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Effect of Halftones on Printing Iridescent Colors

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Abstract

The iridescent effect produced by structural color is difficult (if not impossible) to capture and print using traditional CMYK pigments. The so called RGB reflective pigments, nonetheless, generate angle-dependent colors by light interference. A layered surface structure generated by the pigments' particles on a substrate reflects light waves of different wavelengths at different viewing angles according to the optical principle known as the Bragg Law. In this work, we have studied the influence of different halftone structures on printed images, produced with RGB reflective inks via screen printing. The main goal was to enhance the iridescence of a printed reproduction by studying the performance of different halftone algorithms on a screen printing process. We investigated the influence of different halftone structures in creating different spatial combinations of inks on a print to reproduce the image of an iridescent feathered headdress. We applied first-order, second-order, and structure-aware FM halftones to compare how they influence the reproduction of the material appearance of the object represented in the original image. The results show that the structure-ware halftones improve the representation of the image structures and details. Therefore, it could better convey the 3D surface features that produce iridescence in real feathers.

Introduction

Iridescence in nature, as it occurs in bird feathers, beetle shells [1], [2], mother-of-pearl [3], or precious stones is a visual manifestation of what we call interference color or structural color. This kind of coloration arises not primarily from dyes or pigments, but via diffraction effects from surfaces with periodic features structured on length scales similar to those of light wavelengths in the visible range. The appearance of iridescent materials, whereby the color perceived changes with the viewing angle, is challenging to capture or reproduce, and has engaged artists and scientists around the world for many generations [4]. The feathers of the male peacock (Pavo cristatus) are the archetypal example of structural color throughout western art history. Interference color in peacock and pheasant feathers was observed and studied by a number of scientists including Robert Hooke, Sir Isaac Newton and Sir Chandrasekhar [5]. In precolonial America, the optical qualities of feathers were appreciated by artists in Mesoamerica, who widely used them to give color to mosaics and luxurious garments [6], [7]. In Mesoamerica, the iridescence of feathers is a visual attribute related to the quality of preciousness [8].

The most representative example of feather art from ancient Mexico is a quetzal feathered headdress held by the Ethnological Museum of Vienna, Figure 1, known as Montezuma's headdress (or penacho). This item is made mainly with feathers from the tail of the resplendent quetzal (Pharomachrus mocinno). Nowadays this last exemplar is extremely fragile as well as valuable [9]. While, the angle dependent color emphasizes a three-dimensional interaction of the viewer with the object, this quality is not present in traditional reproduction in either print or display of this headdress.

This work has explored the challenges of the production of an iridescent image using novel RGB pigments via screen printing, a method proven suitable to work with such pigments [10]. Screen printing is a stencil process utilizing a fine mesh stretched over a frame. Stencils are attached to the screen and can be made in a variety of ways. Ink is forced through the openings in the screen [11]. This project is a case study to find suitable ways to reproduce the visual appearance of an original object including its three-dimensional features via printing. We have used the recently proposed structure-aware halftoning algorithm [12] and RGB pigments as colorants to print a color image. The methodology described in this work could be applied to recreate and emphasize appearance qualities of other artistic and natural materials.

Printing with RGB pigments

Both, the ink qualities and its deposition method influence the optical properties of a printed surface. The size, orientation, and structure of the ink pigment particles ultimately affect the visual appearance of the image perceived by the observer. The so-called effect pigments, such as the Spectraval^{TM} range from Merck, have enabled printmakers, artists [13] and the printing industry [14] to produce images based on the phenomenon of interference of structural color. The Spectraval RGB pigments are constituted by layers of mica and titanium dioxide. When printed, their color is produced by light interference, hence strongly dependent on the viewing angle.

Printing an image in color using three primary colors can be done through decomposing the image into the three primary color channels. Each color channel is halftoned independently and the final color image is retrieved by the superposition of all the monochrome halftones. Due to the innovative nature of the Spectraval pigments and the specific color gamut that they are able to render, it is necessary to optimize the printing method and the halftoning technique for this specific application.

Halftoning algorithms convert a continuous-tone image to a binary image for printing purposes, therefore, it is an essential part of image reproduction in printing. The most visible characteristic of halftoning algorithms is the halftone structure. Halftone structures differ in spatial distribution of dots. For instance, in first-order frequency modulated (FM) halftones, single dots are distributed in a stochastic manner, where the size of dots is constant, while their density is changed. In second-order FM (also known as stochastic clustered-dot halftone), both the size and the distance between dots are variable.

Figure 1. *Target image. The archaeological item represented in the image is a headdress made of quetzal feathers in the Americas (presumably in the XVI century), and currently held at the Ethnological Museum of Vienna.*

We have previously proposed the structure-aware halftoning algorithm in Ref [12], however, it had not been applied to hand-printing techniques such as screen printing with RGB inks. This project studies the impact of halftoning on reproducing optical qualities of artistic iridescent artefacts via printing. We verify the merit of structure-aware halftoning in preserving image structure and fine details, thus contributing to achieving more realistic and faithful reproductions.

Method

We used RGB inks (Spectraval^{TM} range from Merck) as colorants, which produce angle-dependent colors and, in contrast to CMYK inks, operate under an additive colour model. This model, also called additive mixing, predicts the appearance of colors by adding the numeric values of coincident component lights [15].

Inks made with effect pigments are not suitable for inkjet printing due to a large pigment size (up to 25 microns), but can be employed in screen printing, flexo printing and even lithography. The deposition technique also influences the appearance of the print. To maximize the generated color of the pigments, it is better for the particles to lay flat on the surface, which can be achieved by screen printing.

Halftone structures define the spatial distribution of pigments. Different halftone structures generate different spatial configurations of the inks' deposition, leading to changes in appearance of the print. The target image is an iridescent archaeological item, Figure 1, namely a headdress made of quetzal feathers. We compared the performance of first-order, second-order, and structure-aware FM halftones in creating the appearance of the feathers.

Halftoning algorithm

We used the Iterative Method Controlling the Dot Placement (IMCDP) to apply different halftone structures [16], [17]. IMCDP is an iterative halftoning algorithm, which initiates with a blank image (to be the halftoned image) the same size as the original continuous-tone image and searches for the location of the pixel holding the highest intensity value (the darkest pixel), and a dot or a "1" is placed at its corresponding position in the blank image. To consider the quantization effect of this dot placement, the low-pass filtered version of the halftoned image is subtracted from the low-pass filtered version of the original image. This process is called the feed-back process and the low-pass filter is called the feed-back filter accordingly. Then, the algorithm continues with finding the pixel holding the maximum value in the continuous-tone image after applying the feed-back filter and places the second dot in its corresponding position in the halftoned image. Because the average gray-tone value in different regions of the continuous-tone and the halftoned image should remain the same, so the number of black dots to be placed in each gray-tone region is known in advance and the algorithm stops iterating when all the predetermined number of black dots are placed and the halftoned image is created. The low-pass filter used in IMCDP is a Gaussian filter as in Equation 1:

$$f(x,y) = Ke^{-\frac{(x^2+y^2)}{2\sigma^2}}. \tag{1}$$

In Equation 1, K is a normalization factor to ensure that the filter elements sum to 1, (x,y) are the spatial coordinates of pixels and σ is the standard deviation of the filter. Using the filter in Equation 1 generates first-order FM halftones.

We leveraged the IMCDP halftoning algorithm because of its flexibility in generating different halftone structures only by modifying the feed-back filter. The Gaussian filter in Equation 1 is symmetrical kernel, resulting in a symmetric distribution of dots in all directions. However, changing the filter to a non-symmetrical filter as in Equation 2, enables us to adjust the orientation of dot distribution,

$$f(x,y) = Ke^{-(Ax^2+2Bxy+Cy^2)}. \tag{2}$$

In Equation 2, K is a normalization factor to ensure that the filter elements sum to 1, and A, B, and C are calculated as:

$$A = \frac{\cos^2\phi}{2k_1\sigma^2} + \frac{\sin^2\phi}{2k_2\sigma^2}, \tag{3}$$

$$B = \frac{-\sin 2\phi}{4k_1\sigma^2} + \frac{\sin 2\phi}{4k_2\sigma^2}, \tag{4}$$

$$C = \frac{\sin^2\phi}{2k_1\sigma^2} + \frac{\cos^2\phi}{2k_2\sigma^2}. \tag{5}$$

In equations 3 to 5, ϕ is angle with the positive x-axis. Setting $k_1 = k_2$ makes the filter symmetrical, however, $k_1 < k_2$ directs dot placement in horizontal direction and $k_1 > k_2$ makes the dots grow faster in vertical direction, generating vertical-line halftones. To create halftones in other directions, one can simply generate horizontal or vertical line halftone and rotate it to any direction by setting ϕ to the desired angle.

To create second-order FM halfones with IMCDP, the feed-back filter should be modified to the form shown in Equation 6, which is a Gaussian subtracted from another Gaussian ($\sigma_1 > \sigma_2$):

$$f(x,y) = K(e^{-\frac{(x^2+y^2)}{2\sigma_1^2}} - e^{-\frac{(x^2+y^2)}{2\sigma_2{}^2}}) \tag{6}$$

In second-order FM halftones, first, dots are placed isolated, then start to grow in size and form clusters of dots when the tones

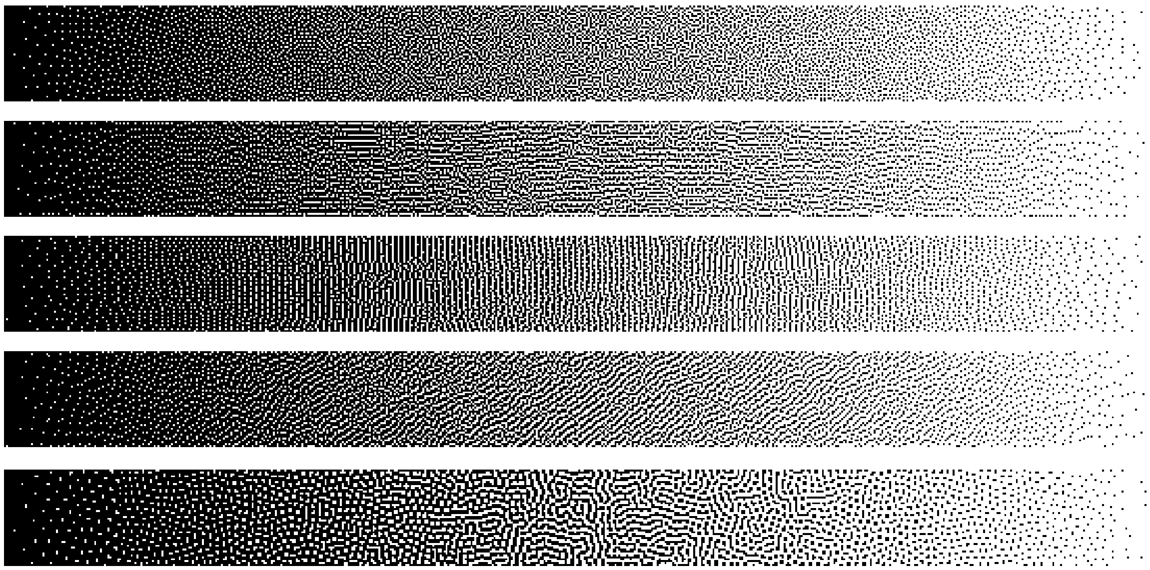

Figure 2. *Examples of halftone structures used in this project: (First) symmetrical first-order FM halftones. (Second) first-order FM halftones with horizontal alignment, halftone structure is aligned at* 0° *with regards to x-axis. (Third) first-order FM halftones with vertical alignment, halftone structure is aligned at* 90° *with regards to x-axis. (Fourth) first-order FM halftones, aligned at* 30° *with regards to x-axis. (Fifth) second-order FM. This is just a simple example to demonstrate the dot placement in different halftone structures. Halftone ramps are displayed at 100 dpi. (This figure is reproduced based on the halftoning algorithm described in our previous work [12].*

get darker. Figure 2 illustrates different halftone structures created by IMCDP.

In our previous work, we leveraged the possibility of generating different halftones with IMCDP and developed a structure-aware IMCDP halftoning technique [12]. The aim is to improve the reproduction of structural details through halftoning. The key idea of the algorithm is to place dots in line with high-frequency details of the image. In structure-aware halftoning, first, the dominant orientation in the neighborhood of each pixel is detected. This could be done through different image processing techniques, such as Hough transform, Gradient-based approaches, and Gabor filters, to name a few. However, according to our experiments, Gabor-based approach is more flexible and faster than Hough transform and Gradient technique [18]. After identifying the dominant orientation in the neighborhood of each pixel, the input image is partitioned into structured (union of pixels having a dominant orientation in their neighborhood) and structure-less (union of pixels without a dominant orientation in their neighborhood) regions. Then, different halftone structures are applied to the structured and structure-less regions. At pixels lying in structured regions, first, a horizontal halftone alignment is created and then it is rotated according to the angle of the dominant local orientation (using the filter in Equation 2). However, in structure-less regions, halftones are distributed symmetrically in all direction (using the filter in Equation 1). In structure-aware halftoning, dot placement is generated with regards to the image content, therefore, the halftone is aligned with structures of the input image and more details are preserved at high-frequency features (edges).

Printing process

For additive RGB color printing it is necessary to use black paper as a substrate and inverting the color of the image. We have separated the colors into red, green and blue color channels, then, halftoned each color separation independently. The final color image is retrieved in the print by the superposition of all three halftoned separations. Each halftoned color separation was printed on transparent film and transferred via UV exposure onto a photo-sensitized screen. Finally, ink is forced through the prepared screen with the help of a floodbar or squeegee and applied onto the paper.

Three different halftone structures: first-order, second-order, and structure-aware FM halftones at resolution of 100 dpi were used. Wedges of first-order halftoning in different angles, with increments of 10 per cent between 0% and 100% of ink coverage were printed in red, green and blue at 100 dpi and 150 dpi. Figure 3 shows an example of wedges with different halftone structures printed at different resolutions.

In screen printing a limitation of the image resolution is determined by the size of mesh apertures, which should not be inferior to three times the particle size. The size of the pigment particles range from 1 to 25 microns, therefore having a mesh with holes less than two times bigger than the pigments can affect the flow of the pigments through the mesh. We have used screens with a high mesh count of 90 and 120 threads per cm (228 and 308 threads per inch). For these, a convenient number of dots per inch is 101 dpi or even 136 dpi, estimated by dividing the mesh count by 2.25 [19].

For a 90T mesh, we were not able to produce a print with first-order FM, however, prints with structure-aware and second-order halftone were successful. The results of printing with these two types of halftones and a 90T mesh is shown in Figure 4. It was clear that a more natural appearance of feathers was produced with the structure-aware halftone.

The mesh was exposed to UV light to create a halftone pat-

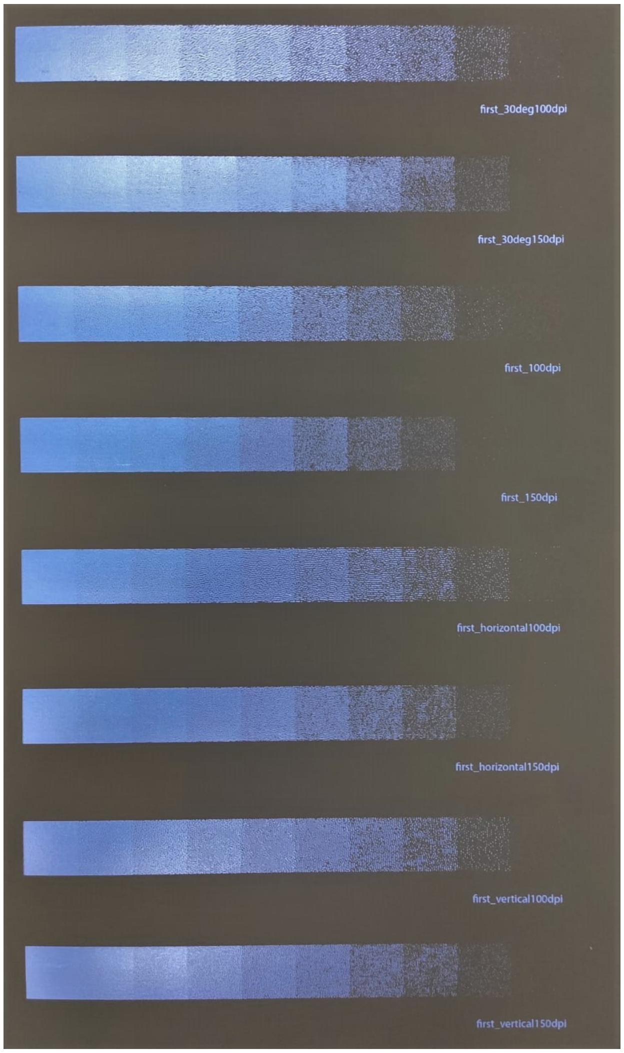

Figure 3. *Example of a set of printed wedges with increments of 10 per cent in intensity, halftoned at 100 dpi and 150 dpi. In descendent order the image shows: First-order halftoning where the structure is aligned at* 30°*, symmetrical first-order FM, horizontal alignment and vertical alignment with regards to x-axis.*

tern for 27 seconds for all screens. With first-order FM halftones, however, it was not possible to remove the emulsion from the halftone dots when washing off the screen. It seems that the dots are too fine for this mesh count so the emulsion hardens around them and closes the holes where the emulsion should remain unhardened. It is possible that reducing the exposure time would allow us to create this pattern, however it should be evaluated how the light-tone areas are affected.

Results

Figure 4 illustrates cropped sections of the prints produced with second-order and structure-aware halftones. Because the structure-aware halftoning algorithm aligns the dots' (pigments) distribution with regards to the image content, it better preserves the texture and structural characteristics of the original image. Structure-aware halftoning improves the representation of the image structures and details by enhancing the sharpness and structural details of the input image, and, therefore, it could better display the feeling of the underlying 2.5/3D structural features and outperforms the second-order halftoning algorithm in terms of capturing and reproducing the iridescence effect of structural color exhibited in the feathers of the headdress.

A final print was made using a 120T mesh, aiming to improve the reproduction of high-frequency features. Figure 5 presents a photograph of the final RGB print. Figure 6 shows a visual comparison of a section of the final print, photographed from different angles and may give the reader an idea of both the influence of halftones and the reflective pigments on creating a more realistic appearance than a regular image. The iridescence of the print was confirmed by informally surveyed observers, although in the future, measurements should be taken to quantitatively describe the variation of color with illumination or viewing angle.

Conclusion

This work has explored the production of a print that conveys the iridescent appearance of a headdress made of quetzal feathers using novel RGB pigments via the screen printing method. Three different halftone structures: first-order, second-order, and structure-aware FM halftones at resolution of 100 dpi were used. It was found that the structure-aware halftones improve the representation of the image structures and details and, therefore, it could better convey the 3D surface features that produce iridescence in the original item. The iridescence of the print was confirmed by observers and shown in photographs. Future research will involve colour or spectral measurements to quantitatively describe the variation of color with illumination or viewing angle.

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References

[1] M. Srinivasarao, "Nano-optics in the biological world: Beetles, butterflies, birds, and moths," *Chemical Reviews*, vol. 99, pp. 1935–1962, 1999.

[2] P. Vukusic and J. R. Sambles, "Photonic structures in biology," *Nature*, vol. 424, pp. 852–855, 2003.

[3] R. Ozaki, K. Kikumoto, M. Takagaki, K. Kadowaki, and K. Odawara, "Structural colors of pearls," *Scientific Reports*, 2021.

[4] M. G. Meadows, M. W. Butler, N. I. Morehouse, L. A. Taylor, M. B. Toomey, K. J. McGraw, and R. L. Rutowski, "Iridescence: Views from many angles," *Journal of The Royal Society Interface*, vol. 6, no. suppl_2, S107–S113, 2009. DOI: 10.1098/rsif.2009.0013.focus.

[5] S. L. Burg and A. J. Parnell, "Self-assembling structural colour in nature," *Journal of Physics: Condensed Matter*, vol. 30, no. 41, p. 413 001, 2018. DOI: 10.1088/1361-648X/aadc95. [Online]. Available: https://dx.doi.org/10.1088/1361-648X/aadc95.

Figure 4. *Details of prints with green and blue layers made with structure-aware halftoning (left) and second-order FM halftoning (right).*

Figure 5. *RGB Print produced with structure-aware halftoning and 120T mesh. Print dimensions 87.9 cm x 67.5cm.*

[6] M. Jansen, V. M. Lladó-Buisán, and L. Snijders, *Mesoamerican Manuscripts: New Scientific Approaches and Interpretations*. Brill, 2018, ISBN: 978-90-04-38811-6. DOI: `https://doi.org/10.1163/9789004388116`.

[7] S. M. Arbeláez, "El arte plumario y sus múltiples dimensiones de significación," es, *Historia CrÃtica*, pp. 121–149, Jun. 2006, ISSN: 0121-1617.

[8] D. Magaloni-Kerpel, "Real and illusory feathers: Pigments, painting techniques, and the use of color in ancient mesoamerica," *Nuevo Mundo Mundos Nuevos [online]*, vol. 1462, 2006. DOI: `https://doi.org/10.4000/nuevomundo.1462`.

[9] K. von Zinnenburg Carroll, "The inbetweenness of the vitrine: Three parerga of a feather headdress," *The Inbetweenness of Things: Materializing Mediation and Movement between Worlds*, pp. 23–38, 2017.

[10] A. Trujillo-Vazquez, H. Fuller, S. Klein, and C. Parraman, "The amber project: A survey of methods and inks for the reproduction of the color of translucent objects," *Applied Sciences*, vol. 12, no. 2, 2022, ISSN: 2076-3417. DOI: `10.`

Figure 6. *Details from an RGB print produced with structure-aware halftoning and 120T mesh count photographed from different angles. The visual comparison shows a qualitative difference in the colors of the feathers.*

3390/app12020793. [Online]. Available: `https://www.mdpi.com/2076-3417/12/2/793`.

[11] B. Fick and B. Grabowski, *Printmaking*, Second. Laurence King Publishing, 2015, ISBN: 9781780671949.

[12] F. Abedini, S. Gooran, V. Kitanovski, and D. Nyström, "Structure-aware halftoning using the iterative method controlling the dot placement," *Journal of Imaging Science and Technology*, vol. 65, pp. 60 404–1, 2021.

[13] F. Schenk, B. D. Wilts, and D. G. Stavenga, "The japanese jewel beetle: A painter's challenge," *Bioinspiration & Biomimetics*, vol. 8, no. 4, p. 045 002, 2013.

[14] F. J. Maile, G. Pfaff, and P. B. Reynders, "Effect pigments—past, present and future," *Progress in Organic Coatings*, vol. 54, pp. 150–163, 2005.

[15] W. B. Cowan, "An inexpensive scheme for calibration of a colour monitor in terms of cie standard coordinates," in *Proceedings of the 10th Annual Conference on Computer Graphics and Interactive Techniques*, ser. SIGGRAPH '83, Detroit, Michigan, USA: Association for Computing Machinery, 1983, pp. 315–321, ISBN: 0897911091.

[16] S. Gooran, "Dependent color halftoning: Better quality with less ink," *Journal of imaging science and technology*, vol. 48, pp. 354–362, 2004.

[17] S. Gooran and B. Kruse, "High-speed first-and second-order frequency modulated halftoning," *Journal of Electronic Imaging*, vol. 24, p. 023 016, 2015.

[18] F. Abedini and S. Gooran, "Structure-aware color halftoning with adaptive sharpness control," *Journal of Imaging Science and Technology (accepted for publication on Nov.10)*, 2022.

[19] *Mesh formulas to know for screen printing with halftone dots*, `https://fusion180ink.com/mesh-formulas-to-know-for-screen-printing-with-halftone-dots/`, Accessed: 2023-02-06.

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