A NEW APPROACH TO DOT GAIN MODELLING

Björn Kruse and Mikael Wedin*

Keywords: Dot gain, Optical dot gain, Reproduction, Colour.

Abstract: The quality of image formation on paper is a many facetted issue. One of the most important problems of tone rendering concerns the ubiquitous optical dot gain of ink on paper. Several attempts to model the dot gain of ink on paper have been made over the years with the Murray-Davis approach being one of the first. This approach was modified by Yule and Nielsen to account for the trapping in the substrate of internally scattered light. A distinction was thus drawn between mechanical dot gain and optical dot gain. This paper will describe a simple but yet effective model for optical dot gain that explains the decrease in the modulation transfer function towards higher screen rulings. The model also sheds some light on reasons for the variation in dot gain with different screen dot geometries. The model allows for the determination of dot gain characteristics in the form of parameters in the model description.

Introduction

The tone rendering problem associated with the printing of halftone dots on paper is usually divided into two sub problems, the physical dot gain associated with the printing process and the optical dot gain associated with the optical properties of paper. The optical dot gain depends largely on the amount of scattering in the paper and on the ink deposition. Light scattering in paper has been studied since the early 30's in e.g. [1], [2]. In this paper we examine the optical properties of paper and propose a model for the dot gain.

To be able to control the image formation on different media, a model of the printing and viewing process is required. One of the known reproduction problems that such a model should explain is the optical dot gain. The term optical

* Image Processing Laboratory, Department of Electrical Engineering, Linköping University, S-581 83 Linköping, SWEDEN. Email: bk@isy.liu.se, mikwe@isy.liu.se

dot gain refers to the increase in optical density of the print that results from the penetration of light into the paper. Due to the penetration and subsequent scattering of the light in the paper substrate, the ink film will to some extent occlude some rays that would otherwise emerge at the surface. Consequently the net reflectance from the non-printed areas between the halftone dots and thus the mean reflectance from the printed area will decrease. The term dot gain is used because the reflectance of a print is lower than it should be i.e. the dots appear to be larger then they actually are.

Attention to the causes of optical dot gain was first drawn by Yule & Nielsen [3] who were concerned with a modification of the Murray-Davis equation. The modification that Yule & Nielsen suggested is referred to as the n-modified Murray-Davis equation, which describes the total density of a halftone print as a function of dot area and the printed solid dot density. The parameter n is a material constant, the value of which varies for different types of paper, coated or uncoated and with the number of lines per inch.

A later paper by Huntsman [4] is concerned with the modelling of multi layer colour proofs and identifies those rays which contribute to the optical dot gain. He also introduces the notion of hyper-gain in which the rays are scattered into the unprinted area of the neighbouring halftone cell, and do not therefore contribute to the optical dot gain. In a study of the optical properties of the paper is [5], measures of the distance light can travel in different types of paper are given.

The behaviour of light within the paper is a complex issue which is poorly understood. The filler and fibres have very dissimilar properties and the mixture is very difficult to model without simplification. An important property not included in the models mentioned is the form and position of the halftone dots. In the following, we present a model that is complex enough to share those properties with the behaviour of the paper and the formation of dot patterns on the paper surface. The main goal is to model and simulate the optical dot gain properties. Other properties have yet to be modelled.

Model

We first develop a model in a general form taking into account the spatial and spectral dependencies of the surface reflection. The resulting non-linear model lends itself readily to the computation of optical dot gain. This will be demonstrated for the monochrome case of varying screen rulings and dot shapes.

Light reflection and diffusion

When light falls on a paper surface some of it is immediately reflected through surface reflection. However, a large portion enters the paper where it is scattered. The fibres are considered to be randomly distributed in the paper and give rise to this diffusion of light. This has been shown in studies regarding the scattering properties of paper [5].

A model that places ink on top of the paper has earlier been considered to be an over-simplified model. However, recent findings show that the ink penetration into the paper is very low, at least in offset printing, [6].

When light falls on a paper surface, some of the light that enters the paper contributes to the overall light emission from the paper surface. Some of the light is absorbed in the paper and some is lost through the back surface of the paper. The well known Kubelka-Munk model expresses this mathematically [7]. This model can be applied to an two-layer material, but since the model does not take partial ink coverage into account, it cannot explain the optical dot gain effect. In fact the whole issue becomes much more complex when we try to model the properties including ink structures on the paper surface.

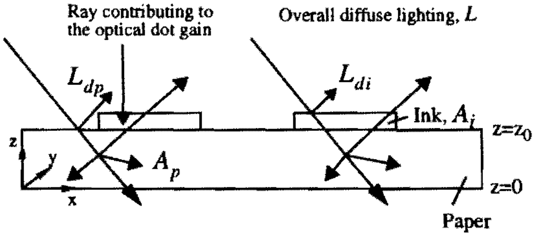

Figure 1. Simplified behaviour of selected scattered rays hitting the printed surface. The rays are reflected in the top layer, transmitted into the paper, scattered, absorbed and/or reflected through the top and transmitted through the bottom surfaces.

Light reflection properties

In this section we develop a spatio-spectral model of the light reflected from the paper surface. Let the incident light at point $\bar{x}$ be described by the spectral distribution $L(\bar{x}, \lambda)$. Also, let $R(\bar{x},\lambda)$ be the direct reflectance from the surface at the point $\bar{x}$. Consequently the light directly reflected from the surface can be written

$$L_d(\bar{x},\lambda) = L(\bar{x},\lambda)\,R(\bar{x},\lambda) \tag{1}$$

If the surface is partially covered by ink and partially without ink, then

$$R(\bar{x},\lambda) = \begin{cases} R_i(\lambda) \text{ for ink} \\ R_p(\lambda) \text{ for paper} \end{cases} \tag{2}$$

Let us further denote the ink coverage function by

$$C(\bar{x}) = \begin{cases} 1 & \text{ink cover} \\ 0 & \text{no ink} \end{cases} \tag{3}$$

Using these simple definitions, the direct reflection from the surface at point $\bar{x}$ may be written

$$L_d(\bar{x}, \lambda) = (1 - C(\bar{x}))\, R_p(\lambda)\, L(\lambda) + C(\bar{x})\, R_i(\lambda)\, L(\lambda) \tag{4}$$

When three inks are used, the reflection from the eight possible combinations of ink reflectance have to be considered separately [8]:

$$\begin{aligned} L_d(\bar{x},\lambda) = L(\lambda) \cdot [\, & (1 - C_c(\bar{x}))\,(1 - C_m(\bar{x}))\,(1 - C_y(\bar{x}))\,R_p(\lambda) + \\ & (1 - C_c(\bar{x}))\,(1 - C_m(\bar{x}))\,C_y(\bar{x})\,R_y(\lambda) + \dots + \\ & \dots \\ & (1 - C_c(\bar{x}))\,C_m(\bar{x})\,C_y(\bar{x})\,R_{my}(\lambda) + \dots + \\ & C_c(\bar{x})\,C_m(\bar{x})\,C_y(\bar{x})\,R_{cmy}(\lambda)\,] \end{aligned} \tag{5}$$

Light scattering properties of the paper

The physical model for the damping and scattering of light in a solid gives rise to a Fredholm integral of the second kind. Since the model we aim at is significantly less complex we can derive it along somewhat different lines.

The incident light at the paper surface is the light that is not directly reflected but is to some extent absorbed in the surface depending on the presence or absence of ink. The absorption in the paper surface is very low whereas the ink film does absorb a large portion of the light, although spectrally selective. For the monochromatic case the incident light $L_i(\bar{x},\lambda)$ can be written:

$$L_i(\bar{x},\lambda) = (L(\bar{x},\lambda) - L_d(\bar{x},\lambda))\,((1 - C(\bar{x}))\,A_p(\bar{x},\lambda) + C(\bar{x})\,A_i(\bar{x},\lambda)) \tag{6}$$

where the first term denotes the reduction due to direct reflection, and the absorption spectra for the paper and ink surfaces are $A_p(\bar{x},\lambda)$ and $A_i(\bar{x},\lambda)$ respectively depending on the position of the ink described by $C(\bar{x})$.

If $L_i(\bar{x},\lambda)$ is the incident light at the surface and $D(\bar{z}, \lambda)$ includes the effect of scattering and damping, the accumulation of the incident light at any position

$\overline{z_0} = (\bar{x}, z_0)$ in the paper, denoted $\Phi(\bar{z}, \lambda)$, can then be written (see Fig. 1):

$$\Phi(\overline{z_0}, \lambda) = \int L_i(\xi, \lambda) D\left(\bar{x} - \xi, z_0, \lambda\right) d\xi \tag{7}$$

This is a simplification assuming a translucent media with diffuse scattering of light from every point (x, y, z_0) in the paper base.

The light that emerges from the surface after internal scattering is called the secondary reflection, $R_s(\bar{x}, \lambda)$. If every point in the paper is regarded as a scattering source, the secondary reflection of a position $\bar{x}$ on the surface originating from the interior of the medium can be written:

$$\begin{aligned} L_s(\bar{x}, \lambda) = {} & ((1 - C(\bar{x}))A_p(\bar{x},\lambda) + C(\bar{x})A_i(\bar{x},\lambda)) \cdot \\ & \int L_i(\xi, \lambda) D\left(\bar{x} - \xi, z_0, \lambda\right) \Phi(\zeta, \lambda)\, d\xi \end{aligned} \tag{8}$$

It is evident that equation (8) involves two convolution integrals containing $D(\bar{z}, \lambda)$. The end result is of course also a convolution. Let the kernel of that convolution be $K(\bar{z}, \lambda) = D(\bar{z}, \lambda) \otimes D(\bar{z}, \lambda)$. Eequations (7) and (8) can then be combined to give:

$$\begin{aligned} L_s(\bar{x}, \lambda) = {} & ((1 - C(\bar{x}))A_p(\bar{x}, \lambda) + C(\bar{x})A_i(\bar{x}, \lambda)) \cdot \\ & \int K\left(\bar{x} - \xi, z_0, \lambda\right) d\xi \end{aligned} \tag{9}$$

The total amount of reflected light, $L_r(\bar{x}, \lambda)$, is the sum of the two components of direct and secondary reflection:

$$L_r(\bar{x}, \lambda) = L_d(\bar{x}, \lambda) + L_s(\bar{x}, \lambda) \tag{10}$$

The model applied to the case of a one-dimensional ink modulation

To derive the model for the simple case of a one dimensional ink structure, we assume that the properties are independent of wavelength. This corresponds to the monochromatic case. The ink layer is modelled as a property of the surface, absorbing only a fraction of the incident light. In order to simplify the description, we use the following notation:

$$M(C, U, V, x) = (1 - C(x))U + C(x)V \tag{11}$$

$$L_d(x) = M(C, R_p, R_i, x) L \tag{12}$$

$$L_i(x) = (L - L_d(x))\, M(C, A_p, A_i, x) \tag{13}$$

$$\Phi(x, z) = \int L_i(\xi)\, D((x - \xi), z)\, d\xi \tag{14}$$

$$L_s(x) = M(C, A_p, A_i, x) \int K(x - \xi)\, L_i(\xi)\, d\xi \tag{15}$$

The resulting reflected light is the sum of the direct and secondary reflections:

$$L_r(x) = M(C, R_p, R_i, x)\, L + M(C, A_p, A_i, x) \int K(x - \xi)\, L_i(\xi)\, d\xi \tag{16}$$

The kernel $K(x)$ is a rapidly decreasing function as x grows in absolute terms. In the following examples, we assume that $K(x)$ is an exponential function. The standard deviation of $K(x)$ then corresponds to what might be called the scatter radius. In Fig. 2 the width of the halftone cell is equal to two units on the x-axis. In this case the cell lies between -1 and 1.

Evaluation of the model

Let us assume that we have a set of paper stock, coated with gradually decreasing coat weight. The scatter distance within the paper coating is then increasing. The optical dot gain would also increase, as the light can travel further in the paper before absorption or reflection. The scattering width of the paper is determined by the width of the kernel $K(x)$ which in turn is determined by σ_x. Other parameters which it is possible to vary are the first surface reflection of the paper and ink surfaces, the absorption of the ink and paper as well as what happens in the surface of the paper. In the following, the first surface reflection property is set to 5% of the incident light.

The image formation in the two dimensional case i.e. the position and form of the halftone dots have been varied in the experiments with both synthetic halftone dot patterns and real halftone patterns. The synthetic patterns have been prepared using different dot form functions. The forms investigated were parallel lines, round dots and dispersed dots.

The 1D case

The sets of curves shown in Fig. 2 result when appropriate values of absorption and reflection are used and the internal scattering coefficient σ_x is varied.

The reflectance from the surface decreases as the scatter radius increases. The maximum relative reflectance loss in Fig. 2 is approximately 20%.

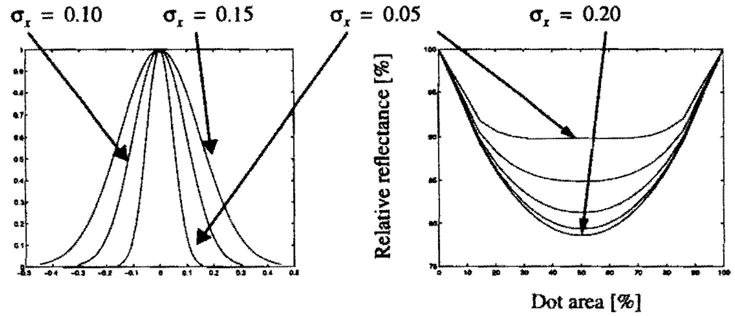

Figure 2. a) The convolution kernel $K(x)$ for medium scattering in paper. The scattering length can be adjusted by the standard deviation, σ_x. The value of σ_x is given relative to the size of the halftone cell, and the width of K is $3\sigma_x$. b) Reflection from a 1D simulation of a print with varying σ_x.

The 2D case

In the two dimensional case the influence of the form and position of different types of halftone dots has been studied. For the real 2D data, $C(\bar{x})$, i.e. the discrimination between ink-covered surface and the paper has been determined using the method described in [9], [10]. This method is in principle based on the derivative of the colour variation within the halftone cell. To decide whether or not a pixel is inside the printed dot the maximum variation is used. The result is a binary image that indicates where the ink is physically placed on the paper. These images are then processed, see Fig. 3a and Fig. 3b. The kernel is now a two dimensional exponential $K(\bar{x})$ see Fig. 3c. The results in Fig. 4a and Fig. 4b are consistent with the fact that round dots should give a larger optical dot gain than the parallel line pattern up to the point were the scattering is very large, $\sigma_x \geq 0.25$.

The reason for the increase is that the amount of optical dot gain is correlated to the length of the edge between the dot and the surrounding paper. If real 2D test data are used, the result becomes dependent on the actual positioning of the ink on the paper in the physical printing process. The amount of edge on the dot is larger in the real data than in the synthetic data, as is apparent in Fig. 5a, where the decrease in reflectance is greater than for synthetic data. The decrease in reflectance leads to a larger perceived dot area and a positive dot gain. The visual effect on the surface can be studied in Fig. 5b, which is the ideal pattern, and in

Fig. 5c which is the simulation result. To be able to judge the results the patches should be viewed at a distance of approximately 4 metres, so that the individual halftone dots are not distinguishable.

In the experiments with real data from thermal transfer printing, the results of which are shown, the reported dot gain for large area coverage is negative. This is due to the fact that the actual halftone dots are physically smaller than they should be.

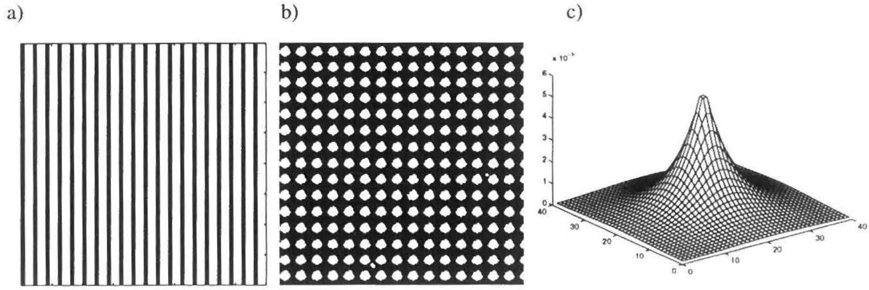

Figure 3. a) A synthetic 35% line pattern used in the simulations for the 2D case. b) An example of the real data used in the 2D simulations, in this case it is a 60% halftone. c) An example of the 2D convolution kernel $K(\bar{x})$ with medium scattering.

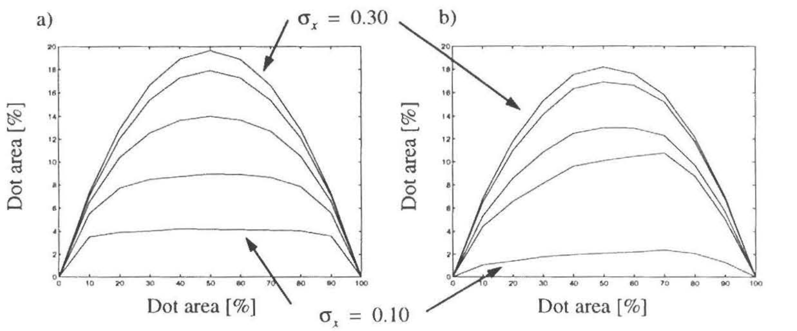

Figure 4. The simulated dot gain from two halftone dot patterns relative to the nominal case on the separation films with no dot gain. The test data are synthetic images and σ_x is varied from 0.1 to 0.3 in steps of 0.05 for a) the parallel line halftone pattern and b) the circular dot halftone pattern.

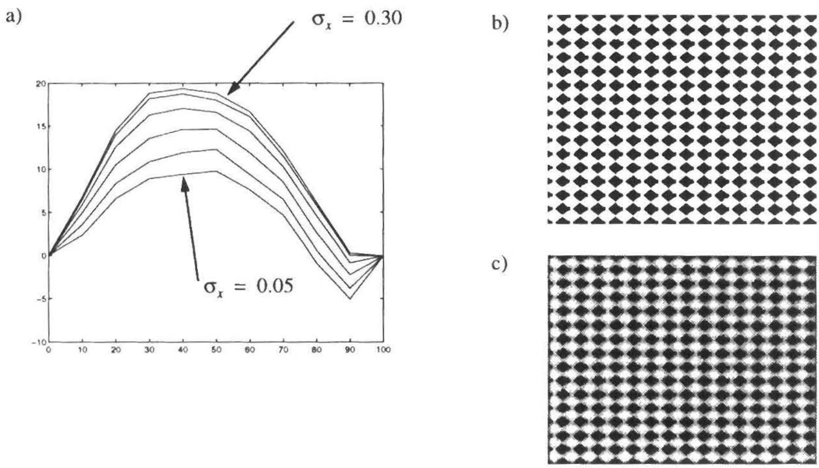

Figure 5. a) Simulated dot gain for real halftone dot data. b) A 30% halftone tint. c) The modelled visual dot gain effect applied to b).

Conclusions

A new approach to the problem of characterizing paper has been made. This makes it possible to simulate the effect of internal scattering in paper. The introduced model has been evaluated in the one-dimensional and two-dimensional cases and extensions to the model have already been anticipated. The model has provided results from the evaluation that have the same characteristics as real optical dot gain, and although it is only a simple model it explains very well the way in which paper causes optical dot gain. The model has been developed for arbitrary spectral characteristics but is has so far only been tested on single colour prints. In the near future, the general model will be tested on multicolour prints. It is anticipated that the model will help to solve some of the problems in rendering colour images.

Acknowledgement

The authors gratefully acknowledge discussions with and the cooperation of the members of the image processing group of Linköping University and the fellow researchers in the NI and PFT programmes. This work has been carried out with financial funding in part from the PFT-programme of the Swedish pulp and paper industries and from the Nordic industrial fund.

References

[1] A. Murray, *Monochrome Reproduction in Photoengraving*, J. Franklin Inst. 221, 1936.

[2] H.E.J. Nuegebauer, *Die teoretischen Grundlagen des Mehrfarbenbuchs-druchs*, Zeitschrift für wissenscaftliche Photographie Photophysik und Photochmie, Band 36, Heft 4, April 1937.

[3] J.A.C. Yule and W.J. Nielsen, *The penetration of light into paper and its effect on halftone reproduction*, TAGA Proceedings, p. 65-75, Vol. 3, 1951.

[4] J.R. Huntsman, *A New Model of Dot Gain and its Application to a Multi-layer Color Proof*, Journal of Imaging Technology, p. 136-145, Vol. 13, No. 5, October 1987.

[5] P. Oittinien and H. Saarelma, *Influence of optical surface properties of paper on information capacity*, Paper and Timber, p. 66-71, Vol. 75, No. 1-2, 1993.

[6] Ø. W. Gregersen, P.O. Johnsen, T. Helle, *Small Scale Topographical Variations of Paper Surfaces, and their Effects on Printing Ink Transfer Distribution*, Proceedings of the TAPPI/CPPA International Printing and Graphic Arts Conference, p. 271-281, October 1994.

[7] C.S. Haase and G.W. Meyer, *Modeling Pigmented Materials for Realistic Image Synthesis*, ACM Transactions on Graphics, p. 305-335, Vol. 11, No. 4, October 1992.

[8] J.A.C. Yule, *Principles of Color Reproduction*, John Wiley & Sons, inc. New York 1967.

[9] M. Wedin and B. Kruse, *Modeling of screened colour prints using Singular Value Decomposition*, SPIE Proceedings Vol. 2179, p. 318-326, Human Vision, Visual Processing and Digital Display V, 1994.

[10] M. Wedin and Björn Kruse, *Halftone Color Prints: Dot Gain and Modeling of Color Distributions*, SPIE Proceedings Vol. 2413, Color Hard Copy and Graphic Arts IV, 1995.