Linköping Studies in Science and Technology
Licentiate Thesis No. 1694

Halftoning for Multi-Channel Printing

– Algorithm Development, Implementation and Verification

Paula Žitinski Elías

Linköping University

Department of Science and Technology
Linköping University, Norrköping, Sweden
Norrköping, 2014

Halftoning for Multi-Channel Printing

– Algorithm Development, Implementation and Verification

Copyright © 2014 Paula Žitinski Elías

Department of Science and Technology
Campus Norrköping, Linköping University
Sweden

ISBN: 978-91-7519-174-4

ISSN 0280-7971

This is a Swedish Licentiate Thesis. The Licentiate degree comprises 120 ECTS credits of postgraduate studies.

Printed by LiU-Tryck, Linköping, Sweden, 2014

“It would be possible to describe everything scientifically, but it would make no sense; it would be without meaning, as if you described a Beethoven symphony as a variation of wave pressure.”

— Albert Einstein

Abstract

A seemingly straightforward way to enhance the quality of printed images is to increase the number of colorants, beyond the four traditionally used, in multi-channel printing. Potential improvements to reproduced images include: increased colour accuracy, enhanced colour smoothness and reduced image graininess. Nevertheless, numerous challenges exist, one of them being the implementation of halftoning algorithms, which transform the original image into a binary one that is reproducible by the printing system. This thesis concerns the development, implementation and verification of halftoning algorithms suitable for an increased number of colorants in multi-channel printing.

The first focus in this thesis is on the implementation of an amplitude modulated (AM) halftoning method for seven-channel printing utilizing CMYKRGB colorants. The proposed AM halftoning method utilizes non-orthogonal halftone screens instead of orthogonal ones (dots), thus enabling a wider angle range for the channels that makes possible to accommodate multi-channel impressions. The performance of the non-orthogonal halftoning method was evaluated by computational simulation of channel misregistration for 1600 different scenarios and assessment of printed orthogonal and non-orthogonal patches. The simulated and printed results demonstrate that the proposed halftoning method utilizing non-orthogonal screens shows no visible moiré and produces smaller colour shifts in case of misregistration when compared to orthogonal halftoning.

However, the layer thickness of the combined colorants is not controlled by the aforementioned multi-channel AM halftoning approach. Therefore, the second focus in this thesis concerns the adjustment and implementation of a multilevel halftoning algorithm for achromatic and chromatic inks. In this algorithm, a channel is processed so that it can be printed using multiple inks of same hue value, achieving a single ink layer. Here, the thresholds for ink separation and dot gain compensation pose an interesting challenge. Since dot gain originates from the interaction between a specific ink and specific paper, compensating the original image for multilevel halftoning means expressing the dot gain of multiple inks in terms of the nominal coverage of a single ink. The applicability of the proposed multilevel halftoning workflow is demonstrated using multiple inks while avoiding dot-on-dot placement and accounting for dot gain. The results also show that the multilevel halftoned image is visually improved in terms of graininess and detail enhancement when compared to a bi-level halftoned image.

Acknowledgments

Countless smiling friendly faces surround me, invigorate me, strengthen me; I am so fortunate for so much support and kindness.

My appreciation list is bound to start with the two people this thesis would have absolutely not been possible without. I am filled with gratitude for their amiability and guidance in form of endless hours dedicated to mutual discussions, comments and ideas. Sasan Gooran, my supervisor, mentor, councillor. Your never-ending support, encouragement, selflessness and uttermost patience helped achieve the work here presented, always bringing knowledge together with a smile to the table. Daniel Nyström, my co-supervisor. No report, scientific paper or thesis chapter could ever have ended up so well without your comments, effort and fruitful conversations. Sincerity, helpfulness and friendliness surround you.

I would like to express my gratitude to the people of the best research project, CP7.0, with special fondness to my dear “E”s; an extraordinary and unique merge of intelligence, teamwork and amusement. I would like to make a mention to Aditya, Carinna, Jérémie, Ludovic, Melissa, Ole, Philipp, Radovan, Sepideh, Steven and Teun. May we never stop combining business and pleasure all over the world. I would like to express an additional appreciation to Ludovic; our fruitful conversations lead to laughter and mutual collaboration; some of the latter is presented in this thesis.

My co-workers at the Department of Science and Technology at Linköping University are one of the strongest reasons I am so eager

for the continuation of my PhD studies. I am so lucky to work side by side with such amazing people. I will limit myself to naming a few of them.

Björn, our group's mood lightens up when you arrive and suddenly everyone wants to have fika to hear the stories, research and adventures you have to share. When I grow up, I want to be like you. Dag with his loud laugh, sparkling eyes and thrilling stories, thank you for your friendliness. Felicia and Lesley, bright faces emanating joy. Gun-Britt, my Swedish mother, you are a selfless soul whose radiant laughter resounds the hallways, having the power to make me smile from afar. Thank you for taking care of me, professionally and privately. Pier, we should buy you that coffee machine very soon, you certainly deserve it. Tobias and his family, wonderful and adventurous people of kind hearts, I am so lucky to know you. Tomas, your humour always spot-on, our Spanish-Swedish conversations are such a pleasure; hur är det med Maja?

My colleagues and friends from the afterwork group: Ahmad, Alex, Ali, Amanda, Andrew, Arash, Dan, Daniel, David, Donata, Ehsan, Eleanor, Elina, Ellen, Erik, Fahimeh, Henrik, Indre, Jesper, Joel, Josefin, Khoa, Lei Chen, Lei Lei, Löig, Magnus, Martin, Negar, Qing, Peter, Rickard, Saghi, Sara, Sattish, Sherp, Simone. Our beautiful times together on barbecues, canoeing, conferences, courses, dancing classes, dinners, excursions, fiestas, fikas, Halloween, hiking, lakes, lunches, meetings, movies, orchestra, parties, Prästgatan events, rock climbing, seminars, SFI, trips, volleyball and world cup matches are the "it" factor in my life in Norrköping. Thank you for your friendship. Special mention to Alex whose methodical mind that never ceases to amaze me, for having my back as such a wonderful friend. Also, to Fahimeh, for the honest and valuable friendship we share.

My former colleagues and very present friends; Erica, mi querida amiga, you express your love and kindness so vividly. Martina, my beautiful curly friend, I am forever eager for our next cup of coffee. Sophie, my artistic soul, my persistent fighting dreamer. Tamara,

because time and distance between us are so relative. Yoyo, for our silent mutual understanding and your unconditional support.

My former colleagues at the University of Zagreb who have supported me in my exploring endeavours; I am forever indebted. Special gratitude goes to Ante, Diana, Gojo, Lidija, obje Ljilje, Mladen, Sanja and Tamara.

Financial support was provided by the Marie Curie Initial Training Networks (ITN) CP7.0 N-290154 funding, which is gratefully acknowledged.

This thesis has been proofed by many volunteers; although the possible remaining mistakes are my doing, I am thankful to Alex, David, Martin, Santi, Sophie and Tamara for their help in reducing them.

My friends are the pillars I can rest surely upon. I am so lucky to have strong bonds with people from all over the world; they taught me globetrotting is all about the people you meet on the way. Thank you, my beautiful friends. Sometimes, however, it takes one special person who will make you truly blossom; I only hope to reciprocate the love and happiness he presents me daily. You are the one whose beautiful mind, encouragement, devotion and understanding overwhelm me. Finally, to my dearest parents, who have loved me and supported me through all my projects and ideas; your unconditional love and encouragement is the nurturing ground allowing me to grow.

Thank you.

Paula

Norrköping, November 2014

Publication list

- [1] P. Žitinski Elías, D. Nyström, and S. Gooran, “Multi-channel printing by orthogonal and non-orthogonal AM halftoning,” in *Proceedings of 12th International AIC Colour Congress: Bringing Colour to Life*, Newcastle, UK, 2013.
- [2] Y. Qu, P. Žitinski Elías, and S. Gooran, “Color prediction modelling for five-channel CMYcLm printing,” in *IS&T/SPIE Electronic Imaging*, San Francisco, USA, 2014.
- [3] M. Namedanian, D. Nyström, P. Žitinski Elías, and S. Gooran, “Physical and optical dot gain: characterization and relation to dot shape and paper properties,” in *IS&T/SPIE Electronic Imaging*, San Francisco, USA, 2014.
- [4] P. Žitinski Elías, S. Gooran, and D. Nyström, “Multilevel halftoning applied to achromatic inks in multi-channel printing,” in *Proceedings of IARIGAI 41st Research Conference*, Swansea, UK, 2014.
- [5] L. Gustafsson Coppel, S. Le Moan, P. Žitinski Elías, R. Slavuj, and J. Y. Hardeberg, “Next generation printing – Towards spectral proofing,” in *Proceedings of IARIGAI 41st Research Conference*, Swansea, UK, 2014.

Table of contents

- Abstract..... i**
- Acknowledgments iii**
- Publication list..... vii**
- Table of contents..... ix**
- 1. Introduction..... 1**
 - 1.1. Background..... 3**
 - 1.2. Scope within the research project..... 3**
 - 1.3. Aim of the study..... 4**
 - 1.4. Structure of the thesis 5**
- 2. Colour theory and reproduction 7**
 - 2.1. Colorimetry..... 9**
 - 2.1.1. Human visual system9
 - 2.1.2. Additive and subtractive colour mixing.....9
 - 2.1.3. CIE colour space 11
 - 2.1.3.1. CIE XYZ colour space12
 - 2.1.3.2. CIE LAB colour space13
 - 2.1.3.3. Colour difference14
 - 2.2. Colour reproduction in printing 15**
 - 2.2.1. Multi-channel printing..... 16
 - 2.3. Summary 17**
- 3. Halftoning reproduction..... 19**
 - 3.1. Introduction..... 21**
 - 3.2. Monochrome halftoning 21**

3.2.1. AM and FM halftoning.....	23
3.2.1.1. Hybrid halftoning	24
3.2.2. Table halftoning.....	26
3.2.3. Threshold halftoning.....	27
3.2.3.1. Ordered dithering.....	27
3.2.4. Error diffusion.....	28
3.2.5. Iterative Halftoning.....	30
3.2.5.1. IMCDP	30
3.2.6. Multilevel halftoning	32
3.2.6.1. Multilevel FM halftoning.....	33
3.3. Colour halftoning	33
3.3.1. AM colour halftoning.....	34
3.3.2. FM colour halftoning	36
3.4. Summary.....	36
4. Dot gain and halftone reproduction models.....	39
4.1. Introduction.....	41
4.2. Dot gain	41
4.3. Models for halftone reproduction	44
4.3.1. Murray-Davies model	44
4.3.2. Neugebauer model	45
4.3.2.1. Demichel's equations	45
4.3.3. Yule-Nielsen model	46
4.4. Summary.....	47
5. Non-orthogonal AM halftoning applied to multi-	
channel printing.....	49
5.1. Introduction.....	51
5.2. Proposed method.....	53
5.2.1. Method assessment.....	55
5.3. Results and discussion	57
5.4. Conclusions	61
6. Multilevel halftoning applied to multi-channel	
printing for achromatic inks.....	63
6.1. Introduction.....	65
6.2. Multilevel FM halftoning algorithm	66
6.3. Methodology	69

6.3.1. Experimental setup	69
6.3.2. Locating thresholds between inks.....	70
6.3.3. Dot gain compensation.....	70
6.4. Results and discussion	71
6.4.1. Thresholds between inks	71
6.4.2. Dot gain compensation.....	74
6.4.3. Implementation assessment.....	79
6.4.3.1. Smoothness	79
6.4.3.2. Graininess	81
6.5. Conclusions	84
7. Multilevel halftoning applied to multi-channel printing for chromatic inks	87
7.1. Introduction.....	89
7.2. Methodology	90
7.2.1. Materials and devices.....	90
7.2.2. Dot gain	91
7.2.2.1. Locating thresholds	91
7.2.2.2. Dot gain compensation.....	92
7.2.3. Evaluation of the multilevel halftoning algorithm	92
7.2.3.1. Colour accuracy	93
7.2.3.2. Graininess	95
7.3. Results and discussion	95
7.3.1. Thresholds between inks	95
7.3.2. Dot gain	97
7.3.3. Colour accuracy	99
7.3.4. Graininess.....	101
7.4. Conclusions	103
8. Conclusions and future work	105
8.1. Conclusions	107
8.2. Future work	108
References.....	109

1. Introduction

- 1.1. Background3
- 1.2. Scope within the research project 3
- 1.3. Aim of the study 4
- 1.4. Structure of the thesis 5

1.1. Background

Several areas of printing are in constant expansion, such as fine-art printing, high quality reproductions, packaging and 3D printing. Expanding the printing process from using the usual four ink channels to a multi-channel setup has been a rising trend in order to keep up with the market's requirements. By applying multi-channel printing, the reproduction quality is expanded in terms of colour reproducibility and visual pleasantness.

Multi-channel printing, however, raises several challenges, such as colorant separation, spectral gamut prediction, paper-ink interaction and adaptation of halftoning algorithms.

Halftoning algorithms are applied to an image before printing, altering it so that it is reproducible by the printing devices. They convert the initial image to a binary one using a series of discrete dots that create the illusion of lighter or darker shades.

These algorithms, however, need to be optimized for multi-channel printing. This is manifested out of the need to control the multi-channel ink overlap due to the paper substrate's (or other medias') physical limitations. A way of controlling the ink placement in dependence to other inks needs to be found by adaptation and development of suitable halftoning algorithms.

1.2. Scope within the research project

This licentiate thesis, focused on halftoning and tonal reproduction for multi-channel printing, is part of the on-going PhD studies at Linköping University. This research, partially funded by the Marie Curie Initial Training Networks (ITN) and partially by Linköping University, is part of the CP7.0 project: Colour Printing 7.0: Next Generation Multi-Channel Printing (www.cp70.org).

The project is executed in a consortium of 6 full partners (Gjøvik University College, Norway, Technische Universität Darmstadt, Germany, Voxvil AB, Sweden, University of the West of England, UK, Océ Print Logic Technologies SA, France and Linköping University, Sweden) and 6 associated partners (METSA Board AB, Sweden, MoRe Research AB, Sweden, Fraunhofer Fokus, Germany, Mid Sweden University, Sweden, The National Gallery, UK and Clariant Produkte, Germany), congregating 7 PhDs and 2 Post-Doc researchers working in the field of expansion of conventional printing to multi-channel printing. The key research areas within the project are spectral modelling of the printer/paper/ink combination, spectral gamut prediction and gamut mapping, paper's optical and surface properties, 2.5 D printing, and halftoning algorithms and tonal reproduction.

1.3. Aim of the study

The aim of this licentiate thesis is to explore possible solutions for control over the ink layer disposition by using appropriate halftoning algorithms. Halftoning algorithms are applied to an original image prior to printing; modifying them or developing new halftoning algorithms that account for the mentioned challenges would represent a solution to ink overlap and improve the final image quality.

Several types of halftoning algorithms exist, with different characteristics that yield different benefits and challenges. In some algorithms, like AM halftoning, halftoning more than four channels raises challenges. For other halftoning algorithms, like multilevel halftoning, their implementation for printing requires development of a certain workflow, which is dependent on the used ink's colorimetric values.

This thesis has the goal to investigate halftoning algorithms that can be applied to multi-channel printing and to try to offer a solution for ink overlap, facing the specific challenges that come with the different chosen setups.

1.4. Structure of the thesis

This thesis has been written as a monograph based on the research that has been published or that will be submitted for publishing as part of the on-going PhD studies. A list of published papers is given in page vii. Choosing to write a monograph has given the opportunity to exceed the imposed publication's page limitations and complement the published research with additional work and ideas, possibly adding to the level of comprehensibility.

This thesis begins with background and theory chapters (Chapters 2, 3 and 4). Chapter 2, Colour theory and reproduction, explains the principles of colour vision and colour reproduction, introducing terms and metrics that were used in the presented research. Chapter 3, Halftone reproduction, gives an overview of the halftoning algorithms available. The aim of this chapter is to present the reader with the benefits and drawbacks of various algorithms and to make the issues of halftoning for multi-channel printing understandable. Chapter 3, Dot gain and halftone reproduction models, has the goal to acquaint the reader with the issues in light-paper-ink interaction and the models used for understanding and quantifying these phenomena.

The research carried out until present date is presented in Chapters 5, 6 and 7. Parts of Chapter 5, Non-orthogonal AM halftoning applied to multi-channel printing, were published in (Žitinski Elías, Nyström, and Gooran 2013), and explain the approach of AM halftoning by altering the shape of the halftone dots, thus allowing the allocation of extra ink channels. Chapter 6, Multilevel halftoning applied to multi-channel printing for achromatic inks (Žitinski Elías, Gooran, and Nyström 2014), presents the research with the multilevel halftoning algorithm implementation, resolving several challenges encountered. The expansion of this method from achromatic to chromatic inks is presented in Chapter 7, Multilevel halftoning applied to multi-channel printing for chromatic inks, where the implementation workflow specific to chromatic inks is presented.

Finally, Chapter 8, Conclusions and future work, concludes the research presented, discussing several future research possibilities.

2. Colour theory and reproduction

2.1. Colorimetry.....	9
2.1.1. Human visual system	9
2.1.2. Additive and subtractive colour mixing	9
2.1.3. CIE colour space	11
2.1.3.1. CIE XYZ colour space	12
2.1.3.2. CIE LAB colour space.....	13
2.1.3.3. Colour difference.....	14
2.2. Colour reproduction in printing.....	15
2.2.1. Multi-channel printing	16
2.3. Summary.....	17

2.1. Colorimetry

Colorimetry is the science and technology used to quantify and physically describe the human colour perception (Ohno 2000). The principles of human visual system must be investigated with the goal of understanding, quantifying and displaying colours.

2.1.1. Human visual system

The human visual system (HVS) responsible for the notion of sight consists of photoreceptors located in the eye's retina that transmit the illumination stimulus to the brain. There are two kinds of photoreceptors: rods and cones. Rods are only useful for vision under low light levels and are not susceptible to colour. When the light levels are higher, the rods become saturated and do not contribute to vision. The cones, nevertheless, become active under normal light levels, and they are the ones responsible for colour vision.

There are three types of cones with different light susceptibility – short (S), medium (M) and long (L) cones, peaking at short (420-440 nm), medium (530-540 nm) and long (560-580 nm) wavelengths of light.

The three cones divide the visible light spectrum into three bands, accounting for the human trichromatic colour vision (Stockman, MacLeod, and Johnson 1993). Any light susceptible by the cones will evoke stimuli that will be interpreted by the neuron cells as a specific colour. Different stimulus combinations accounts for the full range of colours that can be perceived by the HVS.

2.1.2. Additive and subtractive colour mixing

The idea of reproducing the full range of colours by mixing three lights of different colour bands lead to the principles of today's

colour reproduction systems. The three coloured lights were chosen so that their wavelengths were a close match to the light susceptibility wavelengths of the three different types of cones. The mixture of these three lights – red (R), green (G) and blue (B) – renders white, which is why this model is called additive colour mixing (Figure 2.1). The principal components of a colour model are called primary colours or primaries. In additive colour mixing, the colour sensation is achieved by photon emission from a light source. The application is to any device that emits photons of energy to display colours – like monitors or TVs.

Figure 2.1: Additive and subtractive colour mixing.

Contrary to photon emittance, there is the case where colour is created by the combination of the reflected light photons from an external light source, like mixing ink pigments in printing reproduction. A different colour mixing is then used to reproduce colours, using red, green and blue's complementary colours – cyan (C), magenta (M) and yellow (Y) as primaries. Here, contrary to additive colour mixing, the lack of the three primary colours will create the sensation of white (assuming a white background) and is thus called subtractive colour mixing. The amount of cyan pigment applied to the paper will control the amount of red in the white light that will be absorbed by the ink. By applying 100% of cyan, in theory no red will be reflected. By applying 100% ink coverage of cyan, 100% magenta and 100% yellow, in theory, all light will be

absorbed and thus the sensation of black achieved (Figure 2.1). However, in printing technologies, due to the imperfection of ink pigments and paper substrate that results in inhomogeneous surface coverage, black (K) is added as a fourth ink.

2.1.3. CIE colour space

A colour model or a colour space is a mathematical tuple of three or four colour components (primaries), such as RGB or CMYK. According to (Tkalčić and Tašić 2003), a colour space can be described as a precise notation by which colours are specified. Several colour spaces and subdivisions exist, e.g. CIE, RGB and CMYK.

The International Commission on Illumination (The Commission Internationale de l'Eclairage, CIE) is the primary organization responsible for standardization of colour metrics and terminology (Sharma 2002). In 1931, they experimentally found the three colour matching functions, $r(\lambda)$, $g(\lambda)$ and $b(\lambda)$, that best represented the sensitivity functions of the HVS. For some wavelengths this experiment resulted in negative sensitivity values, meaning that the stimuli at those wavelengths could not be obtained by any physically achievable primary (Sharma 2002). Therefore, the $r(\lambda)$, $g(\lambda)$ and $b(\lambda)$ colour matching functions were translated by a matrix multiplication into $\bar{x}$, $\bar{y}$ and $\bar{z}$ colour matching functions (Figure 2.2).

The viewing conditions are important factors in CIE colour spaces. CIE denominates different light illumination sources as standard illuminants – A, B, C and a series of D sources. Among the D standard illuminants, the light source D50 corresponds to daylight illumination source at a temperature of 5003 K and is widely used in graphic industry, while D65 corresponds to 6504 K and it is used in paper industry (Fairchild 2013). The observer is another viewing condition defined by CIE, since the tristimulus values correspond to the observer's field of view. In standard colorimetry, an observer's field that subtended 2° was firstly used in 1931, followed in 1964 by

a supplementary standard colorimetric observer of 10° (Fairchild 2013).

Figure 2.2: CIE $\bar{x}\bar{y}\bar{z}$ colour matching functions.

2.1.3.1. CIE XYZ colour space

The CIE XYZ colour space was created in 1931 to approximate human vision, thus containing the whole range of perceivable colours of the HVS (Smith and Guild 1931). It is derived from the $\bar{x}$, $\bar{y}$ and $\bar{z}$ colour matching functions by:

$$\begin{aligned}
 X &= k \int_l^u I(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda \\
 Y &= k \int_l^u I(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda \\
 Z &= k \int_l^u I(\lambda)R(\lambda)\bar{z}(\lambda)d\lambda
 \end{aligned} \tag{2.1}$$

where $I(\lambda)$ is the spectral photon distribution of the light source illuminating the object, $R(\lambda)$ the spectral reflectance function, and l and u are the lower and upper limits of the wavelength, usually 380 and 780 nm. k is the normalization factor set so that a perfect diffuse surface $R(\lambda) = 1$ always gives $Y = 100$:

$$k = \frac{100}{\int_l^u I(\lambda) \bar{y}(\lambda) d\lambda} \quad (2.2)$$

Unlike the device dependent RGB or CMYK spaces, CIE XYZ is a device independent colour space, based on the colour matching functions of the HVS. In this colour space, Y is defined as luminance, a photometric unit of light coming from the scene to the eye (Sharma 2002). A drawback of CIE XYZ is that it is a perceptually non-uniform colour space.

2.1.3.2. CIE LAB colour space

Perceptual uniformity is a highly desirable characteristic in a colour system where colours correspond to equal distances in the tristimulus space (Sharma 2002).

CIE LAB is a perceptually uniform colour space where colours can be measured and quantitatively compared to each other. The L^* coordinate denotes perceived lightness, where $L^* = 100$ is white stimulus and $L^* = 0$ means black stimulus, a^* is the red-green axis where positive values indicate red and negative values are green, and b^* blue-yellow axis where positive values mean blue and negative ones are yellow. This colour space is derived from CIE XYZ by using the following equations:

$$L^* = \begin{cases} 116 \left(\frac{Y}{Y_n} \right)^{1/3} - 16, & \frac{Y}{Y_n} > 0.008856 \\ 903.3 \left(\frac{Y}{Y_n} \right), & \frac{Y}{Y_n} \leq 0.008856 \end{cases}$$

$$a^* = 500 \left(f \left(\frac{x}{x_n} \right) - f \left(\frac{y}{y_n} \right) \right) \quad (2.3)$$

$$b^* = 200 \left(f \left(\frac{Y}{Y_n} \right) - f \left(\frac{Z}{Z_n} \right) \right)$$

$$f(x) = \begin{cases} x^{\frac{1}{3}}, & x > 0.008856 \\ 7.787x + \frac{16}{116}, & \frac{Y}{Y_n} \leq 0.008856 \end{cases}$$

X_n , Y_n and Z_n are the XYZ values for the white point of the chosen light source.

2.1.3.3. Colour difference

Uniform colour spaces such as CIE LAB allow comparison between different colours. The colour difference is denoted with ΔE . Several formulae exist. Here the most common ones are explained, which were also used in the research presented in Chapters 5 and 7.

CIE 1976 colour difference ΔE_{ab} is the Euclidian distance between two colours' coordinates:

$$\Delta E_{ab} = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \quad (2.4)$$

Perceptual non-uniformity is, however, present at different points of the CIE LAB space (Mahy, Eycken, and Oosterlinck 1994). In order to account for that, other colour difference measures have been proposed, such as CIE 1994 colour difference ΔE_{94} . It is calculated by a weighted Euclidian distance of lightness ΔL^* , chroma ΔC_{ab}^* and hue ΔH_{ab}^* , defined as:

$$\Delta E_{94} = \sqrt{\left(\frac{\Delta L^*}{k_L S_L} \right)^2 + \left(\frac{\Delta C_{ab}^*}{k_C S_C} \right)^2 + \left(\frac{\Delta H_{ab}^*}{k_H S_H} \right)^2}$$

$$\Delta C_{ab}^* = \sqrt{a^{*2} + b^{*2}} \quad (2.5)$$

$$\Delta H_{ab}^* = \sqrt{\Delta E_{ab}^{*2} - \Delta L^{*2} - \Delta C_{ab}^{*2}} = \sqrt{\Delta a^{*2} + \Delta b^{*2} - \Delta C_{ab}^{*2}}$$

Here S_L , S_H and S_C are the weighting functions:

$$\begin{aligned}
S_L &= 1 \\
S_C &= 1 + K_1 C_1 \\
S_H &= 1 + K_2 C_1
\end{aligned} \tag{2.6}$$

K_1 and K_2 are fixed numbers dependent on the application to graphic arts or textiles.

k_L , k_H and k_C are the parametric factors, and are included so that adjustments can be made in the equation in case of deviation of viewing conditions. If no deviations from the model are made, the parametric factors are set to 1 (McDonald and Smith 2008).

2.2. Colour reproduction in printing

It has been explained in Section 2.1.2 that, in order to achieve colour sensation in printing reproduction, subtractive colour mixing and four inks are used – cyan (C), magenta (M), yellow (Y) and black (K).

This means that every image before printing needs to be separated into so-called channels, usually one for each ink used – cyan, magenta, yellow and black channels. After separation, each channel is digitally adapted for the printing process before being sent to the printing device. The reason for this digital adaptation lays in the common nature of the vast majority of printing technologies, where placing ink onto a media substrate is a choice of either depositing or not depositing a drop of ink onto a specific position. The printed image is therefore a result of either printed or non-printed spots – duotone impression. In order to achieve the sensation of a full palette of lighter and darker tones, a digital pre-reproduction step called halftoning is performed, which will be explained in detail in Chapter 3.

2.2.1. Multi-channel printing

A consequence of subtractive colour mixing is lightness decrease by overlapping inks. Therefore, light colours that are reproduced by a mixture of two primaries, such as red (magenta + yellow), green (cyan + yellow) and blue (magenta + cyan) are hard to achieve (Boll 1994).

In addition, because of the halftoning process, it is possible that halftone dots may be visible with the bare eye, decreasing the visually pleasantness of the reproduction. This phenomenon, called graininess or granularity, is highly undesirable, especially when aiming for high quality reproduction.

In the interest of reducing graininess and augmenting the colour gamut in terms of tone, detail and colour for high quality printing, additional channels other than CMYK are introduced (Boll 1994; Jang et al. 2006). These additional channels can be light cyan (lc), light magenta (lm), grey (GY), photo grey (PGY), red (R), green (G), blue (B) and orange (O). Introducing additional channels is a solution to achieve high quality prints in many printing technologies. Printing using more than four channels is called multi-channel printing.

Multi-channel printing also leads to colorimetric redundancy, since a colour under a specific illumination can be reproduced using several different colorant combinations. This flexibility opens for minimising colour mismatch under more than one illuminant, i.e. spectral reproduction (Gustafsson Coppel et al. 2014).

The benefits of multi-channel printing have already been mentioned. Nevertheless, printing using a high number of inks imposes new challenges and physical limitations, one of them being a too large number of ink layers printed on top of each other, which causes ink bleeding and colour inaccuracy problems (Zeng 2000). Control over the ink overlap by means of new or adjusted halftoning algorithms opens a research area that is addressed in this licentiate thesis in Chapters 5, 6 and 7.

2.3. Summary

The purpose of this chapter was to explain the basics of colorimetry and acquaint the reader with colour models that were put into practice and presented in the following chapters. In addition, an attempt was made to explain the basics of colour reproduction and the need to extend the conventional four CMYK inks to multi-channel printing and the issues of ink overlap that come with it.

Since halftoning algorithms can be a way of working towards a solution to this problem, an overview of halftoning algorithms is given in Chapter 3.

3. Halftoning reproduction

3.1. Introduction	21
3.2. Monochrome halftoning.....	21
3.2.1. AM and FM halftoning.....	23
3.2.1.1. Hybrid halftoning	24
3.2.2. Table halftoning.....	26
3.2.3. Threshold halftoning	27
3.2.3.1. Ordered dithering	27
3.2.4. Error diffusion.....	28
3.2.5. Iterative Halftoning	30
3.2.5.1. IMCDP.....	30
3.2.6. Multilevel halftoning.....	32
3.2.6.1. Multilevel FM halftoning.....	33
3.3. Colour halftoning.....	33
3.3.1. AM colour halftoning.....	34
3.3.2. FM colour halftoning.....	36
3.4. Summary.....	36

3.1. Introduction

It has been explained in Section 2.2 that the printing devices usually leave only the choice of printed or not printed spots. In order for the reproduced image to display a range of shades, a digital processing (halftoning) algorithm is applied to the image prior to printing. A halftoning algorithm will transform the original image into a series of microdots varying in size and/or concentration that will create the illusion of a range of lighter and darker tones (Figure 3.1).

Literature reveals a large number of halftoning algorithms (Berns and Wyble 2000) that can mainly be categorized in amplitude modulated (AM) and frequency modulated (FM) algorithms (Sharma 2002). In AM halftoning the size of the dots varies to create the illusion of lighter or darker tones, whereas in FM halftoning, the concentration of dots is the fluctuating factor.

Figure 3.1: A halftoned image.

3.2. Monochrome halftoning

Monochrome halftoning algorithms process an image channel independently of the existence of other channels, making them the

most straightforward and computationally easiest halftoning algorithms.

Some basic concepts related to halftoning need to be explained. To begin with, the shape of the halftone elements can be a varying factor. It is usual that the halftone element is a circle or square, as the simplest shape, which is the reason why it is often referred to as a halftone dot. Nevertheless, other shapes can be applied as well. Besides using orthogonal circular or square shapes, non-orthogonal elements such as ellipses, diamonds, rhombi, etc. can also be used. Using non-orthogonal shapes shows advantages in colour AM halftoning (Wang, Fan, and Wen 2003), which will be further explained in Section 3.3.1.

After a halftone algorithm has been applied to the original image, the halftoned image consists of black and white spots, i.e. microdots. The goal is to have an equal average grey value of an area of microdots (halftone cell) as that of the same area of the original, continuous tone, image. Screen frequency (lines per inch, lpi) denotes the number of halftone cells per inch. Print resolution (dots per inch, dpi) is the number of microdots per inch (Figure 3.2).

Figure 3.2: Halftone cells for a printer with different dpi and lpi.

The lpi and dpi values are dependent on the printing technology and the printing device used. Higher lpi and dpi values mean smaller and visually less noticeable halftone cells and microdots. The number of grey levels of a halftoned image is dependent on the dpi/lpi ratio as in the following equation:

$$\text{Number of grey levels} = \left(\frac{\text{dpi}}{\text{lpi}} \right)^2 + 1 \quad (3.1)$$

Unless stated otherwise, all the images in this chapter are printed at 150 dpi.

Figure 3.3 displays an image AM halftoned with the same dpi, but with different lpi values. The number of grey levels and hence, the image quality, is higher when the lpi is bigger.

Figure 3.3: AM halftoned image with 150 dpi (left) 20 lpi and (right) 30 lpi.

3.2.1. AM and FM halftoning

AM and FM halftoning algorithms are the general disambiguation of all halftoning algorithms (Sharma 2002).

In AM halftoning the size of the halftone elements varies according to the grey level, ranging from very small to larger halftone elements, while the frequency remains constant (Figure 3.4). This makes AM halftoning a technique with good printing stability and low computational requirements (Lau and Arce 2001) and showing less dot gain (explained in Chapter 4) in mid-tone areas when compared to FM halftoning (Gooran 2005). Nevertheless, this regularity in dot placement makes it harder to display fine details and makes it prone to the undesirable moiré optical phenomenon, explained in detail in Section 3.3.1.

Figure 3.4: AM halftoned image (30 lpi).

FM halftoning, on the other hand, generates the effect of lighter or darker areas by altering the frequency of the microdots by placing them in lower or higher concentration depending on the grey level to be reproduced. An example of such a halftone is given in Figure 3.5, which is halftoned by error diffusion algorithm (explained in Section 3.2.4). As opposite to AM, the size of the halftone elements in FM halftoning is constant. The advantages of FM are fine detail reproduction, due to small size halftone elements, and the ability to reproduce very light areas (Gooran 2006). On the other hand, some printing techniques are not suitable for FM halftoning, as it is the instance with printers using electrophotographic (EP) technology, due to their incapacity of stably rendering isolated dots (Goyal et al. 2011). Laser printers are an example of printers using EP technology.

3.2.1.1. Hybrid halftoning

It is possible to combine AM and FM halftoning with the goal of overcoming the issues each of the methods has. In (Gooran 2005) a method for hybrid AM-FM halftoning method was proposed in order

Figure 3.5: FM halftoned image.

to get a better reproduction in flexography. In this printing technology the printing plate is made out of polymers, large organic macromolecules with rather small mechanical endurance, therefore in this printing technology it is not feasible to achieve very precise and small halftone dots, like the ones on very light parts of the image halftoned with AM halftoning. On the other hand, according to (Gooran 2005), AM halftoning has proven to be a better solution in the mid-dark image regions because of the smaller dot gain. Meanwhile, FM is still a better method to reproduce light shades. A hybrid AM-FM halftoning, where the FM is used on light areas and AM on the rest, is presented in (Gooran 2005).

The resulting halftoned image was proven to resolve the issues found with AM halftoning in the light areas. The areas of transition from AM to FM were not visually noticeable at 2100 dpi flexographic printing, and the grey tone representation was correct. According to observers, the proposed method proved to give a better representation of the image's light regions.

3.2.2. Table halftoning

Table halftoning is one of the simplest halftoning algorithms, operating over small areas at a time, with small computational challenges. The original image is run on a series of areas that are replaced by halftone tables (cells). The algorithm calculates the mean of the pixel values in each area and chooses the halftone table that has the closest mean. For instance, for a 3×3 table there exists $3^2 + 1 = 10$ grey levels, ranging from white pixel values for all elements, and adding a single black microdot (a black pixel value for a single microdot, where the rest 8 cells remain white), up to black pixel values for all microdots (Figure 3.6).

The size of the halftone table, which is directly related to the number of grey levels that can be represented, is usually much larger than 3×3 . The halftone dot shapes are determined by the arrangement of the microdots inside the table (e.g. line raster, circular dots, ellipses). Two different dot arrangements, i.e. clustered (grouped) and dispersed (split) dots, are presented in Figure 3.6.

Figure 3.6: Table halftoning: 3×3 cell halftoning with: a) 10 different grey levels, b) arranged in clustered or dispersed dots.

3.2.3. Threshold halftoning

Threshold halftoning is an operation similar to table halftoning, with the difference of using a threshold matrix for calculating the area around the pixel instead of using a table. The form of the threshold matrix will in this case shape the result of the halftone element. The method can be described by the following equation:

$$b(i,j) = \begin{cases} 1 & \text{if } g(i,j) \geq t(i,j) \\ 0 & \text{if } g(i,j) < t(i,j) \end{cases} \quad (4.2)$$

where b is the halftoned image, g is the original image and t the threshold matrix. If the pixel value at a given position (i, j) is bigger than or equal to the threshold matrix value, then a black microdot (1) is placed at the final halftoned image b at that position. Otherwise, a white microdot (0) is placed.

It is possible to shape the output of the halftone element by strategically adjusting the threshold values inside the matrix. One can achieve halftone shapes such as ellipses, lines, etc.

3.2.3.1. Ordered dithering

Ordered dithering uses a fixed threshold matrix and is subdivided into two methods depending on the arrangement of the threshold values inside the matrix.

Clustered ordered dithering creates a clustered disposition of the microdots, while dispersed ordered dithering creates a dispersed disposition. While the clustered microdots are congregated together, as the name suggests, dispersed microdots are scattered, forming isolated pixels. If, in the threshold matrix, the values grow coherently, the halftone dot will result in a cluster, otherwise, if they grow separately, it will get dispersed. Because of the scattered microdots, disperse dithering algorithm achieves a visually more pleasant reproduction.

An image halftoned by clustered and dispersed ordered dithering is shown in Figure 3.7. The matrix used is 8×8 , representing 33 grey levels. As it can be seen in Figure 3.7, this particular choice of number of grey levels results in very low quality images. This choice has been made for displaying purposes only and normally a much higher grey level number is used.

Figure 3.7: Halftoning by ordered dithering with: (left) clustered dots (right) dispersed dots.

Since ordered dithering is a point-by-point operation, it is computationally efficient.

3.2.4. Error diffusion

The error diffusion dithering algorithm was firstly introduced in (Floyd and Steinberg 1976) and at the time it represented the first real FM halftoning, operating not only on point-by-point, but rather on the neighbourhood of the current pixel. It is graphically shown in Figure 3.8, where g is the original and b the halftoned image.

Figure 3.8. Error diffusion algorithm.

The algorithm runs through the entire image row by row, comparing the value of the original pixel g with a threshold (usually set to 0.5), and setting the value of the pixel to 1 (if the value is bigger than the threshold) or 0 (if it is smaller). The difference between the set and the original value is then calculated, producing an error that is diffused to the neighbouring pixel using a previously established error filter. The original error filter proposed by the authors is shown in Figure 3.9. The error filter indicates the weights by which the error is diffused to the neighbouring pixels at each pixel location. Afterwards the algorithm moves on to the next pixel, continuing until it reaches the end of the image.

	●	7
3	5	1

• 1/16

Figure 3.9: Error filter proposed in (Floyd and Steinberg 1976).

The image in Figure 3.5 is halftoned using this algorithm.

It has been shown in (Knox 1992; Gooran 2001) that error diffusion algorithms generally enhance the edges of the image, meaning that they have an inbuilt high-pass filter.

3.2.5. Iterative Halftoning

Iterative halftoning algorithms take into account the entire image, instead of operating point-by-point like in threshold halftoning or on a neighbourhood like error diffusion. This makes the algorithm more computationally challenging, although the result is a high quality halftoned image (Gooran 2001).

Most iterative algorithms use the human visual system (HVS), which acts as a low-pass filter, to define a quality measure. They find the error by calculating the difference between the low-pass version of the original and binary image. The aim is to minimize this error by iteratively changing the initial binary image. The process comes to an end when the initial given condition is met, or when no change in the binary image is achieved. In the next subsection an iterative algorithm used in the work in Chapters 6 and 7 is explained.

3.2.5.1. IMCDP

Iterative Method Controlling the Dot Placement (IMCDP) is one of the iterative halftoning algorithms developed in the last decades, described in (Gooran 2001). Since it has been developed within our research group, thus having full control over the algorithm, it has been the FM halftoning method chosen in most of the research work done in this thesis.

The algorithm works as follows. For a $n \times n$ grey tone image, $2^{n \times n}$ possibilities of a binary halftoned image exist. This number can, however, be significantly narrowed down by calculating the number of black dots k the halftoned image has to have. k is the closest integer of the integration of the sum of the grey values of all the pixels of the original image. For this, the original image has been normalized to values between 0 and 1, where 0 indicates white and 1 indicates black. Halftoning is now a matter of deciding on where to place the k number of black dots.

It is clear that the goal is to minimize the difference e between the original grey scale image, g , and the binary image, b . Since the HVS acts like a low pass filter, the difference between the images can be calculated by the following equation:

$$e = \sum_{i,j} (f_g(i,j) - h_b(i,j))^2 \quad (3.3)$$

where $f_g(i,j)$ and $h_b(i,j)$ are the pixel values at the location (i,j) of the images, f and h are low pass filters and f_g and h_b the filtered images. The low pass filter needs to be a fast decreasing symmetric function (Gooran 2001). The experimental results show that the best general choice is a Gaussian filter with standard deviation 1.3 truncated to 11 x 11 pixels.

The algorithm is displayed in Figure 3.10.

Figure 3.10: IMCDP halftoning algorithm.

Firstly the initial image g is filtered with a filter f , resulting in an image f_g . The algorithm finds the position of the largest pixel value (if there are more, choosing the first one found), and places a dot at this same position in the image b . The difference $f_g - h_b$ is then calculated (called the feedback process) and the algorithm from then on calculates the position of the next highest pixel value in that image. Again, if there exist several pixels with the same maximum pixel value, the algorithm stores the position of the first one found. This process continues until the known number of dots, i.e. k , is placed.

For more details about the algorithm, interested readers are referred to the original paper.

Keeping in mind the high quality of the final halftoned image, two drawbacks of this algorithm exist. First, for images with large uniform areas, the algorithm may result in a highly structured halftoned image for large homogenous areas. This can, however, be avoided by adding a very small amount of noise to the initial image g . Secondly, as any iterative halftoning algorithm, processing time is significantly increased in comparison to algorithms that operate point-by-point or on a neighbourhood. An image halftoned with IMCDP is shown in Figure 3.11.

Figure 3.11: Image halftoned with IMCDP iterative algorithm.

3.2.6. Multilevel halftoning

The basic idea behind multilevel halftoning is to separate the output into more than two levels. This allows a final halftoned image that benefits from the possibility to be printed with multiple inks. Instances of multilevel halftoning algorithms are found in

(Goldschneider, Riskin, and Wong 1997), where the authors use an embedded multilevel Floyd-Steinberg's error diffusion algorithm. In (Zhang et al. 2012) the authors propose a clustered-dot multilevel halftoning in order to maintain surface texture. In (Gooran 2006) the multilevel algorithm separates the image into regions, halftoning them simultaneously and merging them afterwards. This specific instance of multilevel algorithm is used in the research described in Chapters 6 and 7 and is therefore further discussed in Section 3.2.6.1.

3.2.6.1. Multilevel FM halftoning

The multilevel halftoning algorithm described in (Gooran 2006) operates by first separating an image into different regions, then halftoning them simultaneously using a bi-level halftoning algorithm and finally merging them in the post-processing step. This technique can be beneficial when applied to multi-channel printing. From now on, when multilevel halftoning is mentioned, we mean this specific type of halftoning.

As discussed in Section 2.2.1, multi-channel printers use additional, less saturated, versions of the inks. Nevertheless, a paper substrate can absorb only a certain amount of ink. The way to ensure the ink limits are not exceeded is by controlling the placement of the halftone dots.

In the multilevel halftoning algorithm described in (Gooran 2006) it is possible to halftone an image in a way that is printed with multiple inks, but with no ink overlap. The specific details of this halftoning algorithm are described in Chapter 6, together with the obtained implementation results.

3.3. Colour halftoning

When the intention is to print using two or more inks, the halftoning algorithms mentioned in Section 3.2 can be applied to each channel

unrelatedly of the others. There are, however, deviations, some of which are explained in the next sections.

3.3.1. AM colour halftoning

As mentioned in Section 3.2.1, AM halftoning uses halftone elements of different sizes but with same distance (frequency) between them. Thus, when multiple AM halftoned channels are laid on top of each other, an optical grid effect, called moiré, can appear (Figure 3.12). Visible moiré appearance is extremely undesirable, as the visual uniformity is jeopardized. In order to avoid visible moiré, each channel is laid in a specific angle, which alters the formation of this optical phenomenon. While explaining the channels' angle disposition, one has to bear in mind that the possible rotation of a halftone channel using round shapes is limited to 90° , since its symmetry causes that 0° equals 90° . This will be explained with more detail in Chapter 5.

Figure 3.12: Moiré optical pattern.

In order to mask the moiré effect, the highest contrasting colour, black, is laid at 45° , the angle at which the eye is the least sensitive (Sullivan, Ray, and Miller 1991). The next highly contrast colours, cyan and magenta, are separated by a 30° angle from the black ink; cyan at 15° and magenta at 75° . The fourth colorant, yellow, would

optimally be separated by another 30° from cyan or magenta, which is impossible because of the aforementioned round element symmetry. Yellow, the least contrasting colour, is therefore placed at 0° , where the eye is most sensitive. This new angle arrangement causes a pattern with higher frequency than moiré, called rosette pattern (Figure 3.13).

Figure 3.13: AM colour halftoning angles and rosette pattern.

Any angle arrangement can, nevertheless, become easily shredded if the registration is compromised during the printing process. The problem caused by misregistration is also less likely to occur if the channels are laid in a rosette pattern formation (Oztan, Sharma, and Loce 2005).

Thus, with the AM halftoned channels arranged in the angle disposition aforementioned, creating a rosette pattern, the undesirable moiré is unnoticeable and colour stability is achieved, even in case of some misregistration during the printing process.

In the area of multi-channel printing with AM halftoning, the obstacle for incorporating more than four channels is the 90° angle constraint the orthogonal dot shape has. If one were to add more colorants, it would be impossible to separate them by 30° from the remaining channels, and without that, colour inconsistency due to overlapping channels, visible moiré and colour inaccuracy due to misregistration can happen.

As an alternative to the orthogonal circular halftone element, a different shaped element can be used (Wang, Fan, and Wen 2003). An asymmetric, non-orthogonal halftone element helps to achieve a moiré-free solution when printing with more than four colorants. Since the 90° angle is no longer an obstacle, a wider selection of angles is available and can therefore provide a visually more pleasant impression. This reasoning has led to the research that is explained in Chapter 5.

3.3.2. FM colour halftoning

As opposed to AM, FM colour halftoning algorithms vary the frequency of the halftone dots. Being non-periodic, FM algorithms are not as susceptible to moiré visual artefacts as AM are. When using FM halftoning, it is usual that the colour channels are halftoned independently from each other, but there are other alternative methods that halftone the channels dependently (Gooran 2001). For example, in (Gooran 2001) the strategy is to use dot-off-dot printing as much as possible to reduce the colour noise and ink consumption. Dot-off-dot strategy comprehends avoiding overlapping dots in different colorant channels on top of each other.

3.4. Summary

Applying a halftoning algorithm to an image prior to printing is a prerequisite in many reproduction systems. This chapter aimed at

providing an overview of some of the halftoning algorithms, emphasizing those used in the research explained in Chapters 5, 6 and 7. Nevertheless, before applying a halftoning algorithm, a model should be applied to the original image in order to account for the light-paper-ink interactions occurring when ink is deposited onto a media substrate. This is discussed in Chapter 4.

4. Dot gain and halftone reproduction models

4.1. Introduction	41
4.2. Dot gain	41
4.3. Models for halftone reproduction.....	44
4.3.1. Murray-Davies model	44
4.3.2. Neugebauer model	45
4.3.2.1. Demichel's equations.....	45
4.3.3. Yule-Nielsen model	46
4.4. Summary.....	47

4.1. Introduction

This chapter describes the general light-paper-ink interactions occurring in the printing process and the well-known models to understand and quantify these interactions. When ink is applied onto the substrate's surface during printing, physical and optical phenomena occur that cause a different printed result from the digital bitmaps sent to the printer. These phenomena cause the printed halftone elements to become larger and thereby resulting in a darker impression. This occurrence is referred to as dot gain and is explained in Section 4.2.

In order to control the size of the printed dots, i.e. to account for dot gain, different models can be applied prior to halftoning (Kipphan 2001) in order to achieve the correct size of the halftone dots. This is further explained in Section 4.3.

4.2. Dot gain

Dot gain or tone value increase is the result of the interaction between the ink and media substrate (e.g. paper). The printed areas expand in size in contact with the paper. In addition, light scattering within the paper causes the sensation of larger printed elements. As each halftone dot appears to grow in size, the result is a darker image with possible loss of information in the darkest regions. A simulation of the dot gain result is shown in Figure 4.1.

As previously mentioned, dot gain is the result of both physical and optical phenomena and it is therefore also differentiated by those. The result of ink spreading and ink penetration in contact with paper is called physical or mechanical dot gain, while the result of light scattering and light absorption is called optical dot gain. Ink spreading on the paper, causing mechanical dot gain, makes the printed dots grow in size. In addition, when the photons of light enter the paper through the ink layer of the image, they can, for instance,

Figure 4.1: An image (left) and the simulated darker result of the printed image (right) caused by dot gain.

scatter within the paper and get absorbed in it, or exit the paper at a further point (Figure 4.2). The photon paths where light exchange between different chromatic areas occurs, marked as “x” in Figure 4.2, are the reason for optical dot gain, which makes the printed ink dots appear darker than they originally are.

Figure 4.2: Possible paths a photon may take in a paper/ink medium.

Because of dot gain, one differentiates two types of area coverage values – nominal a_{nom} and effective a_{eff} area coverages. Nominal area coverages are the coverage values that are sent to the printer. These values will be larger once printed and are then referred to as effective area coverage values. A dot gain curve, such as the one seen in Figure 4.3, is a way of displaying the relationship between nominal area coverage and dot gain, where 0 means no ink coverage and 1 means fulltone coverage. Effective area coverage is the

measured values of printed ink coverage, while dot gain is the difference between effective and nominal area coverage.

Figure 4.3: Plot of the effective area coverage and dot gain versus nominal area coverage.

Since it is necessary to predict the effective ink coverage values, research has been carried out to characterize dot gain (Arney, Arney, and Katsube 1996; Rogers 1997; Namedanian and Gooran 2010) in order to understand and account for dot gain. This is achieved by adjusting the nominal ink coverage values, in a process called dot gain compensation, which is done by applying models to adjust the original image prior to halftoning.

Dot gain is dependent on the type of substrate, inks used, printing technology, type of halftoning algorithm (AM/FM), screen frequency, print resolution, halftone dot shape, etc. It is logical to notice that the paper properties will have an effect on the dot gain, as different papers absorb ink and scatter light differently (Namedanian

et al. 2014). In addition, the shape of the halftone affects dot gain too; the larger the perimeter of the halftone elements the higher the optical dot gain is (Namedanian and Gooran 2013).

Recent work done by (Namedanian et al. 2013) demonstrates the possibility of optical and mechanical dot gain separation by taking a microscale image of the halftone through both reflected and transmitted light. This separation allows a better ink dot placement characterization of both ink spreading and optical dot gain. What was until now possible to observe as a joint phenomenon can now be divided into two very distinct phenomena.

4.3. Models for halftone reproduction

In the paper by (Berns and Wyble 2000), an extensive study of the pillar models for halftone reproduction has been made. The authors explain several regression-based models, which are, as they explain, relatively simple and reasonably accurate, with the goal of imitating the behaviour of the printing process. An overview of the most used ones is given below.

4.3.1. Murray-Davies model

In (Murray 1936), the author presents a simple output density prediction model of the input dot that the author developed together with his colleague E. R. Davies, hence its name. The formula of the output reflectance is:

$$R = a_i R_i + (1 - a) R_s \quad (4.1)$$

where R is the predicted reflectance, a_i the fractional ink area coverage, R_i the reflectance of the full coverage ink, and R_s the substrate's reflectance. This model is a single-ink prediction model, and even though it has several pitfalls, it has been the basis for future research, with many extensions and improvements.

One of the drawbacks of this model is that it neglects optical dot gain. Another simplification the model makes is the equivalence between nominal and effective area coverage. Because of the mechanical (caused by ink-paper interaction) and optical (caused by light scattering) dot gain, the effective area coverage is always larger than the nominal area coverage sent to the printer.

4.3.2. Neugebauer model

An extension of the Murray-Davies model to account for colour has been made by (Neugebauer 1937). Neugebauer considered multiple colorants in a multi-colorant printing system by calculating the sum of the joined spectral reflectances at full area coverage:

$$R_{\lambda} = \sum_i a_i R_{\lambda,i,max} \quad (4.2)$$

where i are the so-called Neugebauer primaries (NPs): the substrate with no ink, single ink, and multi-ink overlap combinations, summing up to a total of 2^n NPs, n being the total ink number. For a three CMY colorant example, the NPs are white (substrate), cyan, magenta, yellow, blue, red, green and three-colour black. $R_{\lambda,i,max}$ are the spectral reflectance values of each NP at its maximal, full ink coverage. a_i is the corresponding effective fractional ink area coverage.

4.3.2.1. Demichel's equations

The fractional ink area coverages a_i for each of the NPs can be calculated with a probabilistic model introduced by (Demichel 1924). This model assumes ink dots are placed independently onto the substrate, like in FM independent halftoning. For the case of three NPs, cyan, magenta and yellow, the probabilistic area coverages are presented in Equation 4.3:

$$a_w = (1 - a_c)(1 - a_m)(1 - a_y)$$

$$\begin{aligned}
a_c &= a_c(1 - a_m)(1 - a_y) \\
a_m &= (1 - a_c)a_m(1 - a_y) \\
a_y &= (1 - a_c)(1 - a_m)a_y \\
a_r &= (1 - a_c)a_ma_y \\
a_g &= (1 - a_m)a_ca_y \\
a_b &= (1 - a_y)a_ca_m \\
a_k &= a_ca_ma_y
\end{aligned} \tag{4.3}$$

4.3.3. Yule-Nielsen model

Yule and Nielsen's research about light scattering in a substrate published in (Yule and Nielsen 1951) showed that the relationship between predicted and measured reflectance could be approximated with an exponent value:

$$\widehat{R}_\lambda = \left[a_i R_{\lambda,i}^{\frac{1}{n}} + (1 - a_i) R_{\lambda,p}^{\frac{1}{n}} \right]^n \tag{4.4}$$

The fractional ink area coverage a_i refers to physical area coverage, which includes mechanical dot gain. The n parameter, commonly referred to as the n -value or n -factor, accounts for light scattering and light penetration in the substrate. For $n = 1$, Yule-Nielsen is reduced to Murray-Davies, while $n = 2$ accounts for highest scattering substrate.

If, nevertheless, nominal instead of physical area coverage values are used, the values of n could be very high. In (Pearson 1980) it was suggested using $n = 1.7$ if no better choice is known.

4.4. Summary

This chapter describes the mechanical and optical phenomena occurring between light, paper and ink, which make the halftone elements appear larger once printed. This is why the original image must be adjusted prior to printing, which can be done by implementing one of the models for halftone reproduction explained in this chapter.

The following chapters describe the new research work done in developing halftoning algorithms for multi-channel printing. Dot gain compensation and halftone reproduction models, described in this chapter, are applied in the research work presented in Chapters 6 and 7. Since the workflow used in those chapters is specific to that research work, the dot gain compensation techniques will be explained there.

5. Non-orthogonal AM halftoning applied to multi-channel printing

- 5.1. Introduction 51
- 5.2. Proposed method 53
 - 5.2.1. Method assessment55
- 5.3. Results and discussion..... 57
- 5.4. Conclusions..... 61

5.1. Introduction

The benefits and drawbacks of multi-channel printing have been explained in Section 2.2.1. In this chapter and chapters 6 and 7 the research done by the author in development, implementation and verification of halftoning algorithms for multi-channel printing is presented.

Among the possibilities for halftoning algorithms, there is the choice of amplitude modulated (AM) and frequency modulated (FM) halftoning, discussed in Chapter 3. AM halftoning is preferred in some printing technologies like electrophotography (Goyal et al. 2011) or flexography (Gooran 2005), where the nature of the reproduction technology makes this halftoning algorithm reproduce the images in a more stable way and without artefacts (Goyal et al. 2011). The challenge of AM halftoning algorithms is, as discussed in Section 3.3.1, moiré appearance, dealt with by adjusting each channel in a specific angle, thus forming a rosette pattern. In this chapter the focus is on AM halftoning applied to multi-channel printing and facing the challenges of channel angle disposition, moiré appearance and colour shifts caused by misregistration.

Misregistration refers to an “off” registration or misalignment of one or more of the ink channels in relation to each other. Even if the channels are laid in the correct angles, incorrect registration may lead to moiré and colour shifts (Sharma 2002). Laying the colour channels at different angles demonstrates to exhibit very little colour shifts in case of misregistration, as shown in (Oztan, Sharma, and Loce 2005). The angle rotation strategy is to lay the channels so that each one is separated from the others as much as possible, while keeping high contrasting colours (with regards to white paper) at least 30° apart. In addition, one has to bear in mind the limitation of a round halftone screen, whose symmetrical shape allows a rotation of up to 90°, as is shown in Section 5.2. This 90° constraint is an obstacle for incorporating more than four channels using AM halftoning.

Previous work in this area was oriented towards adjusting the colour separations so that they fit in the 90° angle range. In the model presented in (Ostromoukhov 1993), which was applied to seven channels, the suggestion was to use a modified compound Neugebauer equation to adjust the channel on each screen vertex. By doing so, any odd ink number of channels is suppressed into a 3 layer system.

In (Balasubramanian and Eschbach 2001), the authors used the approach of colour replacement strategies to adjust four channels on low resolution printing devices, using both under colour removal (UCR) and grey component replacement (GCR). By doing so, they minimised the visible moiré effect, assuring the total gamut was not sacrificed.

In (Amidror, Hersch, and Ostromoukhov 2005), the moiré phenomenon was observed by using a Fourier-based spectral model. The authors determined that moiré appearance is related to the relative ink superposition angles, not the absolute ones, finding the optimum angle separation within four inks. Their results suggested to adjust the channels on a slightly off symmetry axis in order to break the moiré symmetrical microstructure.

In (Wang, Fan, and Wen 2003) the application of asymmetric, non-orthogonal screens was introduced as an aid to a moiré-free solution. By searching for a rational tangent angle, a non-orthogonal screen gives a wider choice, and can therefore provide a visually more pleasant solution.

This chapter is structured as follows. After this introduction, Section 5.2 explains the proposed method and the way the method assessment was carried out. Section 5.3 presents the results and discusses them, while Section 5.4 offers a conclusion.

The research presented in this chapter has been published in (Žitinski Elías, Nyström, and Gooran 2013).

5.2. Proposed method

In the conventional four colorant AM halftoning, the common practice is to lay black at 45° , magenta at 75° , cyan at 15° and yellow at $0^\circ/90^\circ$ (Figure 3.13). Because of the symmetrical halftone dot shape, the 0° angle is equivalent to a 90° one. The highest contrasting colour, black, is therefore laid at the furthest possible angle from the plane, 45° , at which the human eye is the least sensitive (Sullivan, Ray, and Miller 1991). The next two high contrast colours are magenta and cyan, which are laid apart from black by a 30° angle. The remaining channel, yellow, would optimally be separated by another 30° , which is not possible because of the symmetry of the round screen. Instead, it is shifted by 15° , which proved in practice to be sufficient to mask moiré due to the low contrast of yellow.

To increase the number of channels in AM halftoning, the challenge would be to find suitable angles for a moiré-free solution. One can only place the dots in the range of 90° because of the regular shape of the halftone dots.

The method proposed in this chapter uses non-orthogonal instead of orthogonal screen elements. By definition, “two (or more) intersecting curves that are perpendicular at their intersection are said to be orthogonal” (Weisstein, *accessed on*: 25/09/14). Orthogonal screen elements would thus be the halftone shapes based on perpendicular vectors, such as a circle or a square. Here, by orthogonal halftone, we mean a round halftone shape. Consequently, non-orthogonal curves are those that are not perpendicular at the intersection of their curves. The spatial representations of a halftone orthogonal (in this case, a rhombus) element and a halftone non-orthogonal (in this case, a parallelogram) element are shown in Figure 5.1. The non-orthogonal halftone shape used in this chapter is an elliptical one.

Figure 5.1: Spatial representation of an example of orthogonal (left) and non-orthogonal (right) halftone element.

Since elliptical halftone screens are symmetrical in only 2 quadrants, using this kind of halftone element allows the expansion of the available angle to 180° , which would give the possibility to allocate more than the standard 4 channels. Specifically, this allows the expansion to up to 8 channels. Figure 5.2 is a representation of orthogonal (round) screen and non-orthogonal (elliptical) screen elements at 0° , 90° , 45° and 135° rotations respectively. It can be clearly seen that for the channel with round screen elements (0° and 90°) and (45° and 135°) angles are equivalent, while for the elliptical screen elements, there exists a difference when rotating the halftoned patch.

Figure 5.2: Orthogonal (up) and non-orthogonal (down) screen elements for angles (left to right): 0° , 90° , 45° and 135° .

For this particular research, seven-channel printing was chosen, specifically, CMYKRGB, accommodating the channels into a 180° plane. The angles chosen were black at 45° and yellow at 0°, following the conventional CMYK angle disposition. The highest contrasting among the rest of the channels, i.e. blue, was 45° separated from black and placed at 90°. The remaining four colorants were placed by keeping them, whenever possible, 30° apart from the others. The result was to lay yellow at 0° yellow, cyan at 15°, black at 45°, green at 75°, blue at 90°, red at 105° and magenta at 135°. In order to compare the results with the regular orthogonal case, we chose to lay complementary colours in the same angle – 0° yellow and blue, 15° cyan and red, 45° black and 75° magenta and green, following the reasoning that, in a real printing scenario, two complimentary colours would never be printed on at the same spot, since in that case they would be replaced by the black ink (Kipphan 2001). Figure 5.3 shows a graphic of the channel angle setup chosen in an element plane based on their orthogonal and non-orthogonal screen shape.

Figure 5.3: Orthogonal (left) and non-orthogonal (right) angle setup chosen for CMYKRGB channels.

5.2.1. Method assessment

Once the angles for each channel have been chosen for the CMYKRGB channels, the correctness of this method was verified. In order to do so it is necessary to overlay the channels using the

aforementioned proposed angle disposition and making sure that no visible moiré occurs.

Apart from masking visible moiré, an ideal angle setup should prove to be robust in case of misregistration (Oztan, Sharma, and Loce 2005), since it has been noticed that changes in registration can lead to significant colour shifts (Sharma 2002). This is why, in this assessment, the possibility of misregistration was also considered. In case of misregistration the inevitable colour shift should be very small and ideally no moiré should be visible.

In order to mimic misregistration, the following workflow was performed. From a set of patches and ramps that were used for visual assessment, 20 patches were selected with arbitrary CMYKRGB values, having 5-45% coverage for each channel. The patches were then halftoned at 300 dpi and 20 lpi. Choosing a low lpi value was made in order to better visually observe any moiré pattern appearance. Each patch has been halftoned using AM halftoning with orthogonal and non-orthogonal screens using the proposed angles.

To evaluate the results, both simulations using spectral data and actual prints were made. A total of $2^7 = 128$ patches composed of Neugebauer primaries were printed in the seven-channel Canon iPF5100 multi-colorant inkjet printer. The results were measured by CIE 2° standard observer with D65 illuminant and used to compute sRGB values to visualise the results and CIELAB values for colorimetric computations. All computations were performed using the CIE 1976 colour difference ΔE_{ab} . To simulate misregistration, one to three of the 7 digital bitmaps were slightly translated or rotated in relation to the others. The mismatch was shifted up to half the size of the halftone screen. For each patch, the results of 40 different variations of misregistration were computed, leading to a total of 800 different scenarios for orthogonal and 800 for non-orthogonal screens.

Lastly, in order to identify moiré appearance on actual prints, AM halftoned patches with orthogonal and non-orthogonal screen elements with the proposed angles were created and printed using the

inkjet printer HP Z300. The patches were created with different coverage values of CMYRGB channels. The black ink was in this case omitted in order to avoid displaying the highest contrast colour that would then possibly conceal the other colour channels.

5.3. Results and discussion

Seven-channel patches were created with randomly chosen CMYKRGB values ranging between 5% and 45% coverage value for each channel. The patches were AM halftoned for each of the seven channels independently with 300 dpi and 20 lpi, using both orthogonal (round) and non-orthogonal (elliptical) screens.

On the orthogonal screens the angle range was 0° to 90° , while the non-orthogonal ones left space for a 0° to 180° range. Examples of non-orthogonal halftoning screens for some channels can be seen in Figure 5.4. One can observe the different channel rotation: on the left 0° for the yellow channel, in the middle 90° for blue and on the right 135° for magenta.

Figure 5.4: Non-orthogonal screen shape and rotation for: (left) yellow 30% screen value, (middle) blue 25% screen value, (right) magenta 25% screen value.

Each patch was halftoned independently shifting the angles according to the proposed angle disposition described in Section 5.2. After halftoning them independently by AM halftoning, the channels were merged to a seven-channel image. A detail of simulated patch

displayed with sRGB values is shown in Figure 5.5, composed of 10% cyan, 10% magenta, 15% yellow, 10% black, 20% blue, 25% green and 20% red. It was also observed that no moiré effect appeared on the samples.

Figure 5.5: Detail of a simulated non-orthogonal seven-channel halftoned image.

The next step was to investigate what happens in case of misregistration by measuring the colour shift result and checking for moiré appearance. To simulate misregistration, each of the 20 orthogonal and 20 non-orthogonal halftone patches were run in a code in which the digital bitmaps were slightly translated or rotated in relation to the others. All simulated misregistration scenarios were made for one to three channels out of the seven channels at a time. In one of the scenarios one to three channels were rotated by a 4° or by an 8° angle, while the translation changes were set for a 4 pixel shift. For each patch, a total of 40 different alterations were simulated. For each alteration, ΔE_{ab} between the altered and the original patch was computed.

Figure 5.6 displays the resulting colour shift in case of misregistration, calculated as the mean ΔE_{ab} between the original and the 40 variations of misregistration for each patch.

Figure 5.6: Results of the mean ΔE values for orthogonal (light grey) and non-orthogonal (dark grey) screens.

It is clearly shown that almost all of the 20 patches show lower ΔE_{ab} values for non-orthogonal screens than for orthogonal ones, proving that the non-orthogonal screens are more robust to colour shifts in case of misregistration. The mean ΔE_{ab} values of the misregistered 800 orthogonal and 800 non-orthogonal halftone screens are 2.67 and 1.98, respectively.

Apart from colour differences, the misregistered patches were also observed in search for possible moiré. For each patch, the twenty biggest colour differences between the correct and incorrect registration were calculated. That led to a total of 20 non-orthogonal and 20 orthogonal images, which were then observed in search for moiré.

The orthogonal and non-orthogonal halftoned patches showed a regular rosette pattern with no visible moiré even in case of some misregistration. Figure 5.7 shows a ramp ranging from 0 to 30% colorant coverage for each channel, halftoned using non-orthogonal

screens. The Figure 5.7 also shows a simulation of misregistration by rotating the magenta channel by 8° . Apart from no moiré appearance, one can verify that there is not significant colour change in case of some misregistration.

Figure 5.7: Non-orthogonal AM halftoning with our proposed angle setup: (top) without misregistration, (bottom) with 8° magenta misregistration.

The results can be explained by the mere nature of the non-orthogonal screens. Since the available angle for the channels is doubled in comparison with orthogonal screens, it is logical that the halftoned results are less susceptible to rotation and translation. Moreover, a certain rotation degree or a certain pixel number translation over a 180° range is more likely to pass unperceived when comparing it to the 90° range. This makes non-orthogonal AM halftoning a solid solution in case of misregistration.

In order to evaluate the proposed model in a real print, AM halftoned patches with orthogonal and non-orthogonal screen elements using six-channel CMYRGB printing were created and printed at 1200 dpi at 120 and 150 lpi. The printed patches were then scanned using the scanner Konica Minolta bizhub C284 PS at 600 ppi (pixels per inch). Some of the results are displayed in Figure 5.8.

As seen in Figure 5.8, the patches produce moiré artefacts when printed with orthogonal (round) screen elements. Nevertheless, when

that exact colorant combination was printed using non-orthogonal (elliptical) elements, the moiré effect was significantly reduced.

Figure 5.8: Orthogonal and non-orthogonal printed and scanned patches of two different colorant combinations at 120 lpi and 150 lpi.

In addition, a colour difference between the patches can be clearly observed in Figure 5.8. The first reason for the colour difference is that the patches were halftoned using different angle setups, making it logical that their hue values also vary. Furthermore, scanning the printed samples means a computation done by the scanner's software of the colorimetric values from CMYK to RGB space that alters the hue. In addition, printing this thesis uses a different printer system that may also cause colour variations.

5.4. Conclusions

In this chapter, a non-orthogonal AM halftoning angle setup suitable for seven-channel printing was proposed. By using non-orthogonal elliptical halftone screens, the available angle range is doubled compared to orthogonal round screens, leaving the necessary space to separate all channels, except the low-contrast yellow, by a 30° angle. Both the simulated and the printed results indicated that the non-

orthogonal screens produced a moiré free impression. Furthermore, they proved to be less sensitive to misregistration, giving smaller colour shifts compared to orthogonal multi-channel screening technique.

Although the non-orthogonal halftone screen shape proves to be more robust in terms of moiré and colour shifts, this proposed method does not offer a solution for controlling the ink layer overlap in multi-channel printing. Therefore, in the following chapters the focus is shifted from AM to FM halftoning, where the research done in FM algorithm implementation for multi-channel printing controlling the ink overlap is presented.

6. Multilevel halftoning applied to multi-channel printing for achromatic inks

6.1. Introduction	65
6.2. Multilevel FM halftoning algorithm.....	66
6.3. Methodology.....	69
6.3.1. Experimental setup.....	69
6.3.2. Locating thresholds between inks.....	70
6.3.3. Dot gain compensation	70
6.4. Results and discussion.....	71
6.4.1. Thresholds between inks	71
6.4.2. Dot gain compensation	74
6.4.3. Implementation assessment	79
6.4.3.1. Smoothness.....	79
6.4.3.2. Graininess.....	81
6.5. Conclusions.....	84

6.1. Introduction

In Chapter 5 an adaptation of the AM halftoning method was presented as a way of applying this halftoning algorithm to multi-channel printing. Nevertheless, as discussed in Section 2.2.1, too big ink overlap causes undesired consequences, and this algorithm does not account for ink thickness. In this chapter, multi-channel printing is accomplished by taking into consideration ink overlap.

In Section 3.2.6.1 the multilevel FM halftoning algorithm proposed in (Gooran 2006) was discussed, where an image is separated into different lightness regions, halftoned, resulting in a bi-level result in each region, and then merged into a multilevel halftoned image.

As discussed in Section 3.2.6.1, this multilevel halftoning algorithm has the potential to be applied to multi-channel printing using lighter versions of the conventional inks (light cyan, light magenta, light grey and grey).

This chapter deals with the implementation of the proposed multilevel FM halftoning using three achromatic inks – photo grey (PGY), grey (GY) and black (K). Creating a single channel that will be printed with three different inks proves to be challenging for dot gain compensation, as each ink has a different dot gain curve (Section 4.2). In order to perform a successful dot gain compensation, it is necessary to express the dot gain of the three inks in terms of nominal area coverage of a single, black, ink. In order to do that, correct ink limits for colorant separation must be determined, dependent on the combination of inks, substrate, halftoning algorithm and printing resolution.

This chapter is structured as follows. After this introduction, Section 6.2 explains the halftoning algorithm used in (Gooran 2006). Section 6.3, Methodology, describes the experimental setup, how the ink limits for colorant separation are located and how dot gain is compensated. In Section 6.4, Results and discussion, the results of the dot gain compensation are shown. Results of the graininess

calculations are also discussed. Finally, a conclusion is given in Section 6.5.

The research done in this chapter has been published in (Žitinski Elías, Gooran, and Nyström 2014).

6.2. Multilevel FM halftoning algorithm

When the term multilevel halftoning is used in this chapter, it will refer to the particular multilevel halftoning algorithm introduced in (Gooran 2006).

The multilevel halftoning algorithm separates the image into different regions according to lightness values and bi-level halftones each region by itself. Therefore, with this technique, it is possible to assign each lightness region to be printed with each ink. This means that the achromatic inks can be printed together with no ink overlap between them.

To illustrate how the algorithm operates on an image, a grey-scale ramp was created and halftoned by this method. To better show the way halftoning is applied, the ramp was halftoned in low resolution so that the halftone dots are clearly visible. As seen in Figure 6.1, this multilevel FM halftoning workflow can be divided in three steps, called pre-processing, bi-level halftoning and post-processing.

The first, pre-processing step, is where the original image gets divided into regions according to lightness values at each position (i, j) of the image.

Figure 6.1: Multilevel FM halftoning workflow.

Two things to consider are the number of regions the image will be divided into and the lightness value limits (thresholds) where one region ends and another one begins. The number of regions is dependent on the number of inks of the same hue values one will print with. For instance, if three inks are used, three lightness regions would exist. As for the lightness thresholds where one ink stops and another one begins, those can be located by measuring the CIEY (correlated with lightness) values of the inks. One needs to measure the lowest CIEY value the lighter inks produce, which logically corresponds to 100% ink coverage. Now one needs to observe the CIEY values of the darkest ink, because all the values are expressed in correspondence to that one. The threshold is the coverage value of the darkest ink at which its CIEY value matches the CIEY value of the lighter ink at fulltone. As an example, assume that the lightest ink at 100% coverage value has the measured CIEY 22. When taking a look at the measured CIEY values of the darkest ink, assume that $\text{CIEY} = 22$ is found at 33% ink coverage. Thus, 33% is the threshold where the lightest ink stops and the next one continues. Following the example of the existence of a third ink, let us say the CIEY value of 100% ink coverage of the medium ink measures to be 16. $\text{CIEY} = 16$ of the darkest ink is found at 66% coverage, thus 66% is the other located threshold.

Locating the thresholds means that the regions between them will be printed with each ink, ranging from 0 to 100% ink coverage in each region. In the lightest region, i.e. region 1, the lightest ink is used. In region 2, i.e. between [0.33, 0.66], the lightest and the medium dark inks are used, and finally, in region 3, the medium dark and the darkest inks are used.

The algorithm in the pre-processing step prepares the three regions by assigning them values between [0, 1] to be bi-level halftoned. Starting with region 1, its values are normalized/scaled between [0, 1], region 2 between [1, 0] and region 3 between [0, 1]. The reasoning why region 2 shifts its values is to avoid neighbouring opposite interval limits. If it would be the case that region 1 (between [0, 0.33]) and region 2 (between [0.33, 0.66]) would both have

assigned values between $[0, 1]$, it would be creating a jump from 1 to 0 around the threshold 0.33, which would create a discontinuation around these values (Figure 6.1). Nevertheless, if the interval limit where the regions meet is the same (in this case 1), this problem is easily solved.

The next step of the multilevel FM halftoning algorithm is the halftoning itself. Since each region has been scaled between $[0, 1]$, any bi-level halftoning algorithm can be applied to the pre-processed image (Figure 6.1).

In the final, post-processing step, a bitmap with three halftoned regions exists. According to the region each pixel belongs to, the algorithm now replaces the 0s and 1s by the corresponding threshold values. For instance, in the region between $[0, 0.33]$, the 0s stay 0s and 1s become 0.33. In the region corresponding to $[0.33, 0.66]$, 1s are replaced by 0.33 and 0s by 0.66 and in the region corresponding to $[0.66, 1]$, 0s are replaced by 0.66 and 1s remain 1s. The result is a multilevel halftoned image holding at each pixel 0, 0.33, 0.66 or 1, meaning no ink, lightest, darker or the darkest ink will be applied at that pixel location.

6.3. Methodology

This section deals with the implementation of multilevel halftoning as part of a setup for multi-channel inkjet printing. For the purpose of this study the focus is on achromatic inks, i.e. in this case photo grey (PGY), grey (GY) and black (K), aiming for a multilevel halftoning with three different levels, spanning from no ink to fulltone black.

6.3.1. Experimental setup

The implementation challenges lie in determining the correct threshold levels used for colorant separation and in compensating for dot gain for three different inks. These thresholds are dependent on

the ink combination, type of substrate, halftoning method and print resolution. In order to find proper thresholds for our setup, patches with 0 to 100% nominal ink coverages, in steps of 1%, were printed for all three inks. All prints were made using an inkjet 12-channel printer Canon imagePROGRAF iPF6450. All samples were printed on 90 g/m² uncoated office paper and on 170 g/m² matte coated paper at a resolution of 600 dpi. Nevertheless, the same workflow can be applied to other media substrates and other printing resolutions. CIE XYZ values and spectral data of the printed patches were measured using the spectrophotometer BARBIERI electronic Spectro LFP RT, light source D50 with 2° standard observer. The measured spectral data contained 41 reflectance values at wavelengths ranging from 380 nm to 780 nm by 10 nm steps.

6.3.2. Locating thresholds between inks

Since achromatic inks vary in lightness, measured CIEY values were used to find the thresholds between the inks. As explained in Section 6.2, the thresholds are the ink coverage values at which the CIEY value of the black ink matches the CIEY value at 100% ink coverage of the lighter inks, photo grey and grey. The results and a more elaborate explanation are presented in Section 6.4.1.

6.3.3. Dot gain compensation

Paper-ink-light interaction causes dot gain with ink areas appearing larger once printed. As mentioned in Section 4.2, dot gain is a consequence of multiple factors, one of them being the ink used. In order to compensate for dot gain so that the final result (effective ink coverage) has the intended tone value, the nominal ink coverage for each channel sent to the printer has to be adjusted prior to halftoning and printing. Nevertheless, in multilevel halftoning, each channel is printed using multiple inks, each with different dot gain curves. This is the reason that dot gain compensation for all the inks must be

expressed in terms of nominal tone coverage of as single ink, black. The following methodology was performed.

The calculated thresholds were applied in order to multilevel halftone the patches from 0 to 100% ink coverages in steps of 1%. The bi-level halftoning algorithm was IMCDP. Afterwards the patches were printed using all three inks simultaneously on the two paper substrates at 600 dpi. The resulting CIEY values of the printed patches allowed us to adjust the initial image for dot gain compensation using Murray-Davies formula. After printing, measurements were conducted to verify whether successful dot gain compensation has been accomplished.

Results are presented in Section 6.4.2.

6.4. Results and discussion

Implementation of the multilevel halftoning algorithm comprehends, as explained, locating thresholds between inks and dot gain compensation. The results are categorized and presented in this section. In addition, evaluation of the multilevel halftoning algorithm implementation was carried out in terms of smoothness (around the thresholds) in search for banding or other artefacts and graininess.

6.4.1. Thresholds between inks

Figures 6.2 and 6.3 show the CIEY values of the three inks – PGY, GY and K, plotted against their nominal ink coverages, for the uncoated 90 g/m² paper and 170 g/m² matte coated paper. The thresholds between the regions (marked with T1 and T2) are also shown.

Figure 6.2: CIEY values PGY, GY and K and the thresholds T1 and T2 for uncoated 90 g/m² paper.

Figure 6.3: CIEY values PGY, GY and K and the thresholds T1 and T2 for matte coated 170 g/m² paper.

For the example of the uncoated paper in Figure 6.2, the CIEY value of fulltone GY matches the CIEY value of 38% K, while the CIEY value of fulltone PGY corresponds to the CIEY value of 28% K. Thus for this setup one can conclude that the limits between the regions should be set at 28% and 38% black ink coverage. Region 1 would correspond to the light tones up to 28%, so $[0, 0.28]$ should be printed with the lightest, PGY ink; region 2 with values from 28% to 38% black ink coverage, i.e. $[0.28, 0.38]$, should be printed with PGY and GY inks with no ink overlap, and region 3, between $[0.38, 1]$, with GY and K. At each of these intervals ($[0, 0.28]$, $[0.28, 0.38]$, $[0.38, 1]$) the specific ink used spans from 0 to 100% ink coverage.

Accordingly, the thresholds for the coated paper were found at 42.5% and 62.5% black ink coverage (Figure 6.3).

It is worth discussing that, as an alternative method, spectral values can also be used to find the thresholds between inks by using the ΔRMS (root mean square difference), according to Equation 6.1:

$$\Delta RMS = \sqrt{\frac{1}{N} \sum_{\lambda=l}^u (R_1(\lambda) - R_2(\lambda))^2} \quad (6.1)$$

where λ is the wavelength, l and u are the lower and upper limits of the wavelength (380 and 780 nm), N is the number of wavelength samples used, i.e. 41, and $R_1(\lambda)$ and $R_2(\lambda)$ are the spectral reflectance of the two patches compared.

For the matte coated 170 g/m² paper the smallest $\Delta RMS = 0.0217$ was found between 39% K coverage and 100% PGY coverage. The smallest $\Delta RMS = 0.0115$ was found between 59% K coverage and 100% GY coverage, indicating that those would be the thresholds calculated by spectral values. These reflectance spectra are shown in Figure 6.4.

In theory, PGY, GY and K inks should not display spectral variations and should reflect all the wavelengths equally. Nevertheless, the ΔRMS difference calculated and the plotted spectral values show that the PGY and GY inks might have different colorimetric values when

Figure 6.4: Spectral reflectance values of PGY, GY and K inks at coverage values corresponding to the thresholds found by Δ RMS calculations, for matte coated 170 g/m² paper.

compared to the K halftones. This issue will be part of the future work investigation.

6.4.2. Dot gain compensation

The dot gain curves for the three inks were plotted against their own nominal ink coverage values using the Murray-Davies formula (Section 4.3.1) and shown in Figures 6.5 and 6.6. The calculated thresholds were used to multilevel halftone the patches, print them on the two different papers and measure them. The dot gain curve of the multilevel halftoned PGY+GY+K channel for the two papers was also plotted and displayed Figures 6.5 and 6.6.

Figure 6.5: Dot gain curves for three inks individually, in reference to their own nominal values, and combined, in reference to black, in multilevel halftoning for uncoated 90 g/m² paper.

Figure 6.6: Dot gain curves for three inks individually, in reference to their own nominal values, and combined, in reference to black, in multilevel halftoning for matte coated 170 g/m² paper.

It can be seen in Figures 6.5 and 6.6 that the dot gain curves vary from ink to ink and from paper to paper. Each ink has a unique dot gain curve, but it is the three ink combination measurement values that need to be used in order to perform dot gain compensation for multi-channel printing using all three inks.

In Figures 6.7 and 6.8 the effective versus nominal area coverages are displayed for the three inks in reference to their nominal values. In addition, the effective area coverages of the multilevel halftoned patches are displayed, in reference to black ink. This is shown for both uncoated 90 g/m² office paper and 170 g/m² matte coated paper.

It can again be observed that the effective coverages are different for the patches printed with each ink and for the multilevel halftoned patches printed with three inks.

In order to verify the correctness of the dot gain compensation the CIEY values of the compensated patches were measured. Using Murray-Davies formula (Section 4.3.1) the effective area coverages were calculated. If the effective area coverage values are plotted against the nominal area coverage values, the assumption is that they will be the same, thus showing a linear response in the plot. The results are shown in Figures 6.9 and 6.10 for both papers.

As can be seen in Figures 6.9 and 6.10, the plot of the effective area coverage versus the nominal area coverage is a straight line for both papers, proving a successful dot gain compensation in our workflow. It can also be seen that there is no unordinary fluctuation around the thresholds (around 0.28 and 0.38 area coverage for the uncoated and around 0.425 and 0.625 for the coated paper), which proves smoothness between the ink limits.

Figure 6.7: Effective vs. nominal area coverages for three inks individually, in reference to their own nominal values, and combined, in reference to black, in multilevel halftoning for uncoated paper.

Figure 6.8: Effective vs. nominal area coverages for three inks individually, in reference to their own nominal values, and combined, in reference to black, in multilevel halftoning for matte coated paper.

Figure 6.9: Effective versus nominal area coverages for the combination of three inks in reference to black in multilevel halftoning, compensated for linear dot gain response, for uncoated 90 g/m^2 paper.

Figure 6.10: Effective versus nominal area coverages for the combination of three inks in reference to black in multilevel halftoning, compensated for linear dot gain response, for matte coated 170 g/m^2 paper.

6.4.3. Implementation assessment

Once the implementation has been carried out, the multilevel halftoning algorithm implemented for achromatic inks was assessed in terms of two parameters. Firstly, although the correct thresholds between the inks have been located, smoothness was verified around those thresholds, as it is important that the halftoning algorithm does not demonstrate artefacts around the thresholds. Secondly, since using three different inks should improve the results in terms of visual pleasantness, graininess between patches was calculated and compared.

6.4.3.1. Smoothness

Multilevel halftoning makes the transitions between inks very smooth, which was verified by applying this algorithm with thresholds at 42.5% and 62.5% to a digital grey ramp from 0 to 100% coverage, shown in Figure 6.11. Parts of the halftoned digital image, marked with numbers 1 and 2 in Figure 6.11, are enlarged 5 times and displayed in Figures 6.12 and 6.13.

Figure 6.11: Multilevel halftoned ramp for three achromatic inks.

The halftoned digital grey map in Figure 6.11 was printed at 600 dpi and the result showed the same smoothness, even around the ink thresholds. The printed image was however not scanned and

displayed here to not introduce any non-linearities or artefacts caused by the scanner.

Figure 6.12: Part 1 of the multilevel halftoned ramp around the first threshold (transition between paper-PGY and PGY-GY inks).

Figure 6.13: Part 2 of the multilevel halftoned ramp around the second threshold (transition between PGY-GY and GY-K inks).

Figures 6.12 and 6.13 show details of the digital ramp, marked as 1 and 2 in Figure 6.11, around the two ink thresholds, magnified 5 times. These enlarged parts of the ramp show the transitions from paper-PGY to PGY-GY and from PGY-GY to GY-K. One can observe in the figures the smoothness of the transitions between the inks, enlarged 5 times.

One should nevertheless keep in mind that, in order for the grey ramp to appear smooth in the printed dissertation, dot gain compensation must be performed for the specific ink and paper used. Since this information is not available, note that the ramp may not appear smooth in a printed manuscript.

6.4.3.2. Graininess

It has already been mentioned that using three achromatic inks (PGY, GY, K) instead of only one (K) gives the advantage of a less grainy result and therefore a visually more pleasant image. In order to illustrate this, a 10% black ink coverage patch was digitally created and halftoned in two different ways – once using only one, black, ink and bi-level halftoning it with IMCDP and the second time using three inks and multilevel halftoning the patch with IMCDP (Figure 6.14).

Note that the patches of Figure 6.14 are digital representations, not printed result. Therefore, it is likely that on the printed image the overall impression of the halftoned patches differ due to dot gain. Since different inks have different dot gain value, the printed images will most likely appear visually different, since this image has not been compensated for dot gain for any paper-ink setup.

Although both halftoned images have the same mean value of 10% black ink coverage on the digital representation, it can easily be seen that the multilevel halftoned patch (down) shows a less grainy result. This is because while bi-level halftone algorithm defaults to halftone using a single colorant (in this case K), the multilevel halftone algorithm halftones under the assumption of using multiple

Figure 6.14: 10% black ink coverage patch bi-level halftoned (up) and multilevel halftoned (down).

colorants. For this example, the used setup was three inks and the ink limits found for coated paper, in which 10% black ink coverage corresponds to $10\% \cdot 1/0.425 = 23.5\%$ PGY ink coverage (Figure 6.3). The multilevel halftone algorithm then makes use of the PGY ink, with lighter tone than K, and halftones the dots in a denser configuration. Both of these factors account for the fact of a less grainy result, which was also verified by calculating the standard deviation. The standard deviation for the pixel values in the patch bi-level halftoned with IMCDP was 0.3023, while for those of the multilevel halftoning was smaller and equals 0.1815.

Similarly, standard deviation was calculated for digitally produced patches ranging from 0 to 100% black tone value, bi-level halftoned (with IMCDP) and halftoned with the multilevel algorithm using the thresholds found for the coated paper (0.425 and 0.625). Figure 6.15 shows the results.

Figure 6.15: Standard deviation of pixel values of the patches.

It can be seen that the curve indicating the standard deviation of the patches halftoned with the bi-level algorithm is always above the curve of the standard deviation of the multilevel halftoned patches, which proves a less grainy result in the latter case. It can also be observed that the standard deviation of the bi-level halftoned patches display a curve with a single maximum at 50%, while the standard deviation of the multilevel halftoned patches display a curve with three maxima, at 21%, 52% and 81% black tone coverage. The number of inks used in the halftoning algorithm easily explains the number of maxima. The bi-level halftoned patches make use of a single ink. As the tone value increases, the number of halftone dots becomes larger, resulting in higher standard deviation values. The standard deviation peaks at 50%, where the white paper – black halftone dots ratio is equal, making it the noisiest patch. From that point on the standard deviation decreases as the number of halftone dots keeps getting larger and the noise level smaller, reaching 0 at fulltone black.

In the case of the multilevel halftoned patches, the number of maxima again corresponds to the number of inks used. The standard deviation of each of the three inks has its peak at the point of 50%

tone coverage of that ink and 0 value at 100%. For instance, the standard deviation of the PGY ink reaches its maximum at 50% tone coverage of the PGY ink, which corresponds to 21% tone coverage of the K ink.

A detail of a digital image was halftoned with the bi-level IMCDP and with the multilevel algorithm using the thresholds at 42.5% and 62.5% (Figure 6.16). It is visible not only that the upper (bi-level halftoned) image displays more graininess than the lower (multilevel halftoned) one, but also that the latter one adds to the level of detail. This higher level of detail can be easily explained by the nature of the multilevel algorithm. Since multiple inks, each ranging from 0 to 100% ink coverage, are used to reproduce the image channel, it is obvious that such an image will have a higher detail reproduction than the one being reproduced with only one ink.

6.5. Conclusions

A multilevel halftoning approach introduced in (Gooran 2006) has been implemented in a multi-channel printing setup. The implementation has been done using three different achromatic inks – grey, photo grey and black. Challenges include determining the threshold between each of the ink pairs and achieving a linear dot gain compensation response. Dot gain is ink-specific and therefore it is necessary to calculate a joined dot gain for three different inks in relation to one. Once the initial image has been compensated for a linear dot gain response, the multilevel halftoning algorithm was again applied to the patches, which were then printed and measured. Results of the effective versus nominal area coverage shown in Figures 6.9 and 6.10 verify that the multilevel halftoning workflow for the printer, inks and substrates used was successfully controlled and can be applied to other frameworks. This means a setup in which multiple inks are used without an ink layer overlap (dot-off-dot impression). In addition, the overall image quality is improved in

terms of graininess (verified by measuring the graininess by means of standard deviation) and detail enhancement.

Figure 6.16: Image detail: (up) bi-level halftoned, (down) multilevel halftoned.

Since the research presented in this chapter proves a successful implementation of the multilevel halftoning algorithm to achromatic inks, the next logical step is to apply the algorithm to chromatic inks as well. This, however, imposes new challenges, presented in the next chapter.

7. Multilevel halftoning applied to multi-channel printing for chromatic inks

7.1. Introduction	89
7.2. Methodology.....	90
7.2.1. Materials and devices	90
7.2.2. Dot gain	91
7.2.2.1. Locating thresholds.....	91
7.2.2.2. Dot gain compensation	92
7.2.3. Evaluation of the multilevel halftoning algorithm..	92
7.2.3.1. Colour accuracy.....	93
7.2.3.2. Graininess.....	95
7.3. Results and discussion.....	95
7.3.1. Thresholds between inks	95
7.3.2. Dot gain	97
7.3.3. Colour accuracy.....	99
7.3.4. Graininess	101
7.4. Conclusions.....	103

7.1. Introduction

In Chapter 6, a multilevel halftoning algorithm proposed in (Gooran 2006) was suggested as a way of dealing with ink thickness control in multi-channel printing. Instead of the traditional colorant separation, where each channel is halftoned and then printed with a single ink, in multilevel halftoning a channel can be halftoned in a way that is printed using multiple inks of same hue values. Using this strategy ensures that no ink overlap between multiple inks would occur. This presents a possible solution to ink thickness control problems in multi-channel printing.

The research presented in Chapter 6 deals with the implementation of multilevel halftoning method to achromatic inks. The achromatic inks photo grey (PGY), grey (GY) and black (K) were chosen for this purpose. The two challenges faced were locating the ink limits (i.e. finding the thresholds between the inks) and dot gain compensation of a channel in which multiple inks were used, but expressed in terms of a single ink.

The logical continuation is an extension of multilevel halftoning to chromatic inks, with the goal of printing with eight inks: cyan, light cyan, magenta, light magenta, yellow, photo grey, grey and black. Those inks, divided into channels according to their hue values, yield four different channels (C+lc, M+lm, Y, PGY+GY+K), where the Y channel would simply be bi-level halftoned, and the rest multilevel halftoned.

Nevertheless, multilevel halftoning implementation for (C+lc) and (M+lm) channels imposes a workflow specific for chromatic inks, different from the one presented in Chapter 6. This chapter presents a workflow to control the dot gain response for chromatic inks. The proposed multilevel halftoning method, avoiding ink overlap, and halftoning algorithms, with random ink overlap, usually reproduce different colours, despite using the same ink coverage for each colorant (Gooran 2008). Therefore, a verification of colour

reproducibility is carried out by a comparison between the two printing strategies.

This chapter is organized as follows. In Section 7.2, a description of the methods and algorithms used is given, including the methods for dot gain control and evaluation of the multilevel halftoning algorithm. In Section 7.3 the results are presented and discussed. Section 7.4 gives a conclusion.

7.2. Methodology

In order to implement multilevel halftoning to a multi-channel setup, a complete control over dot gain must be achieved for the printed result to reproduce the intended effective ink coverages.

Once this is done, an assessment of the multilevel halftoning algorithm must be performed by comparing it to a halftoning algorithm with random dot overlap in terms of colour accuracy and graininess.

7.2.1. Materials and devices

For the purpose of this study, a 12-channel inkjet printer Canon imagePROGRAF iPF6450 was used. All samples were printed on 170 g/m² matte coated paper at a 600 dpi resolution. The samples were measured with the spectrophotometer BARBIERI electronic Spectro LFP RT, light source D50 with 2° standard observer. The measured spectral data contained 41 reflectance values at wavelengths ranging from 380 nm to 780 nm by 10 nm steps.

The samples were printed using four inks: cyan (C), light cyan (lc), magenta (M) and light magenta (lm), which for the purpose of the multilevel algorithm have been divided into two channels based on their hue levels, i.e. (C+lc) and (M+lm).

7.2.2. Dot gain

In order to successfully implement any halftoning algorithm, the dot gain of the specific ink and paper setup must be taken into account so that the effective ink coverage values are the ones intended.

In the case of bi-level halftoning, dot gain is adjusted by measuring printed patches and applying the Murray-Davies formula for dot gain compensation.

In multilevel halftoning, a channel is printed using multiple inks. For example, a (C+lc) channel is printed using light cyan and cyan with no ink overlap. Since each ink produces different dot gain values for different ink coverages, applying the correct nominal coverages to a channel printed with multiple inks requires a certain workflow. This workflow has been explained in Chapter 6 for achromatic inks (PGY+GY+K channel), and is here adapted for chromatic inks, i.e. for the (C+lc) and (M+lm) channels.

7.2.2.1. Locating thresholds

The first step of the dot gain compensation workflow is to locate the correct thresholds between the inks. The threshold is, like for achromatic inks, the coverage value at which 100% of the lightest ink in the channel has the closest match to the value of the darker ink.

To locate the thresholds, patches from 0 to 100% ink coverage with steps of 1% were halftoned using the IMCDP algorithm (Section 3.2.5.1.) and printed for C, lc, M and lm. They were measured with the spectrophotometer to find the CIE LAB and spectral values of each patch.

In the case of achromatic inks, the correct thresholds between inks were located by using the inks' CIEY values (Section 6.3.2.). In case of the channels that will be printed with chromatic inks, CIE LAB values were used to calculate the ΔE_{94} colour difference (using $K_1 = 0.045$ and $K_2 = 0.015$), as defined in Section 2.1.3.3, and

spectral values to calculate the ΔRMS . The nominal area coverage at which the darkest ink (cyan/magenta) has the smallest $\Delta E_{94} / \Delta RMS$ difference to the 100% coverage of the lightest ink (light cyan/light magenta) determines the threshold. This will be further discussed in Section 7.3.1.

7.2.2.2. Dot gain compensation

After the thresholds between inks have been located, in the next step of the workflow dot gain is compensated for each channel using the Murray-Davies formula.

For this purpose patches from 0 to 100% coverage were created using the multilevel algorithm, creating two channels: (C+lc) channel and (M+lm) channel. They were printed separately and measured to locate their CIE XYZ values. Using the Murray-Davies formula, the CIE X values for the (C+lc) channel and the CIE Y values for the (M+lm) channels were applied to compensate for dot gain. As explained in (Gooran, Namedanian, and Hedman 2009), since cyan is most absorbent in the longer wavelength interval, using the CIE X values is the most suitable choice for the cyan ink, and correspondingly, CIE Y is for magenta.

The result of the dot gain compensation is presented in Section 7.3.2.

7.2.3. Evaluation of the multilevel halftoning algorithm

Two aspects need to be verified in order to assess whether this halftoning algorithm performs satisfactory. Firstly, this strategy using multilevel halftoning and thus avoiding ink overlap needs to be checked versus the strategy using random ink overlap to examine whether the same colours can be reproduced. Secondly, a halftoning algorithm must not appear visually unpleasant in terms of graininess and smoothness of the tonal value transitions.

7.2.3.1. Colour accuracy

Colour accuracy assessment was carried out to verify whether the multilevel halftoning algorithm could reproduce the same range of colours as a halftoning algorithm with random ink overlap would. One must bear in mind that multilevel halftoning results in no ink overlap, which gives a different impression than an independently halftoned image (Gooran, Namedanian, and Hedman 2009). For this purpose, independently halftoned patches of the four colour channels (C, lc, M, lm) were created and compared with the multilevel halftoned colour channels (C+lc), (M+lm).

For the case of independent halftoning, the patches created were made in 5% steps from 0 to 100% coverage for each colour channel (C, lc, M, lm) and bi-level halftoned independently. These four channels were then combined and printed in three different combinations: C and lc, M and lm, C and M (Figure 7.1). Each of these printed samples thus contained 441 combinations of the channels' coverages in 5% steps, ranging from 0 to 100% coverage values.

Next, the same created 5% step patches were halftoned by multilevel algorithm, which resulted in three samples: one printed using only the (C+lc) channel, one with (M+lm), and one with the two channels: (C+lc) and (M+lm), as shown in Figure 7.2.

All the printed samples were then measured with the spectrophotometer to find their CIE LAB values. For each independently halftoned patch, the multilevel halftoned patch with the smallest ΔE_{94} between them was found. The goal was to find the mean and maximum ΔE_{94} in order to assess whether the colours reproduced with independent halftoning could be reproduced with multilevel halftoning as well.

The results are presented in Section 7.3.3.

Figure 7.1: Channel combinations for independent halftoning from 0 to 100% coverage values in steps of 5%.

Figure 7.2: Channel combinations for multilevel halftoning: a) $(C+lc)$ channel, b) $(M+lm)$ channel, c) $(C+lc)$ and $(M+lm)$ channels, all from 0 to 100% coverage values in steps of 5%.

7.2.3.2. Graininess

Another desirable characteristic of a halftoning algorithm is that it is visually pleasant. One of the halftone quality criteria is its graininess. The larger the graininess, the more the halftoning dots are visible to the eye, the more visually unpleasant is the image.

The bitmaps created for assessing the colour accuracy in Section 7.2.3.1 were used to quantify graininess. The results are presented in Section 7.3.4.

7.3. Results and discussion

The results of this workflow implementation are presented in this section.

7.3.1. Thresholds between inks

The thresholds between cyan and light cyan and magenta and light magenta inks were found by looking at the ΔE_{94} and spectral ΔRMS between each cyan and magenta patch and 100% coverage values of light cyan and light magenta (Figures 7.3 and 7.4). The lowest point of each graph is where the difference between the two is minimum, making that coverage value the optimal one for the threshold.

Figure 7.3: ΔE_{94} between cyan and 100% coverage light cyan and magenta and 100% coverage light magenta.

Figure 7.4: ΔRMS between cyan and 100% coverage light cyan and magenta and 100% coverage light magenta.

The results indicate a slight, but not severe, discrepancy between the results of the CIE LAB and spectral values. With the CIE LAB results, the threshold between cyan and light cyan was found at 38% cyan coverage with $\Delta E_{94} = 2.04$, and with the spectral values the threshold was at 37% coverage with $\Delta RMS = 0.02$. The threshold between magenta and light magenta was at 36% according to the CIE LAB values, with $\Delta E_{94} = 1.67$, and at 34% according to spectral values, with $\Delta RMS = 0.02$.

The thresholds calculated using CIE LAB and spectral values were not identical, but showed a very small difference of 1% - 2% tone coverage steps between them. Taking this into account, it was resolved to use the ΔE_{94} measured to locate the thresholds. This makes the threshold for the (C+lc) channel at 38% cyan coverage and for the (M+lm) channel at 36% magenta coverage.

Thus, the (C+lc) channel will be separated into two regions. Region 1 from 0 to 38% coverage should be printed using the light cyan ink, spanning from 0 to 100% coverage values. Region 2, from 38% to 100%, should be printed using light cyan and cyan inks, with no ink overlap. Similarly for the (M+lm) channel, region 1 from 0 to 36% will be printed with the light magenta ink, while region 2 from 36% to 100% with the light magenta and magenta inks.

7.3.2. Dot gain

A dot gain curve is the curve of the tone value increase plotted against the nominal area coverage. The tone value increase (dot gain), as already mentioned, is specific to the type of ink, substrate and halftoning method used. Thus, to be able to plot a dot gain curve, patches from 0 to 100% coverage values were created, halftoned, printed, and measured to obtain their CIE XYZ values. For cyan and light cyan inks, the CIE X values were used to plot the dot gain curves, while for the magenta and light magenta inks CIE Y values were used.

The resulted dot gain curves are shown in Figures 7.5 for lc , C and multilevel halftoned ($lc+C$) and in Figure 7.6 lm , M and ($lm+M$) respectively.

Figure 7.5: Dot gain curves for lc , C (in reference to their nominal area coverage values) and $lc+C$ (in reference to cyan nominal area coverage values).

Figure 7.6: Dot gain curves for lm , M (in reference to their nominal area coverage values) and $lm+M$ (in reference to magenta nominal area coverage values).

The CIE_x values of cyan and CIE_y values of magenta were used in the Murray-Davies formula to compensate for a linear dot gain response in the multilevel halftoned patches. They were then halftoned, printed and measured to verify the results. The results shown in Figure 7.7 for the light cyan and cyan ink combination prove a control over the dot gain response was achieved.

Figure 7.7: Effective versus nominal area coverage for multilevel (C+lc) in reference to C compensated for linear dot gain response.

7.3.3. Colour accuracy

One of the important aspects to investigate is to find the set of colours (colour gamut) that can be reproduced with multilevel halftoning using (C+lc) and (M+lm). This can be done by printing and measuring the patches shown in Figures 7.1 and 7.2. In this section, however, we instead investigate whether it is possible to reproduce all colours that can be reproduced by independent halftoning.

Therefore, in this chapter, the goal is not to represent a colorant separation to (C+lc) and (M+lm) for a given target colour. The goal is instead to use the colours inside the gamut of independent halftoning using C, M or C, lc or M, lm as the target colour and evaluate whether these colours would be possible to reproduce using multilevel halftoning with two channels, i.e., (C+lc) and (M+lm).

Therefore, we investigate whether the same colours as independent halftoning can be reproduced by multilevel halftoning. In order to do this, multilevel halftoned patches and independently halftoned patches were created, printed and measured to obtain their CIE LAB values. Next, an algorithm was created to find the ΔE_{94} between each of the independently halftoned patches and their closest colour match among the multilevel halftoned patches. The ΔE_{94} values are used to evaluate whether the same colour can be reproduced with multilevel halftoning. The results are displayed in Table 7.1. A patch marked as (C+lc) denotes a multilevel halftoned patch printed using C and light cyan, while a patch marked as C, lc means two independently halftoned channels printed on top of each other, one with cyan and the other with light cyan ink.

	$\overline{\Delta E_{94}}$	$\min \Delta E_{94}$	$\max \Delta E_{94}$	$\Delta E_{94} > 2$	$\Delta E_{94} > 4$
(C+lc) – C, lc	0.86	0.07	3.64	53	0
(M+lm) – M, lm	0.59	0.04	2.33	10	0
(C+lc), (M+lm) – C, M	1.41	0.11	4.85	84	20

Table 7.1: Colour difference results.

The calculated ΔE_{94} colour differences indicate that the multilevel halftoning algorithm, with no ink overlap, is able to reproduce colours as the independent halftoning algorithm with colour differences below 5. The mean ΔE_{94} values are below 1.5. If maximum ΔE_{94} values below 5 can be tolerated, multilevel halftoning proves to be satisfactory in the colour reproduction aspect.

Notice that the colour differences were calculated between patches printed by steps of 5% without using interpolation. The mean error would most probably be lower if interpolation was used to calculate the in-between steps.

7.3.4. Graininess

To quantify the multilevel halftoning algorithm in terms of visual pleasantness, the graininess was evaluated by calculating the standard deviation of the pixel values of the halftones. Patches from 0 to 100% area coverage were created and halftoned using two different strategies – using the bi-level halftoning algorithm and with the multilevel halftoning algorithm. This was done first for the ink threshold of 38%, thus creating a (C+lc) channel, and then for the ink threshold of 36%, suitable for the (M+lm) channel. Standard deviation was compared for each of the patches and displayed in Figures 7.8 and 7.9.

Similar as for the achromatic patches' graininess shown in Section 7.3, the results indicate that using two inks instead of one with the multilevel halftoning algorithm significantly reduces standard deviation, i.e. graininess.

Figure 7.8: Standard deviation of pixel values in the C patches and $(lc+C)$ patches.

Figure 7.9: Standard deviation of pixel values in the M patches and $(lm+M)$ patches.

7.4. Conclusions

The multilevel halftoning algorithm (Section 6.2) offers the possibility of printing a channel using multiple inks of same hue, operating in a way so that the used inks are never on top of each other. Applying the multilevel halftoning algorithm for multi-channel printing means a way of dealing with the problem of a too high ink overlap.

Challenges of implementing the algorithm to a real printing setup were investigated in this chapter and Chapter 6. Concretely, in this chapter, the implementation to chromatic inks was carried out. The specific challenges were to achieve control over the dot gain response, accurate colour reproduction and visually pleasant halftones.

Firstly, threshold between inks had to be found. Instead of using CIEY values like for achromatic inks, CIE LAB and spectral data were used. Once the thresholds were determined, dot gain characterization was achieved.

The results proved a successful control over the dot gain response. Although a linear dot gain response was achieved, any kind of a dot gain curve could be accomplished as well. In addition, the algorithm was tested in terms of colour accuracy and graininess. Colour accuracy ensured that the algorithm was able to reproduce the same colours as the traditional, independent, way of halftoning the channels with a ΔE_{94} lower than 5. The calculated ΔE_{94} values also suggested colour reproduction could be achieved without considerably reducing colour reproducibility. In addition, the low graininess values when using multiple inks in this halftoning algorithm proved that the visual impression of the halftones was enhanced.

8. Conclusions and future work

8.1. Conclusions 107

8.2. Future work 108

8.1. Conclusions

The aim of this licentiate thesis has been to adapt, develop and implement halftoning algorithms suitable for multi-channel printing. For this purpose, both AM, FM and multilevel halftoning algorithms were taken into consideration, their opposing characteristics raising different practical and implementable challenges.

First, an extension from the four conventional channels to seven-channel CMYKRGB printing was done with AM halftoning. In order to accommodate the additional channels and reduce the distortions caused by misregistration, the orthogonal halftone dot shape was replaced by a non-orthogonal elliptical halftone shape. A new wide-angle setup for non-orthogonal screens was also proposed. The non-orthogonal patches were tested for colour robustness and visually inspected for moiré in case of misregistration. The results of the simulations for the non-orthogonal halftone shapes showed less colour shifts and no visually observed moiré when compared to orthogonal screens. Nevertheless, this proposed method does not tackle the issue of controlling the printed ink layer thickness and therefore other methods were also investigated.

A multilevel FM halftoning algorithm was implemented for multi-channel reproduction. Specifically, the idea was to apply the multilevel halftoning algorithm introduced in (Gooran 2006) to channels that could be printed using multiple inks of same hue values, e.g. light magenta and magenta. This way, a channel containing colorants of same hue would have only one ink layer, regardless of the number of inks used to print it. The implementation of the algorithm comprehended locating thresholds between inks, controlling the dot gain and algorithm assessment.

Multilevel halftoning was successfully implemented to both achromatic and chromatic inks. The evaluations and test results indicate that this halftoning algorithm could be applied to any type of ink or paper by following the steps of the presented workflow. In addition, a full control over the dot gain response was achieved.

Assessment of the algorithm implementation was done by verifying graininess, smoothness and colour reproducibility.

Naturally, the benefit of this method is limited to instances where multiple inks of same hue are used. However, in many reproduction systems, inks having the same hue with varying lightness are utilized, as this ensures lower graininess levels while avoiding ink overlap between them.

8.2. Future work

Future work related to the presented research in this thesis can be divided into future work for the AM and for multilevel halftoning methods.

In case of AM, a somewhat unrealistic seven-channel printing scenario for orthogonal screens was chosen, placing complimentary colours on the same angle. A different choice of angle setup could have therefore been more suitable, perhaps limiting the simulations with orthogonal screens to four-channel printing. In addition, the chosen angle setup of the proposed non-orthogonal screens meant that it was necessary to assign some of the high-contrast colours channels close to 90° . Thus, part of the future research is to apply different angle setups and different screen frequencies to the channels for AM halftoning using both non-orthogonal and orthogonal screens.

As for future work with multilevel halftoning, the measured spectral values of inks with the supposed same hue values showed discrepancies between them in terms of spectral values. Therefore, part of the future work with multilevel halftoning is to focus on compensating for this colour difference by adding the darkest ink to the regions where it was not originally used in the multilevel halftoning approach while still avoiding ink overlap.

References

- Amidror, Isaac, Roger D. Hersch, and Victor Ostromoukhov. 2005. "Spectral Analysis and Minimization of Moiré Patterns in Color Separation." *Journal of Electronic Imaging* 3 (3): 295–317.
- Arney, Jonathan, Charles Arney, and Miako Katsube. 1996. "An MTF Analysis of Papers." *Journal of Imaging Science and Technology* 40 (1): 19–25.
- Balasubramanian, Raja, and Reiner Eschbach. 2001. "Reducing Multi-Separation Color Moiré by a Variable Undercolor Removal and Gray Component Replacement Strategy." *Journal of Imaging Science and Technology* 45 (2): 152–160.
- Berns, R. S., and D. R. Wyble. 2000. "A Critical Review of Spectral Models Applied to Binary Color Printing." *Color Research and Applications* 25 (1). John Wiley & Sons: 4–19.
- Boll, Harold. 1994. "Color-to-Colorant Transformation for a Seven Ink Process." In *Proceedings SPIE*, 108–118. San Jose, California.
- Demichel, E. 1924. "Le Procédé." 17–21, 26–27.
- Fairchild, Mark D. 2013. *Color Appearance Models*. John Wiley & Sons.

- Floyd, R. W., and L. Steinberg. 1976. "An Adaptive Algorithm for Spatial Greyscale." In *Proceedings of the Society of Information Display*, 75–77.
- Goldschneider, J R, E A Riskin, and P W Wong. 1997. "Embedded Multilevel Error Diffusion." *IEEE Transactions on Image Processing* 6 (7): 956–964.
- Gooran, Sasan. 2001. "High Quality Frequency Modulated Halftoning." *PhD Dissertation No. 668*. Linköping Studies in Science and Technology.
- Gooran, Sasan. 2005. "Hybrid Halftoning, A Useful Method for Flexography." *Journal of Imaging Science and Technology* 49 (1): 85–95.
- Gooran, Sasan. 2006. "A Novel Hybrid AM/FM Halftoning Based on Multi-Level Halftoning." *Journal of Imaging Science And Technology* 50 (2): 157–167.
- Gooran, Sasan. 2008. "Optical Dot Gain and Color Halftoning with Three Different Printing Strategies: Independent, Dot-on-Dot and Dot-off-Dot." In *Proceedings of TAGA (Technical Association of the Graphic Arts)*. San Francisco, California.
- Gooran, Sasan, Mahziar Namedanian, and Henrik Hedman. 2009. "A New Approach to Calculate Colour Values of Halftone Prints." In *Proceedings of IARIGAI*. Stockholm, Sweden.
- Goyal, Puneet, Madhur Gupta, Carl Staelin, Mani Fischer, Omri Shacham, and Jan Allebach. 2011. "Cost Function Analysis for Stochastic Clustered-Dot Halftoning Based on Direct Binary Search." In *Proceedings SPIE*. San Francisco, USA.
- Gustafsson Coppel, Ludovic, Steven Le Moan, Paula Žitinski Elías, Radovan Slavuj, and Jon Yngve Hardeberg. 2014. "Next Generation Printing - Towards Spectral Proofing." In *Proceedings of 41st International Research Conference of IARIGAI*. Swansea, UK.

- Jang, In-Su, Chang-Hwan Son, Tae-Yong Park, Kyung-Woo Ko, and Yeong-Ho Ha. 2006. "Colorimetric Characterization Based on Color Correlation in CMYKGO Printer." In *Color Imaging XI: Processing, Hardcopy, and Applications*, 210–219. San Jose, California.
- Kipphan, Helmut. 2001. *Handbook of Print Media: Technologies and Production Methods*. Springer Science & Business Media.
- Knox, Keith T. 1992. "Error Image in Error Diffusion." In *Proceedings SPIE*, 268–279. San Jose, California.
- Lau, Daniel L., and Gonzalo R. Arce. 2001. *Modern Digital Halftoning*. CRC Press.
- Mahy, M., L. Eycken, and A. Oosterlinck. 1994. "Evaluation of Uniform Color Spaces Developed after the Adoption of CIELAB and CIELUV." *Color Research & Application* 19 (2): 105–121.
- McDonald, R., and K J Smith. 2008. "CIE94-a New Colour-Difference Formula." *Journal of the Society of Dyers and Colourists* 111 (12): 376–379.
- Murray, Alexander. 1936. "Monochrome Reproduction in Photoengraving." *Journal of The Franklin Institute-Engineering and Applied Mathematics* 221 (6): 721–744.
- Namedanian, Mahziar, and Sasan Gooran. 2010. "High-Resolution Analysis of Optical and Physical Dot Gain." In *Proceedings of TAGA (Technical Association of the Graphic Arts)*, 399–408. San Diego, California.
- Namedanian, Mahziar, and Sasan Gooran. 2013. "Optical Dot Gain Study on Different Halftone Dot Shapes." In *Proceedings of TAGA (Technical Association of the Graphic Arts)*. Portland, Oregon.
- Namedanian, Mahziar, Ludovic Gustafsson Coppel, Magnus Neuman, Sasan Gooran, Per Edström, Petter Kolseth, and Wei

- Koh. 2013. "Analysis of Optical and Physical Dot Gain by Microscale Image Histogram and Modulation Transfer Functions." *Journal of Imaging Science and Technology* 57 (2): 1–5.
- Namedanian, Mahziar, Daniel Nyström, Paula Žitinski Elías, and Sasan Gooran. 2014. "Physical and Optical Dot Gain: Characterization and Relation to Dot Shape and Paper Properties." In *Proceedings SPIE 9015, Color Imaging XIX: Displaying, Processing, Hardcopy, and Applications, 901509*. San Francisco, USA.
- Neugebauer, H. E. J. 1937. "Die theoretischen Grundlagen des Mehrfarbendrucks." *Zeitschrift für wissenschaftliche Photographie* 36: 73–89.
- Ohno, Yoshi. 2000. "CIE Fundamentals for Color Measurements." In *NIP16: International Conference on Digital Printing Technologies*, 540–545. Vancouver, Canada.
- Ostromoukhov, Victor. 1993. "Chromaticity Gamut Enhancement by Heptatone Multicolor Printing." In *Proceedings SPIE*.
- Oztan, Basak, Gaurav Sharma, and Robert P. Loce. 2005. "Quantitative Evaluation of Misregistration-Induced Color Shifts in Color Halftones." In *Color Imaging X: Processing, Hardcopy, and Applications*, 501–512. San Jose, California.
- Qu, Yuanyuan, Paula Žitinski Elías, and Sasan Gooran. 2014. "Color prediction modeling for five-channel CMYLcLm printing." In *Proceedings SPIE 9015, Color Imaging XIX: Displaying, Processing, Hardcopy, and Applications, 901509*. San Francisco, USA.
- Pearson, ML. 1980. "N-Value of General Conditions." In *Proceedings of TAGA-Technical Association of the Graphic Arts*, 415–425.
- Rogers, Geoffrey L. 1997. "Optical Dot Gain in a Halftone Print." *Journal of Imaging Science and Technology* 41 (6). Society for Imaging Science and Technology: 643–656.

- Sharma, Gaurav. 2002. *Digital Color Imaging Handbook*. CRC Press, Inc.
- Smith, T, and J Guild. 1931. "The C.I.E. Colorimetric Standards and Their Use." *Transactions of the Optical Society* 33 (3): 73–134.
- Stockman, Andrew, Donald I. A. MacLeod, and Nancy E. Johnson. 1993. "Spectral Sensitivities of the Human Cones." *Journal of the Optical Society of America A* 10 (12): 2491–2521.
- Sullivan, J.R., L.A. Ray, and R. Miller. 1991. "Design of Minimum Visual Modulation Halftone Patterns." *IEEE Transactions on Systems, Man, and Cybernetics* 21 (1): 33–38.
- Tkalčić, M., and J.F. Tašić. 2003. "Colour Spaces: Perceptual, Historical and Applicational Background." In *The IEEE Region 8 EUROCON 2003: Computer as a tool*: 304–308. Ljubljana, Slovenia.
- Wang, Shen-ge, Zhigang Fan, and Zhenhuan Wen. 2003. "Non-Orthogonal Screen and Its Application in Moire-Free Halftoning." In *Proceedings SPIE*, 399–408. Santa Clara, California.
- Weisstein, Eric W. 2014. "Orthogonal Curves." From *MathWorld* – A Wolfram Web Resource. Accessed September 25, 2014. <http://mathworld.wolfram.com/OrthogonalCurves.html>.
- Yule, J. A. C., and W. J. Nielsen. 1951. "The Penetration of Light into Paper and Its Effect on Halftone Reproduction." In *Proceedings of TAGA (Technical Association of the Graphic Arts)*, 65–76.
- Zeng, Huanzhao. 2000. "Ink Limit Control for Ink-Jet Printer Color Calibration." In *Photonics West 2001 - Electronic Imaging*, 93–96. San Jose, California.
- Zhang, Xujie, Alex Veis, Robert Ulichney, and Jan P. Allebach. 2012. "Multilevel Halftone Screen Design: Keeping Texture or

Keeping Smoothness?” In *Proceedings of ICIP*, 829–832. Orlando, Florida.

Žitinski Elías, Paula, Sasan Gooran, and Daniel Nyström. 2014. “Multilevel Halftoning Applied to Achromatic Inks in Multi-Channel Printing.” In *Proceedings of 41st International Research Conference of LARIGAI*. Swansea, UK

Žitinski Elías, Paula, Daniel Nyström, and Sasan Gooran. 2013. “Multi-Channel Printing by Orthogonal and Non-Orthogonal AM Halftoning.” In *Proceedings of 12th International AIC Colour Congress: Bringing Colour to Life*. Newcastle, UK