Quadtone Inkjet Printing Technology

Author: Stephen Herron

Abstract

Accurate, automatic color reproduction is the goal of much of color technology. However there is a need to improve reproduction in only the luminous or gray axis. Quadtone reproduction takes advantage of the four device CMYK color planes to provide greater gray-scale depth within the limitations of 8-bit per channel band-width. "Quadtone" refers to photos reproduced using four tones of the same colorant. It is the printed imposition of four carefully selected shades of ink that result in a greater number of densities. Quadtone printing is a collection of algorithms using the CMYK channels to simulate traditional photography on an inkjet printer. Quadtone printing increases density values, defines detail and produces near continuous-tone screens.

Key Words: density, frequency modulation screening, inkjet printers, luminosity, quadtone

Prepared for: SPIE Electronic Imaging 1999

Color Imaging:Device-Independent Color....

San Jose, CA, January 1999

1. Introduction

Quadtone reproduction, especially when produced on inkjet printers, is a new area of computer-controlled printing. Quadtones take advantage of the many types of four-color printing presses available to print a photograph in what appears to be one color but, in reality, is made from four shades of the same color.

Photos printed with black ink or the CMYK inkset are disappointing in their lack of density levels. Quadtone printing increases the number of density levels and improves the smoothness of gradients, removes noise or graininess, and increases the perception of detail. Isis Imaging's frequency modulated (FM) screens produce sharp photographs without dot pattern changes, no banding, open shadow detail, linear dot gain, linear dot clustering and more accurate color and luminosity values.

1.1 Why Isis Imaging's FM screens?

Isis Imaging's Icefields screening technologies are used on more types of imagesetters producing more types of printed materials than any other type of non-conventional screen. Icefields is the leading stochastic screening technology. Icefields is the only non-conventional screening technology to win awards. Icefields is the only FM technology described in prepress trade instruction books. Photographers use Icefields to produce high-quality platinum and silver contact prints, and pigment transfer prints. They turn to Icefields when they observe that inkjet printers have device resolutions fine enough to reproduce photographs.

2. An examination of a quadtone inkset

A quadtone photograph looks like a photograph printed in one color – usually gray. The four inks that comprise a quadtone increase gray scale range. Detail definition is also increased because the spatial frequencies of the photograph are repeated by each of the four inks. Repetition of the photograph structure defines the photograph.

Each of the inks in a quadtone inkset is different in density, percentage of hue saturation and amount of reflected light. The photograph may be in shades of gray, or shades of any color. A quadtone can be sepia-tone, olive or any color. The photograph may be created with various inksets. For example, the inkset developed for testing purposes consists of a warm gray at a luminous level of 25%, neutral gray at 50%, cool gray at a level of 75%, and black (supplied by the manufacturer at a luminous level of 96%). Density was measured from custom ink patches. The patches were made by applying ink droplets to a generally available 100% cotton bond paper.

2.1 A quadtone is charted as a one-dimensional axis in a color space

A color space is a three-dimensional organization of colors. The simplest color space is an HLS cone with cyan, blue, magenta, red, green and yellow primaries charted at the perimeters, and black and white at the apexes[1] *(Fig. 1)*. A slice of the solid shape produces a two-dimensional plane. The plane consists of one hue with a horizontal saturation axis and a vertical white to black axis *(Fig. 2)*.

A quadtone is represented in one dimension. While the point of origin, termination point and length of the axis may be plotted anywhere within the plane, most quadtone axes begin at white and end at black *(Fig. 3)*. The lighter the origin and the darker the end shade, the greater the density range.

A CMYK quadtone is created with cyan, magenta, and yellow primaries in balance. A gray level is the result of the tristimulus combination of primaries. When the primary colors are printed in "gray balance" no particular color dominates and the result is a gray photograph. The primaries can be out of balance. When "out of balance" occurs a chromatic element is present. For example if magenta is too saturated the result is a sepia tone (represented by the curved axis in Fig. 3). An "out of balance" photograph is charted as a one-dimensional arc through color space and within a color plane.

3. Comparison of quadtones to grayscale and CMYK gray balance

Quadtones have a much larger grayscale range than gray balanced CMYK trajectories or gray-scale tones. Quadtone gradients are smoother, and FM screens exhibit an almost continuous tone appearance.

Most computer systems use 8 bits of data per color. Eight bits is equal to 255 shades of gray plus white, therefore the normal range of a gray-scale photograph consists of 256 steps of gray from black to white. CMYK and trichromatic inksets also have a range of 256 levels. In the test case, using the four shades of black inkset described, the result is a range of 560 shades. Actual number of gray levels of a quadtone will vary. Most photos will exhibit fewer levels due to limitations of ink tonal compression, ink absorption, lack of range within the source photograph and the reflection capability of the paper.

A gray level in tristimulus color space requires three primaries. In CMY space, 255 shades of gray are produced by the trichromatic combinations. Luminous values in a four shade inkset are additive. Icefields produces 560 gray levels from the inkset of three shades of gray

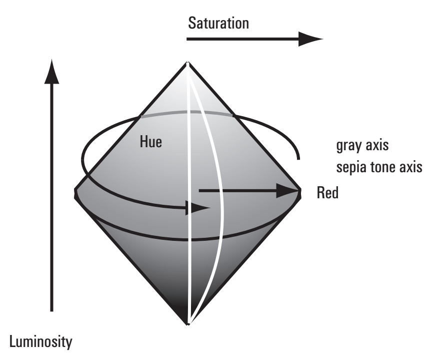

Fig.1 HSI color space illustrating luminous axis.

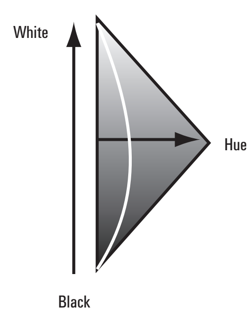

Fig. 2 Plane of HSI color plane illustrating luminous axis.

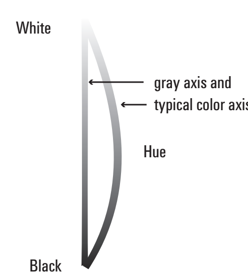

Fig. 3 Quadtone luminous axis.

gray %	100% black	75% gray	50% gray	25% gray	Luminous positions
100 to 75	64	32	1	1	96
75 to 50	64	64	32	1	160
50 to 25	0	64	64	32	160

and black *(Chart 1).*

Chart 1. Number of grays produced in the test inkset

Total ink density is also increased. The black ink is a 96% gray when printed on 100% rag paper. When combined with the three other inks, black approaches 98% *(Chart 2).* While the white point must be the white of the paper, shades of gray lighter than gray produced by the lightest 8-bit gray level are possible.

Target density	100% gray	75% gray	50% gray	25% gray
Measured density	96%	76%	50%	25%
100% gray +		98%	98%	97%
100% gray + 75% gray +			98%	98%
100% gray +75% gray + 50% gray +				98%
75% gray + 50% gray +				83.50%
75% gray +			83%	80%
50% gray +				51%

Chart 2. Densities of ink combinations

The 560 gray levels produced by the four shades of ink produce smooth gradients without optical banding. The highest density visible in a gradient is the result of the absorption of the four inks, and the lightest shade from the one light ink. The smoothness is also a result of a difficulty seeing individual dots and dot clusters. When a gray dot touches another gray dot and the two dots slightly bleed into each other, it is almost impossible to see distinctive dots.

A black-and-white photograph created with balanced CMYK inks does not look the same as a quadtone reproduced photograph. Besides the lack of gray levels, there is a difference in "feel". Shadows built with CMYK colors do not look as rich and black as shadows composed of four shades of black. CMYK gradients are not as smooth. Most importantly, a quadtone simulates the density range of a photograph more accurately than possible with cyan, magenta, yellow and black device color-spaces.

4. Quadtone preparation

It is assumed that the photograph generating software properly adjust the photograph data to compensate for the psychophysical perception of lightness[2]. The photograph is transformed from RGB to CIE L*a*b*[3,4,5] and the luminous channel (L*) is repeated four times and placed into each of the four CMYK data planes. The CIE Lab chroma channels are discarded. Each of the four luminous planes is then adjusted for reproduction with inks in four densities. The adjustment is accomplished in six steps.

In a test, the inkset described above with densities of 100%, 75%, 50%, and 25% were used. The darkest gray level that 25% gray ink can produce is 25% or the 64th level of a possible 255 levels of grays. The darkest value that the 50% gray ink can produce is 50% or the 128th gray level, and the darkest value the 75% shade can produce is 75% or the 192nd level. Each luminous plane is truncated accordingly *(Fig. 4).*

The white values are then adjusted *(Fig. 5)*. This white point adjustment ensures that the tones from 0% to 25% are accurately reproduced by the 25% gray ink while the other inks will be lighter than the actual gray levels. The 50% gray begins at 6%. The 75% gray begins at 12%. The black begins at 50%. In the first quarter portion of the gradient, the major gray is the 25% ink and the others are minor grays. The tones from 25% to 50% are reproduced by the major 50% gray ink. The tones from 50% to 75% are reproduced from the major 75% gray ink, and the tones from 75% gray to 100% by the major black ink. It is only the major gray that is accurate. The minor inks are always lighter than the actual gray level.

The densities of each ink are increased to reproduce the correct gray levels *(Fig. 6)*. For example, the 12% gray level is reproduced by the 25% gray shade of ink, the resulting density is 0.25X = 0.03, X = 0.12. All gray levels from 0% to 25% are increased. Each of the gray levels is increased to compensate for the luminous decrease. Black

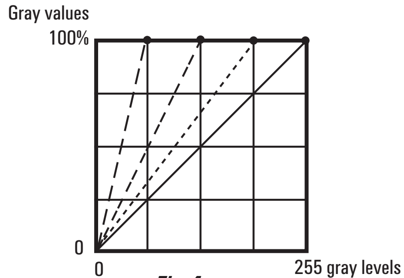

Fig. 4

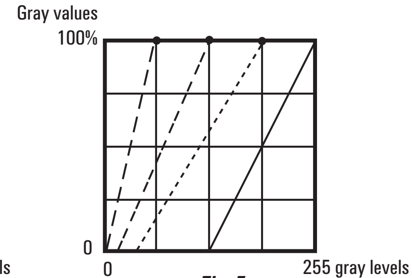

Fig. 5

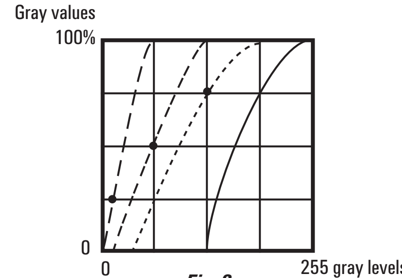

Fig. 6

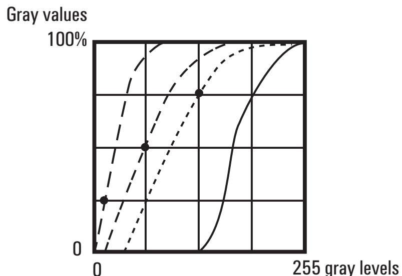

Fig. 7

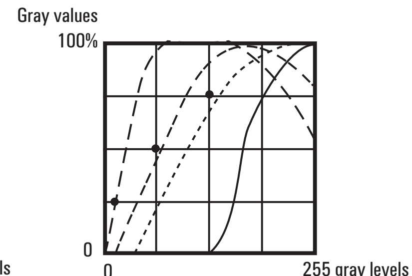

Fig. 8

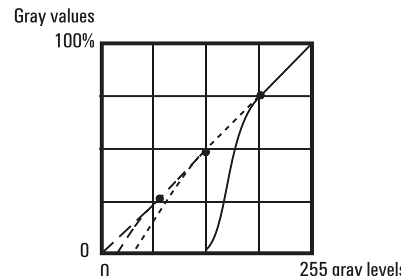

Fig. 9

is treated differently. The values of black from 75% to 100% remain at their actual percentages, and values from 75% to 25% are adjusted by a power function to compensate for the monitor's approximation of the lightness response of vision using R'G'B' signals.[6]

The values of each ink are then lightened by a gamma of .80 *(Fig. 7)*. Optically 75% gray is not the same as a 75% screen of black. The slight gamma amount merges the interface between major inks.

The physical mixing of inks produces a difference in total ink density. Inks at target percentages are measured and compensated by lowering the density values of the major ink.

Ink wetness or liquid saturation of the paper is calculated next *(Fig. 8)*. An intuitive procedure is used to calculate the wetness of the paper. The amount of absorption depends on type of paper. A wetness measurement is based on the amount of bleed outward of droplets of ink. The bleed is measured, and trial and error adjustments made to the amount of ink dropped on to the substrate. The two lightest gray inks are adjusted because they produce the least ink density change. It was found that total wetness of 360% was acceptable on most 100% rag paper. Wetness above 360% was adjusted downward.

The Icefields screen exhibits a dot-gain of 1.8 gamma[7]. The inkjet printer exhibits a nonlinear ink density to gray level ratio of about 2.8. A global gamma compensation is made for density gain caused by ink perimeter movement.

The resulting curves were applied to a test photograph and printed. The resulting gray values were measured and graphed *(Fig. 9)*. The result is a linear gray ramp. Results of the applied curves are demonstrated in *Fig. 10 through Fig. 14*.

Fig. 10. 25% density

Fig. 11. 50% density

Fig. 12. 75% density

Fig. 13.100% density

Fig. 14. result of over-print

5. The perception of grain in FM screens

A photograph is printed with a FM dot screen. A quadtone made with CMY/K inks consist of dots that are relatively easy to see. A quadtone created with four screens, one screen for each of the four shades of a color, are composed of dots that are difficult to distinguish from each other. The result is a continuous-tone appearance.

The human eye is most acute at recognizing differences under maximum contrast. The grain formed by random clustering and distances of dots in low frequency areas within a frequency modulated screen is most visible when reproduced with black ink. Differences of high contrast values are more acutely seen than differences of low contrast values. Similar luminous values are less easily discernable than similar chromatic values[5]. Dots of different primary colors are therefore easy to visually separate. Dots of close shades of the same color are difficult to distinguish. Dots of unsaturated color and light colors are difficult to see. The lack of contrast and low ink density reduces visual acuity of random frequencies in quadtone inksets[6].

6. Photographic elements duplicated in quadtone inkjet printing

A photograph contains high spatial-frequencies or detail. There are two ways a screen can lose detail and one way the print head can lose detail. Detail is the frequency of change in pixels. Sharpness is the amount of change (amplitude)[8]. When a pixel of one gray value adjoins a pixel of another gray value, the larger the differences in gray values, the sharper the detail. For example, the unsharp mask filter sharpens detail by increasing the difference in pixel gray values.

All FM screens balance various aspects of reproduction. For every good effect there is a bad side-effect. Some screens produce very flat colors but they blur detail. Dots that are widely isolated result in a significant amount of dot-gain which darkens the photograph. Dots that touch each other reduce their perimeter gain by the length of the joined edge. Dots that cluster have graininess but less dot gain.

Frequency modulated screens that use diffusion matrices blur detail over the matrix area. Detail can be further diffused by an algorithm that rearranges dots for better reproduction of flat colors. The blue noise filter is an example. While grain-free flat colors is the goal of all screens, the cost may be the loss of texture and sharp detail. Flat colors require regimented placement of dots which means dots must be moved and dot movement is blurring.

The print head can lose detail by producing dots that are larger than the device resolution and larger than the photo's spatial resolution. In most cases, the gray values in the shadow areas are lost[9].

Absorbent paper such as watercolour paper obscures detail to a small degree by expanding the size of the dot. Absorbent paper reduces brightness and hence reduces contrast. The perception of sharpness is diminished. The optimum FM screen is one that does not blur and consists of widely placed dots that cluster linearly to control dot-gain and are aligned in a 45° inclination. (The 45° screen angle is the least perceptible to the eye.) Icefields screens for inkjet printers meet these requirements.

6.1 The photograph consists of a texture or grain

There are perceptual differences between high- and low-contrast areas of a photograph. A high contrast photograph usually contains higher spatial frequencies than a low-contrast photograph. The greater the contrast, the higher the amplitude; the greater the amount of detail, the greater the spatial frequency. Usually frequency and amplitude directly correspond. Frequency is the primary method whereby an Icefields screen controls noise or grain. The greater the frequency the less the grain. Screens that organize dots by the structure of the photograph have little positioning guidance when reproducing low frequency areas. The dots fall in a semi-random pattern. The combination of semi-randomness and the pattern of dots create a texture. Certain textures are more pleasing to the eye than other textures. A screen that approximates the grain and pattern of a photographic print is valued by photographers. In comparison, halftone patterns look too mechanical.

7. Conclusion

A photograph consists of a large number of density levels, high spatial frequencies, good contrast amplitude, and a pleasing grain texture. An inkjet printer with proper screening and density controls can replace the photographer's darkroom. Icefields screens produce the tactile quality that makes fine art prints stand out from commercial reproductions. The photographer can produce a photograph in original colorants by controlling the ink chroma and density. A palette unique to the photographer has always been an advantage.

Until the 1930s, FM reproduction processes such as aquatint and photogravure were preferred by photographers such as Alfred Stieglitz, Edward Curtis and Paul Strand. They considered the halftone as a simplified mechanical reproduction. They knew that a halftone lacks definition and clarity. To missquote Peter Henry Emerson, "The artist who works in photography must not rest until he has mastered quadtone printing with Icefields FM screens."[10].

Appendix 1. Scanning

It is difficult to determine the proper scan resolution. Scan resolution should be three time the highest spatial frequency. There is no input to output ratio guidline as there is with a halftone screen. Scan at about 300 ppi (pixels per inch). Most people have difficulity seeing more detail than produced at this resolution in a continuous-tone field. Most people can see black and white lines of about 1200 ppi. This is the maximum discernable resolution. Therefore if you do not wish to show any grain, and you do want the maximum detail, scan the photograph at 300 dpi or greater (continuous tone) and print at 1200 dpi or greater (line count).

Appendix 2. Selection of paper

The paper you select to print contributes to the sharpness and continuous-tone aspects of the printed image. Properties of the paper that affect reproduction include material characteristics such as sizing, moisture content, thickness, color tinting, fibre direction, gloss and laid pattern.

Which is best – coated or non-coated paper? Watercolor paper or synthetic paper? This is a question with no definite answer. Here are a few guidelines:

Absorbent paper such as watercolor paper softens the perimeters of the dots, resulting in dots that bleed into each other.

Sizing, such as starch, limits the bleeding edges of the dots and holds back the dyes from soaking into the paper fibers. Too much sizing results in too great of ink bleed.

Moisture content contributes to bleeding. The result is a softer but more continuous image. Moisture when used with water-base dyes blends shades together. Moisture when used with oil-based dyes keeps dots from spreading. Water is used in offset printing to control dot gain. Moisture and water-based dyes do not result in a darker image. The bleeding dot does not darken the image because the amount of pigment does not increase by the spreading phenomena.

Paper thickness provides stability. Inkjet dyes make the paper substrate wet. Wet paper stretches and warps. There is also a pleasing tactile quality to thick paper.

A laid pattern makes the paper surface uneven. Since an inkjet drops the dye onto the laid paper the texture does not noticeably change the shade of the dye. Laid paper absorbs and refracts light. It is not as bright as the same paper without a laid texture. Colors appear darker and grayer.

Gloss indicates paper that is coated with a white clay or plastic. The smoother, flatter, surface reflects more light. The light passes through the applied dyes and the colors appear brighter and cleaner.

Colored paper changes the dye coloration. A buff paper makes a quadtone appear warm. Coloring the paper with one of the cartridge sections helps keep a black quadtone black.

Fiber direction controls the direction of the dot bleed. The liquid flows in the direction of the fibers. All non-gloss paper has a fibre direction. Fiber direction does not significantly affect reproduction. Fiber size has a greater effect by making colors a shade darker.

Appendix 3. Mixing and using custom dyes

Many photographers would prefer to mix their own colors. To mix a lighter shade of a dye, dilute with distilled water before filling the cartridge. To ensure the dye and water viscosity is correct, add a drop of propylene glycol. With a Q-tip make a mark on a scrap of paper to test that the shade is correct.

Appendix 4. Increasing the tactile quality of the inkjet print

An artistic consideration of the surrounding paper can add an artistic quality and increase the craftsmanship of the print. Try tinting the paper by splashing a natural color such as very thin iodine. Mask the image area first to protect it from coloration. Emboss the image by moistening the paper and pressing it down and around a thick piece of cardboard cut to the size of the image perimeter.

References

1. Henry R. Kang, *Color Technology for Electronic Imaging Devices,* SPIE Optical Engineering Press, WA, 1997.
2. M. Mahy, B. Van Mellaert, L. Eycken, and A. Oosterlinck; *The Influence of Uniform Color Spaces on Color Image Processing: A Comparative Study of CIELAB, CIELUV, and ATD,* IS&T Journal of Imaging Technology, Vol 17, No 5, pgs 232-243, October/November 1991.
3. Mark D. Fairchild, *Color Appearance Models,* Addison-Wesley Reading, MA, 1998.
4. Alan Roberts and Adrian Ford, *Colour Space Conversions,* <ftp.westminster.ac.uk in directory /pub/itrg>, 1995
5 Mark D. Fairchild, *CIECAM97s.pdf,* <http://www.awl.com/cseng>, 1997
6. Charles A. Poynton, *Gamma and Color.pdf,* <http://www.inforamp.net/~poynton/>, 1995
7. Stephen Herron, *Color Gamut Analysis of Frequency Modulation Screen Reproduction,* IS&T PICS Proceedings, pgs 4391-394, May 1998.
8. Ralph Norman Haber and Maurice Hershenson, *The Psychology of Visual Perception,* Holt, Rinehart and Winston, Inc., New York, 1973
9. Kazumichi Shimada, *Image Quality, Image Capture Systems*, IS&T PICS Proceedings, pgs 424-426, May 1998.
10. Taneli Eskola and Kari Holopainen, Polymer Photogravure: *A New Method for Photographers and Graphic Artists,* LIBRIS, Finland, 1996

Isis Imaging Corporation
www.isisimaging.com

isis