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Dot Off Dot Screen Printing with RGBW Reflective Inks

Alina Pranovich
Linköping University, Norra Grytsgatan 10, 602 33 Norrköping, Sweden
E-mail: alina.pranovich@liu.se

Sergiy Valyukh
Linköping University, Olaus Magnus väg, 583 30 Linköping, Sweden

Sasan Gooran
Linköping University, Norra Grytsgatan 10, 602 33 Norrköping, Sweden

Jeppe Revall Frisvad
Technical University of Denmark, Richard Petersens Plads, 324/161, 2800 Kgs. Lyngby, Denmark

Daniel Nyström
Linköping University, Norra Grytsgatan 10, 602 33 Norrköping, Sweden

Abstract. *Recent advances in pigment production resulted in the possibility to print with RGBW primaries instead of CMYK and performing additive color mixing in printing. The RGBW pigments studied in this work have the properties of structural colors, as the primary colors are a result of interference in a thin film coating of mica pigments. In this work, we investigate the angle-dependent gamut of RGBW primaries. We have elucidated optimal angles of illumination and observation for each primary ink and found the optimal angle of observation under diffuse illumination. We investigated dot off dot halftoned screen printing with RGBW inks on black paper and in terms of angle-dependent dot gain. Based on our observations, optimal viewing condition for the given RGBW inks is in a direction of around 30° to the surface normal. Here, the appearance of the resulting halftoned prints can be estimated well by Neugebauer formula (weighted averaging of the individual reflected spectra). Despite the negative physical dot gain during the dot off dot printing, we observe angularly dependent positive optical dot gain for halftoned prints. Application of interference RGBW pigments in 2.5D and 3D printing is not fully explored due to the technological limitations. In this work, we provide colorimetric data for efficient application of the angle-dependent properties of such pigments in practical applications.* © *2023 Society for Imaging Science and Technology.*
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1. INTRODUCTION AND RELATED WORK

Recent advances in printing technologies and printing materials fabrications allow recreation of realistic replicas of real-life objects, including angularly dependent appearance. On one hand, 2.5D and 3D printing allows reproduction of angle-dependent appearance by combining isotropically scattering colorants with varying surface and volume structures. On the other hand, application of thin film fabrication technologies allowed production of coatings and inks that are capable of goniochromatic appearance on their own. Such special effect (pearlescent, metallic interference) inks are able to mimic appearance of materials with complicated micro- and nanostructures. One of the examples of such is structural colors, where reflectance properties of the material cannot be purely expressed with light absorption and scattering by the pigment or dye particles. Structural colors result from the selective behavior of material nanostructure towards different wavelengths. Recently introduced RGBW pigments by Merck are an example of structural colors. Reflective iridescent pigments are achieved by coating mica flakes with thin (up to 100 nm) films of titanium dioxide. The resulting colors are guided by the constructive interference for wavelengths satisfying phase difference conditions at each individual pigment particle. The colors of reflected spectra thus depend on the thickness of the thin layer and the angle of light incidence. While spectral and angularly dependent reflectance properties of thin films can be expressed analytically, appearance property of a mixture of individual coated flakes with solvent (binding) medium applied with screen printing technology depend on individual arrangement and alignment of pigment particles, and surface quality of fabricated coated pigments.

In this work, we explore dot off dot screen printing with inks prepared with Merck RGBW pigments and acrylic base. One of the most important observations is that it is beneficial to print layers with thickness close to the thickness of individual particles, avoiding stacking of the pigments on top of each other. The reason is that the spectrum transmitted through the pigments is complementary to the reflected spectrum. Light transmitted through a pigment particle will be reflected from the layers below that will lead to the color shifted towards the white point of the gamut. For this reason, we work with dot off dot halftoning to avoid overlapping layers. The angle-dependent reflected

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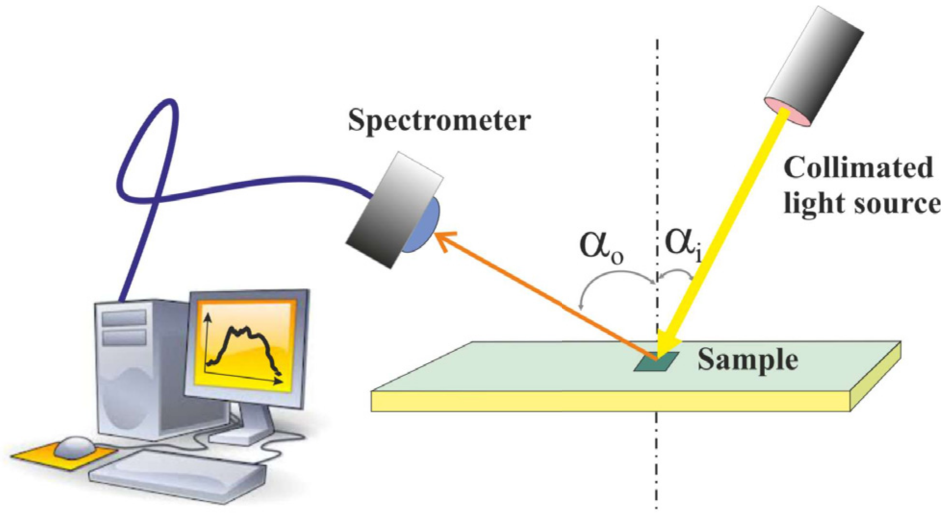

Figure 1. Setup for measuring angle-dependent colour of the printed samples with angle notation. Our setup is similar to the one presented by Pranovich et al.

spectrum of screen-printed layers prepared with different pigment concentrations and numbers of applied layers was investigated in a previous work [1]. Recommended concentration of pigments in acrylic based inks for screen printing is about 25 wt.%. We follow this recommendation.

Modelling of flake-pigment coatings is presented in Ref. [2]. The RGBW inks studied in this work have similar structure, except individual mica flakes are coated. In this sense, not only the direction of the individual reflections, but also reflected spectrum depends on the orientation of individual flakes. As opposed to this work, we experimentally characterize the primaries and their printed combinations using a home-built set up.

Screen printing with Merck RGBW pigments is presented in Ref. [3]. There, the authors indicate the need of the dot off dot printing with RGBW inks. As authors state, angularly conditioned wavelength selective reflectivity makes this type of pigment suitable for security printing applications. At the same time, so far, 2.5D printing with Merck RGBW pigments has not been explored. In the later work, [4], the ability of recreating 3D visual experience while printing with RGBW inks with focus on reproduction of translucent appearance was explored.

Potential applications in security printing, or implementation of 2.5D or 3D printing involving studied RGBW inks, requires understanding of angularly dependent appearance properties of individual inks and their combinations. We experimentally study color characteristics of RGBW inks and their combinations for dot off dot printing under different illumination and observation directions.

2. MATERIALS AND METHODS

We printed patches of 100% area coverage by individual primary inks (Red (R), Green (G), Blue (B) and White (W)), pairs of primaries (RG, GB, RB) and RGB mixture (33% of R, G and B). For the calculation of the total dot gain we printed patches of 10–90% covered with individual primaries. Inks were prepared with 25% pigment concentration in acrylic binder. We used mesh T120 and 0.03-inch square dots halftoning.

Angle-dependent color was measured using a custom setup consisting of a goniometer, a light source, and a spectrometer, as described in previous work [1], see Figure 1. In this work, the bidirectional reflectance distribution function (BRDF) of samples was obtained by calibrating obtained spectral reflectivity values of our setup with a white reference. After BRDF data for the samples were collected, RGB color coordinates were calculated under the condition of daylight illumination (D50 standard light source). Appearance of the prints under diffuse illumination (sample illuminated from all directions in a positive hemisphere) was done by cosine weighted averaging of spectra under each angle of illumination.

Calculated color of the halftoned patches was made by weighted averaging of corresponding individual spectra (Neugebauer formula [5]).

3. RESULTS AND DISCUSSION

In our measurement, light was incident at angles between 30° and 70°.

From a theoretical point of view, collimated light beam illuminating a thin film structure will be reflected in one direction, and interference colors generated by the ideal thin films are observed in specular directions. However, mainly surface roughness of individual coated mica flakes and overall rough surface of the print will effectively result in a spread of the observation angles where desired color can be still observed. As observation direction distances from the specular direction, diffuse components of reflected light (light transmission and reflections from multiple layers of pigments, reflection from the pigment edges, inhomogeneities in the ink etc.) become dominant

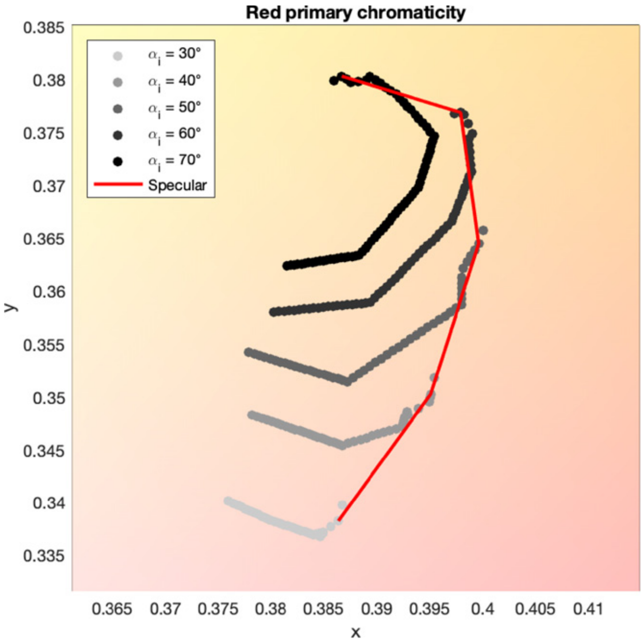

Figure 2. *xy* coordinates of Red primary. Dots indicate chromaticity coordinates for different observation angles, red curve connects chromaticity points for specular directions (angle of observation is equal to the angle of illumination).

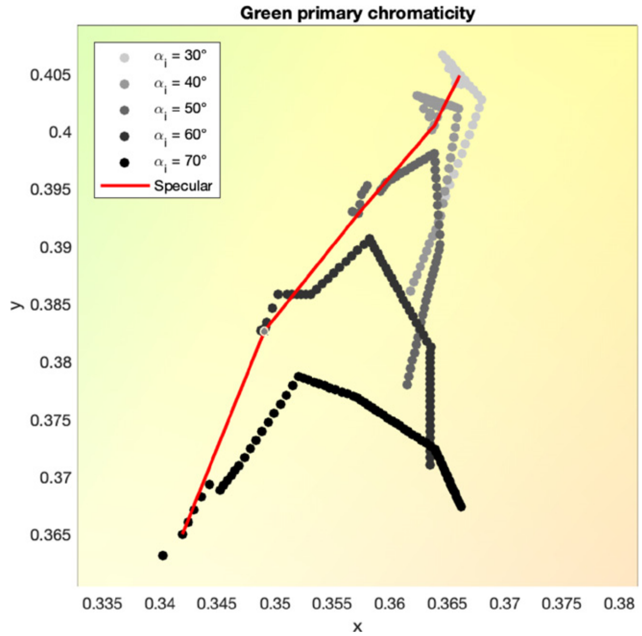

Figure 3. *xy* coordinates of Green primary. Dots indicate chromaticity coordinates for different observation angles, red curve connects chromaticity points for specular directions (angle of observation is equal to the angle of illumination).

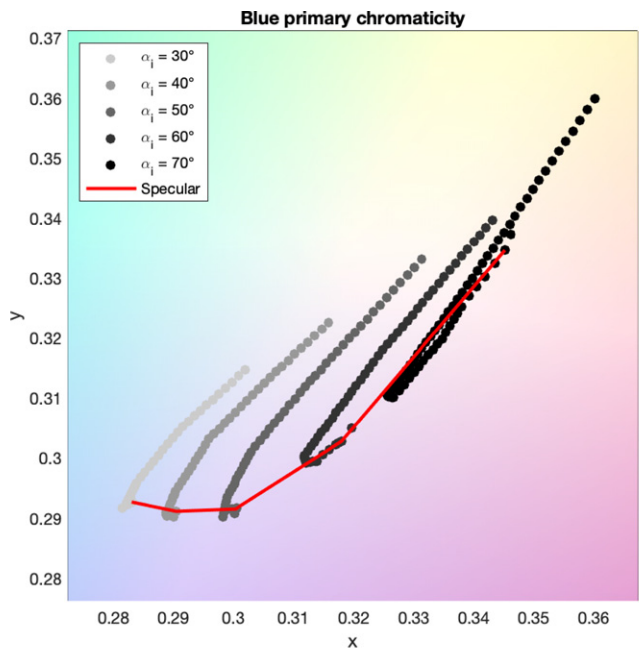

Figure 4. *xy* coordinates of Blue primary. Dots indicate chromaticity coordinates for different observation angles, red curve connects chromaticity points for specular directions (angle of observation is equal to the angle of illumination).

and therefore the grayish appearance. At the same time, reflected spectrum in the specular direction depends on the angle of incidence. Chromaticity diagrams of measured color coordinates provide sufficient information to be able to judge color saturation and make an observation of optimal viewing conditions. Therefore, we display measured color values using xy chromaticity coordinates with visualized RGB values in the background and make empirical conclusions about optimal illumination and observation directions.

3.1 *Viewing Conditions under Directional Illumination*

Figures 2–4 display chromaticity diagrams of individual R, G and B primaries for angles of incidence from 30° to 70° for varying angles of observation. To demonstrate angularly changing color characteristics, we plot x and y values distinguishing between angles of incidence. Coordinates measured in specular directions are connected with a red line. As can be seen from the displayed data, specular reflections are concentrated in the part of the diagram closest to the saturated R, G and B in the xy-diagram. At the same time, specular reflection at 30° incident direction provides the most saturated primary color. On the other hand, observation in normal direction to the surface normal will result in grayish color.

3.2 *Halftoned Patches*

Halftoned patches were prepared with stochastic 50% area coverage for combinations of each two primaries, and with three primaries at 33% each (totally 100% area coverage). Given the color coordinates for individual primaries shown above, we demonstrate measured and predicted appearance of stochastic dot off dot combinations (on a black paper) at 30° illumination and viewing directions. We calculated predicted color coordinates and halftoned patches using the simple Neugebauer formula [5] and considering no interaction of the inks with the substrate. Figure 5 demonstrates resulting colors of individual patches and predicted color with a straightforward approach based on spectral

Figure 5. Measured (left) and calculated (right) RGB values of halftoned patches of combinations of primaries under 30° illumination and observation angle. Top to bottom: RG, GB, RB and RGB.

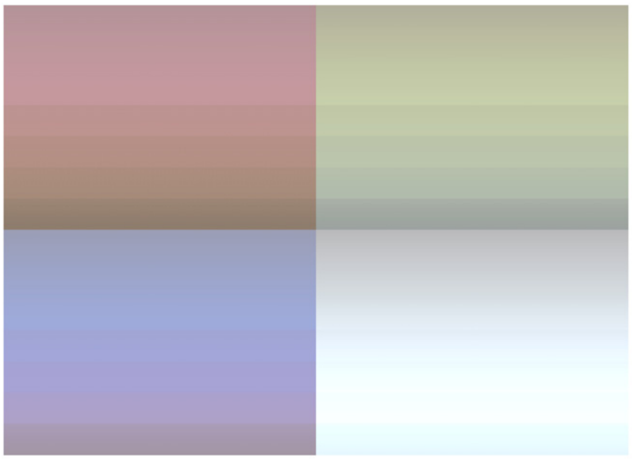

Figure 6. RGBW primaries appearance under diffuse illumination.

Table I. Comparison of measured and predicted colors of halftoned patches with Red (R), Green (G) and Blue (B) primaries. Left column: combination of primaries and DE2000 color difference. Right column: CIE LAB values (D50 white point) as measured (M) and calculated (C).

RG: DE2000 = 6.9	M: L 71.2 a 3.4 b 11.2
	C: L 80.8 a 4.1 b 12.1
GB: DE2000 = 2.7	M: L 78.0 a -4.4 b -5.8
	C: L 81.5 a -5.3 b -5.4
RB: DE2000 = 0.9	M: L 72.6 a 10.6 b -16.0
	C: L 72.5 a 11.2 b -17.4
RGB: DE2000 = 10.9	M: L 65.3 a 2.4 b 1.1
	C: L78.4 a3.0 b-3.4

reflectance of individual primaries. The measured colors appear darker due to the physical screen printed negative dot gain on the black substrate. Color difference values according to the CIEDE2000 standard [6] are demonstrated in Table I. Closer look into obtained color difference values suggest good estimation of LAB a^* and b^* values, and discrepancies are observed mainly in the lightness coordinate. We attribute this difference to the negative physical dot gain and slight misalignment of the individual screen printed dots, which is common for screen printing process in general.

3.3 *Simulation of Colors Under Diffuse Illumination*

After capturing BRDF of individual patches filled with primary color inks, we simulated color coordinates under

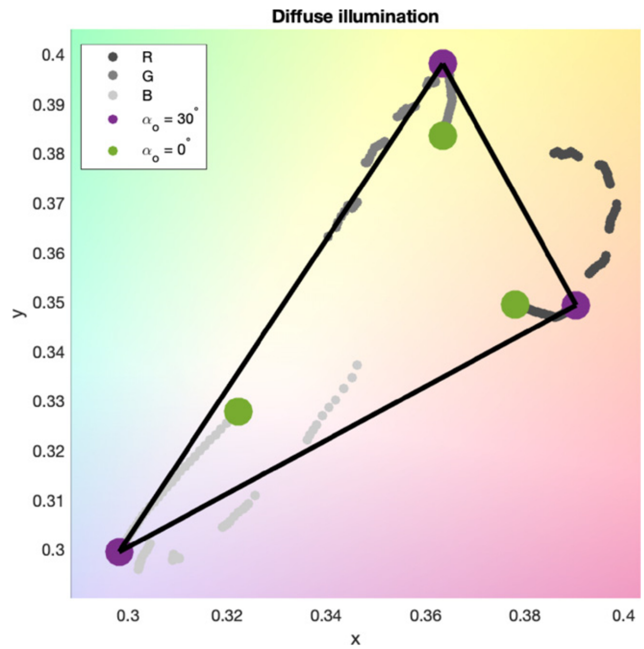

Figure 7. Primaries chromaticity diagram under diffuse illumination. Dots: Chromaticity values for observation angle 0° and 30°.

the conditions of diffuse illumination. The values were computed by cosine weighted average of reflectance values obtained under corresponding incident illumination directions. Figure 6 demonstrates appearance of individual primaries under diffuse illumination in RGB color space representation. For the demonstration purposes, RGB values are displayed in rectangular images corresponding to the observation directions 0° (top of the image) to 70° (bottom of the image). Figure 7 shows chromaticity diagram of three primaries under diffuse illumination. For all three primaries xy-coordinates located closest to the saturated R, G and B correspond to the observation direction with angle 30° with the surface normal (marked with a filled circle in the figure). Based on the measured BRDF data, we conclude that the optimal angle for observing the colors produced by interference RGBW inks is around 30° with the surface normal. Solid black lines in Fig. 7 connect xy-coordinates of individual primaries demonstrating the gamut that is possible to obtain by employing such primaries. The only missing points are the colors of the Red primary ink under observation directions above 30°. These values, however, lay farther away from the sRGB red primary. Numerical calculations for the ideal thin film of titanium dioxide and incidence angle [7, 8] do not suggest more

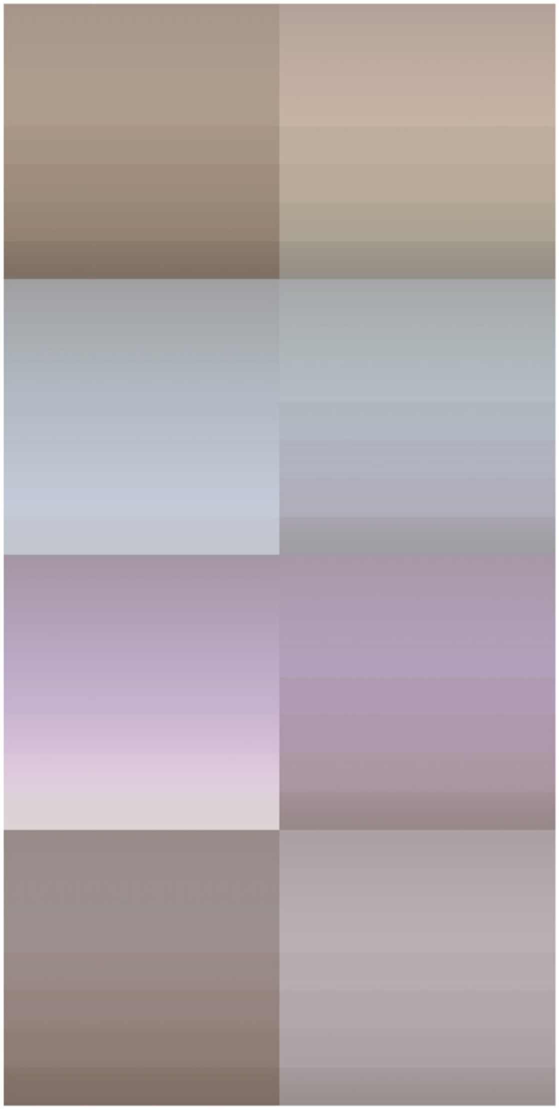

Figure 8. Halftoned printed mixtures of primaries. Top to bottom: RG, GB, RB, RGB. Colours represent appearance under diffuse illumination and observation angles from 0° to 70° (top to bottom). Left column represents measured prints, and right column is calculated values using Neugebauer formula with spectral data respectively. Horizontal axis carries no information.

saturated colors for angles of incidence below 30°. Taking into account missing measured data, we conclude that optimal observation direction is between 20° and 30°. As in the previous example, we also demonstrate appearance of halftoned patches under diffuse illumination and predicted appearance based on the individual reflectance spectra of the primaries, as shown in Figure 8. We compare measured color coordinates to the simulated based in terms of CIE dE2000 standard [6] for each observation direction, as shown in Figure 9. Increasing values of color difference between measured and calculated values most likely result from specular reflections from the substrate and edges of printed dots and are approached in the next section on the example of one primary printed with different area coverage and can be treated as angular-dependent dot gain.

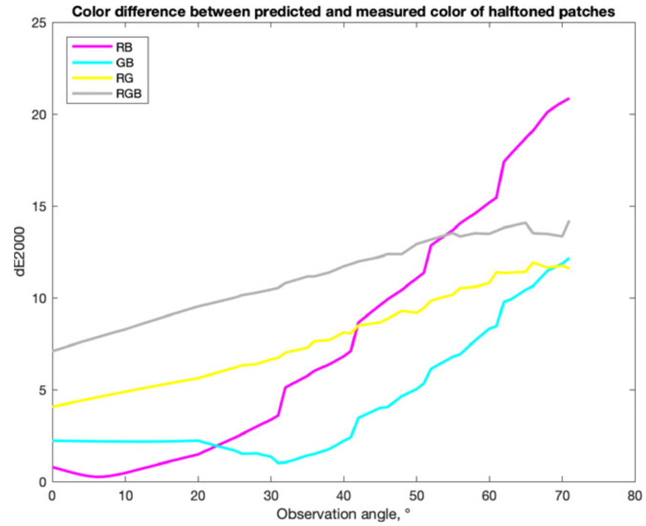

Figure 9. Color difference between measured and calculated values for halftoned patches in Fig. 8 (Calculated with Spectral values) for different observation angles.

3.4 *Dot off Dot Screen Printing Dot Gain*

In the case of blue primary ink, we estimated the angle-dependent dot gain. While during printing we could observe negative physical dot gain from the normal direction of observation, optical dot gain can propagate in a form of brighter appearance of the inks from oblique illumination and observation directions due to the present physical height of individual dots. We therefore estimate angle-dependent total dot gain expressed as effective area coverage by the blue ink. Here, we use CIEZ-value for the blue primary Z_{primary} obtained from reflectance values of the 100% covered patch, where the contrast between the printed primary and black paper is the highest (for red and green primary one should choose X and Y respectively). Comparison of Z_{measured} measured and expected value of Z_{primary} coordinate is expressed as an effective area a_{eff} (that in this case turns out to be higher than the nominal) [9] as:

$$a_{eff}(\alpha_i, \alpha_o) = \frac{Z_{\text{measured}} - Z_{bp}}{Z_{\text{primary}} - Z_{bp}}, \quad (1)$$

where Z_{bp} corresponds to the Z-coordinate of the black paper.

We compared patches filled with 10–90% area coverage with simulated results under diffuse illumination. The comparison between measured results and calculated values in terms of spectral mixing is displayed in Figure 10.

As can be seen in the Fig. 10, the calculation results match the measurements really well for larger coverage of blue (patches on top) and not that well otherwise. The reason is that we have used the Z-values to estimate the effective coverage, corresponding to the shorter wavelength of the visible wavelength interval. One suggestion to improve the estimation is that instead of using only one dot gain characteristic curve based on Z-values, we use three different curves based on CIE X, Y and Z, as suggested in Ref. [10] or more rigorous estimation of angle-dependent reflectance

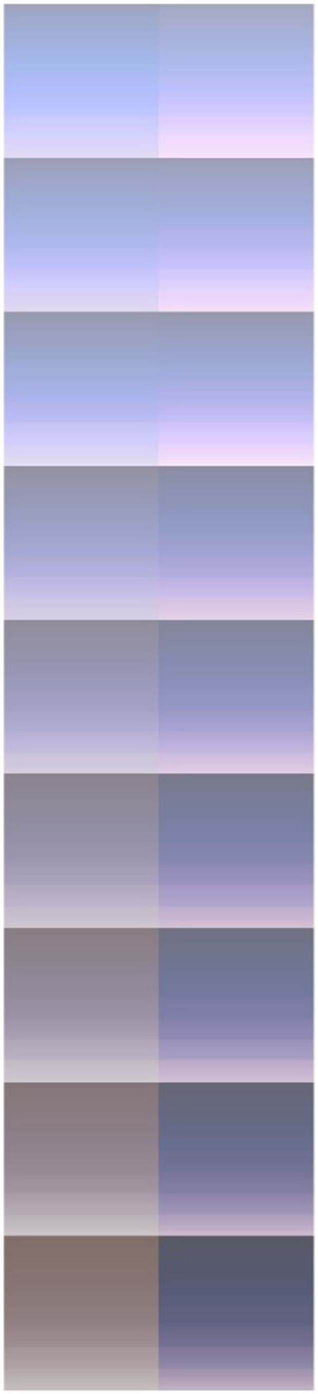

Figure 10. 90–10° per cent (top to bottom) halftoned patches. Comparison of measured values (left), and calculated spectrally after accounting for the angular dependent dot gain (right).

properties based on the knowledge of surface micro- and macro roughness alignment of the pigments, and taking into account specular reflection from the print surface.

4. CONCLUSION

In this work, we provide experimentally obtained angular-dependent colorimetric data for inks prepared with reflective RGBW pigments. Our study highlights the importance of considering the angle-dependent visual properties of these inks when used in security printing and 2.5D and 3D printing.

We focused on color coordinates for different directions of light incidence and observation. By comparing obtained xy- chromaticity coordinates with those of saturated R, G and B we suggest optimal direction of illumination of 30° and specular direction of observation. Obtained angle-dependent color coordinates may provide a practical guidance for future applications of RGBW reflective inks in prints utilizing color blur for non-optimal viewing directions.

In case of diffuse illumination, the range of optimal angles of observation is between 20 and 30°, giving the widest gamut for optical mixing.

While the appearance of the halftoned patches could be well predicted for the optimal observation directions, oblique illumination results into additional light scattering from the edges of the individual printed dots. We include this correction by means of the experimentally estimated angle-dependent positive dot gain.

Future work will be focused on accurate prediction of interference pigments taking into account individual surface roughness, alignment distribution of the pigment particles and their concentration, and development of the best suitable model for color prediction of the halftones.

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