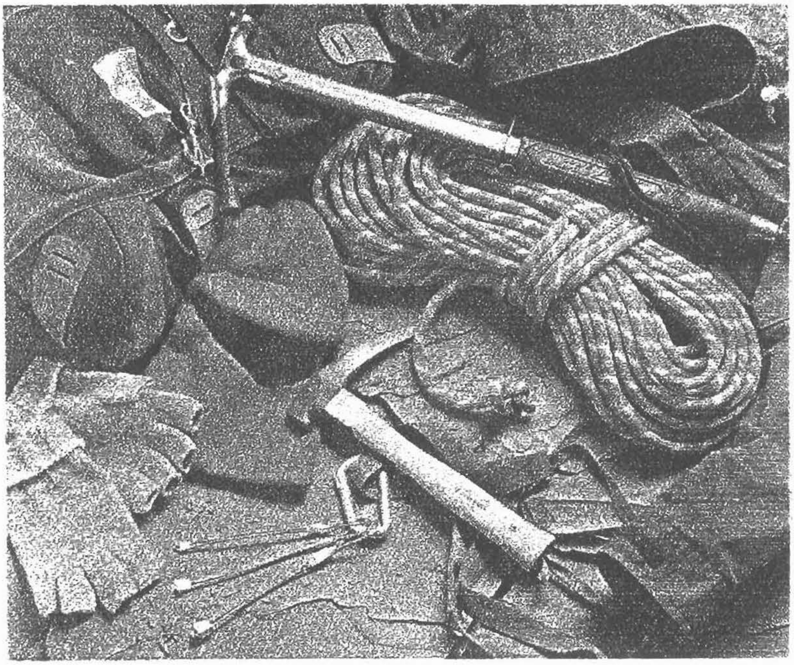

Figure 7. Error diffused with random threshold and lightness corrected ink-jet reproduction of climbing materials print

Acknowledgements

The authors wish to thank Mike Barry and Janice Bent of Eastman Kodak for their help in selection, preparation and scanning of the pictorial material.

References

Bartleson, C.J. and Brenneman, E.J.
1967. "Brightness perception in complex fields", J. Opt. Soc. Am., Vol. 57, pp 953-957

CIE
1978. "Recommendations on Uniform Color Spaces, Color-Difference Equations, Psychometric Color Terms," Supplement No. 2 of CIE Publ. No. 15 (E-1.3.1) 1971, Bureau Central de la CIE, Paris

Dom, B.
1981. "Grey scale compression in reprography", Photogr. Sci. Eng., Vol. 25, pp 216-218

Godlove, I.H.
1933. "Neutral Value Scales II. A comparison of results and equations describing value scales", J. Opt. Soc. Am., Vol. 23, pp 419-425

Gur, Yigal and O'Donnell, F.X.D.
1985. "Half-Toning Using Ink-Jet: Part 1. Algorithm of Discretization", this publication

Munsell, A.E.O., Sloan, L.L. Godlove, I.H.
1933. "Neutral Value Scales I. Munsell Neutral Value Scale", J. Opt. Soc. Am., Vol. 23, pp 394-411