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Addressing the colorimetric redundancy in 11-ink color separation

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Abstract

To improve color reproduction, many printers today use extra colorants, in addition to the traditional four inks (Cyan, Magenta, Yellow and Black). Adding the complementary colorants (Red, Green and Blue) increases the gamut of reproducible colors, while lighter versions of the primary inks can be added to reduce graininess and dot visibility. Using more than three inks introduces colorimetric redundancy in the color separation process, because different ink combinations can reproduce the same target color. When additional inks are introduced, this redundancy rapidly increases, and it is thus crucial to introduce additional constraints in the color separation process, to improve determinacy and to optimize different aspects of print quality.

This study focuses on an analysis of the redundancy in the color separation process for an 11-ink printer. It is investigated how the extensive colorimetric redundancy can be utilized to select optimal ink combinations to meet the, sometimes contradictory, criteria of color accuracy, graininess and ink consumption. Analysis of the results of applying different criteria in the color separation process shows that the result heavily depends on the selected criterion. For example, prioritizing graininess will improve print quality by reducing dot visibility, imposing the use of lighter inks, but it will also increase ink consumption.

Introduction

Traditionally, color printing has been achieved using the four colorants Cyan, Magenta, Yellow and Black (CMYK). With the demand for high quality color reproduction, achieving images of superior color and detail, the use of additional inks is increasing, and even many desktop printers of today employ more than four inks. By adding the complementary colorants Red, Green and Blue (RGB), the gamut of reproducible colors is increased. Furthermore, the addition of the complimentary colors makes ink saving possible, e.g. by replacing cyan and magenta combinations with the complementary blue ink (in a similar way that black ink is used in four-color printing, to save ink and increase the gamut).

Another approach to add additional inks is to use lighter versions of the primary colors (e.g. light cyan, light magenta, gray and light gray). The addition of lighter inks can help reducing graininess and dot visibility. By reproducing light tones in an image by lighter inks, with lower contrast to the substrate, graininess is clearly reduced compared to when dark inks are used. However, the reduction in graininess by using light inks comes with the cost of increased ink consumption, since lighter inks naturally require larger amounts of ink to reproduce the same target color, compared to the darker inks.

Employing additional inks increases the complexity of the printer characterization process, required to achieve a consistent color reproduction. The forward characterization function predicts the resulting color for a given ink combination, sent to the printer [1]. The inverse characterization function, also referred to as color separation, determines the ink combination that reproduces a target color (typically specified in CIELAB). For a three-ink printer (CMY), this can be a unique one-to-one mapping. However, even for the traditional four-ink printer (CMYK) the addition of the black ink introduces redundancy, because different ink combinations can reproduce the same color. The CMYK color separation is typically handled by controlling the black ink, using methods such as under-color removal (UCR) or gray-component replacement (GCR) [2]. When additional inks are introduced, the colorimetric redundancy increases rapidly; with numerous of different ink combinations that can be used to reproduce the same target color [3]. To fully utilize the potential in multi colorant printers, it is thus crucial to introduce additional constraints in the color separation process, to improve determinacy and with the potential to optimize different aspects of print quality.

Objective

This study focuses on an analysis of the colorimetric redundancy in the color separation process for an 11-ink printer, utilizing both the complementary inks and the lighter inks. The printer and the printing workflow is thus fully utilizing the benefits of multi colorant printing, but the usage of both light and complementary inks greatly increases the complexity for both printer characterization and color separation. With 11 inks, the colorimetric redundancy is extensive, with at times thousands of ink combinations producing the same color, differing in other aspects such as graininess and ink consumption. Another crucial aspect of 11-channel printing is to control the ink overlap, making sure that the number of overlapping inks never exceeds the amount that the specific paper grade can handle.

The study builds on the authors’ previous work, proposing a colorant separation process for 7-ink printers, utilizing the lighter inks, based on a multi-level halftoning algorithm [4-7]. Grouping the light and dark inks together in four separate channels, assures that ink overlap within the channels is avoided, and that graininess is minimized. However, introducing the complimentary inks Red, Green and Blue, not only considerably increases the redundancy, but also the risk of causing visible graininess in the print. The complementary inks expand the gamut and make ink saving possible, but they do not offer any lighter versions, reducing graininess. Ink saving and reduced graininess are often contradictory criteria, since using lighter inks to reduce graininess naturally increases ink consumption. The main focus of this study is thus to extend the previous color separation model to incorporate the complimentary colors, red, green and blue. It will also be investigated how the extensive colorimetric redundancy can be utilized to select optimal ink combinations to meet the, sometimes contradictory, demands of color accuracy, graininess and ink consumption.

Methodology

Multi-channel printing

The basis of this work is a method for multi-channel halftoning, grouping the primary inks and their lighter versions into separate subgroups, i.e. C_S (cyan and light cyan), M_S (magenta and light magenta) and K_S (black and two shades of gray). For an CMYK-printer, adding these four light inks, the color separation is thus reduced to addressing only four individual channels; C_S, M_S, Y and K_S [7]. Each channel is expressed in terms of the nominal coverage of the primary inks (CMK) in the color separation process. Then, the multi-level halftoning algorithm [4] handles the separation between lighter and darker inks, within each channel, as a subsequent step, greatly reducing the complexity of color separation, and inherently also the colorimetric redundancy.

The multi-level halftoning algorithm divides each channel into separate regions, based on thresholds defined by the colorimetric properties of the inks [5-6]. For example, the black channel (employing three inks) is first divided into three different regions. The first region contains only the lightest gray ink, from 0% up to fulltone coverage. The second region, starting where the light gray reaches its fulltone coverage, is then a combination between the two gray inks, printed dot-off-dot. Finally, the third (and darkest) region is a combination between the dark gray and the black ink, printed dot-off-dot. This way, the method assures that no ink overlap occurs within each channel, which can prevent over-inking. It will further inherently reduce graininess, since the darker inks will only be printed in dot-off-dot combinations with the lighter inks, where the contrast is significantly lower compared to dark ink against paper [7].

Printer characterization

To derive the forward characterization function, i.e. the relationship between the colorant control values sent to the printer, and the colorimetric values of the resulting print, it is more feasible to first divide the printer gamut into subgamuts. The inks are arranged in groups of four (thus restricting the output to four overlapping inks) and the subgamuts are selected as the ones adjacent on the chromaticity plot [9-10]. Using the multilevel workflow, this gives the four subgamuts $C_SM_SYK_S$, M_SYK_SR, C_SYK_SG and $C_SM_SK_SB$. With the primary and lighter inks treated as subgroups (or channels), this means that the subgamuts are all formed by four subgroups, but actually include more individual inks. However, the multilevel halftoning assures that the maximum ink overlap is still constrained to four inks.

This study will be limited to focus primarily on evaluating the results for the "blue" ($C_SM_SK_SB$) subgamut. This subgamut (including the colorants Cyan, light Cyan, Magenta, light Magenta, Blue, Black, Gray and light Gray) contains as many as 8 colorants. It is also the subgamut including the inks having the highest contrast to the paper. Therefore, it is the subgamut with both the highest complexity (the largest number of colorants), and also the one that potentially will have most to benefit from reducing graininess.

For each of the four subgamuts, the forward characterization function has then been derived using the cellular Yule-Nielsen modified Neugebauer model (cYNMN) [1]. For each subgamut, 5^4=625 training patches have been used to optimize the model parameters. For the subgamut in focus ($C_SM_SK_SB$), the accuracy of the characterization has been thoroughly verified by printing patches in 10% steps for each channel, i.e. 11^4=14641 patches. The result of the forward model is the relation between nominal ink coverage, sent to the printer, and the resulting colorimetric values (CIELAB) for the print. The model was applied for totally 81^4 = 43046721 different ink combinations for each subgamut (the ink's coverage steps were 0:1:60:2:100 for each subgroup). The computed values were stored in a color look-up-table (CLUT), for each subgamut, forming the basis for the color separation model.

Graininess

To characterize graininess, or dot visibility, the previously proposed Graininess Index, GI, is used as metric [3]. GI is defined as the mean CIEDE2000 color difference between the mean CIELAB value of the original patch and the S-CIELAB representation of the printed patch. S-CIELAB (or Spatial-CIELAB) is an extension of CIELAB color space; incorporating spatial properties, based on the contrast sensitivity functions for the human visual system [11].

To derive the S-CIELAB representation, printed halftone patches were scanned and converted to an opponent color space, where low-pass filters mimicking the human visual contrast sensitivity functions are applied, for each channel. After conversion to CIELAB, the resulting S-CIELAB representation can be used to evaluate the visual difference between images, depending on the spatial resolution and viewing distance. By comparing the S-CIELAB representation of a printed halftone (for each pixel) to the mean CIELAB value (representing the target color, without variation), the Graininess Index aims to quantize the visible graininess of a printed patch.

The graininess indices were measured for printed patches in the $C_SM_SK_SB$ subgamut, in 10% steps for each channel. In the range 0-10% nominal coverage, where the GI has large variations, additional patches were measured in 2% steps. For all intermediate ink combinations, the GI was predicted using cubic interpolation to 1%. The viewing distance 25 cm was used in S-CIELAB computations.

The derived graininess indices (GI) were added to the colorimetric data in the color look up table, to be available as an additional criterion in the color separation process.

Experimental setup

All patches were printed using the Canon IPF 6450 inkjet printer, employing the inks: cyan (C), light cyan (lc), magenta (M), light magenta (lm), yellow (Y), photo gray (pgy), gray (gy), black (K), red (R), green (G) and blue (B). The Voxvil print engine overrides the internal RIP, allowing us to print separate bitmaps for each of the 11 channels. The patches were printed using 600 dpi print resolution, on 170 g/m^2 matte coated paper, using the halftoning algorithm IMCDP [12].

The spectrophotometer BARBIERI electronic Spectro LFP RT was used for colorimetric measurements, under D50 illumination and the CIE 1936 2º standard observer.

For S-CIELAB computations, the patches were scanned using the Epson Perfection V500 Photo, at 1200 ppi scanning resolution. With the selected viewing distance of 25 cm, this scanning resolution gives approximately 206 samples per degree in the S-CIELAB computations. The conversion from scanner RGB to CIEXYZ was based on polynomial regression techniques, expressing X, Y and Z as polynomial functions of R, G and B, optimized for the given ink and substrate [13].

Results

Analysis of the color look up table (CLUT), containing ink coverage, colorimetric values and graininess indices, reveals that the colorimetric redundancy is extensive. Figure 1 illustrates how the redundancy for the $C_SM_SK_SB$ subgamut (in 2% steps) varies with the position in CIELAB color space. It is obvious that the largest redundancy occurs for darker colors (low L*), where often thousands of different ink combinations, reproducing the same target color, within $1\Delta E_{94}$, exist.

Figure 2 shows the graininess index, GI, for the single colorants in the $C_SM_SK_SB$ subgamut, as well as for the subgroups used in multilevel halftoning, measured in 1% steps. As expected, the black ink produces the largest graininess, since the black dots have the highest contrast to the white paper. However, in the multi-level set up, the black ink is never printed alone, but used only in the subgroup (K_S) with the two gray inks. As seen in figure 2, the graininess for the K_S subgroup is considerably lower than for the single black ink, with the maximum GI reduced to one third of the black ink. It is clear that the multi-level halftoning greatly reduces the graininess by using dot-off-dot placement of the inks within the subgroup, avoiding high contrast ink against paper.

With the multi-level set up, the subgroups C_S, M_S and K_S all produce low GI for all ink coverages. Thus, the blue ink is the only colorant without a lighter version, which cannot be combined in a subgroup, using the multi-level approach. It is clear from figure 2 that the blue ink stands out (since no other single ink is used), giving considerably higher GI values than the subgroups C_S, M_S and K_S.

Visual inspection of the printed patches confirms the results from the computed graininess index. Patches printed using the single colorants black and blue clearly appear as grainy, with visible halftone dots, at low ink coverages. The multi-level halftoned subgroups do not exhibit visible graininess at all.

The reason that the GI for the single colorants drops for high ink coverages, is a natural consequence from the fact that the contrast between ink and paper lowers when the ink covers the substrate. The GI for the subchannels has lower variation, because the high contrast (darker) inks are never seen directly against paper, but only in dot-off-dot combinations with their lighter inks. For full ink coverage the GI is not zero, even though there can no longer be any dot visibility (because there are no dots). This is due to the fact that the GI metric inevitably also captures the small variations that occur even for fulltone tints.

Few target colors can be reproduced using a single colorant (or a single subgroup), but require combinations of multiple colorants. Figure 3 visualizes how the graininess index depends on the combined ink coverage for C_SM_SB combinations, with nominal coverage up to 60%. Clearly, high total ink coverage gives low GI values, and C_SM_S combinations give lower GI, compared to when the blue ink is used. The highest GI appears for combinations including low nominal coverage of B, which could be expected from the results in figure 2. The reason that M_SB combinations generally give higher GI than C_SB combinations is due to the fact that the blue ink has larger color difference to magenta than to cyan.

A closer inspection of the GI for all combinations in the CLUT further leads to the general conclusion that GI values for total ink coverages exceeding 150% are low, independent of the ink combinations, and thus not need to be considered in the color separation.

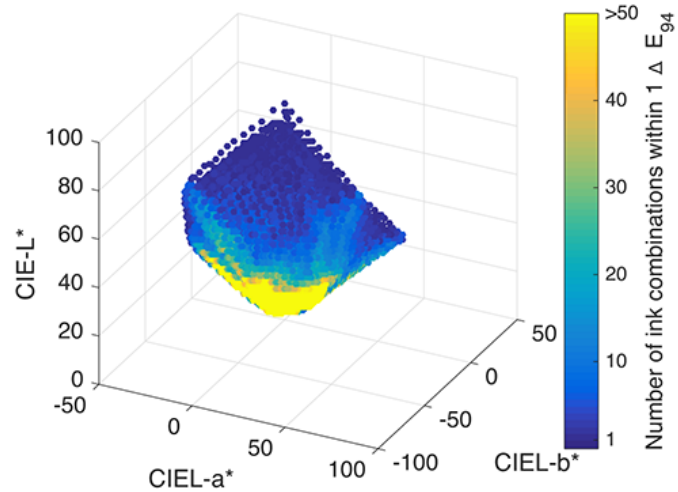

Figure 1. Colorimetric redundancy in CIELAB, showing the number of different ink combinations reproducing the target color within 1 ΔE94.

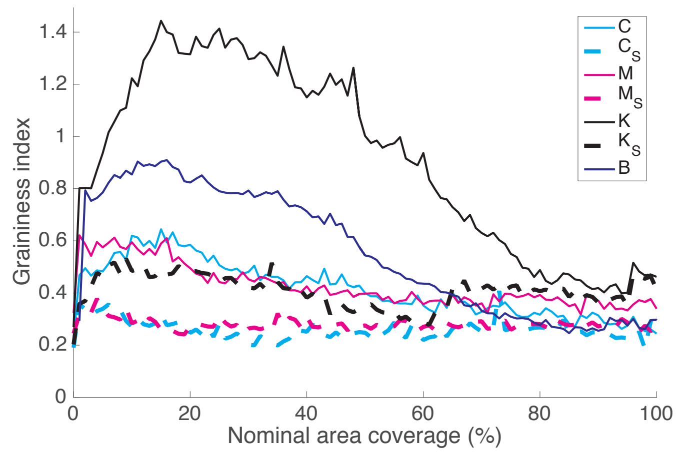

Figure 2. Measured Graininess Index (GI) for single colorants, cyan, magenta, black and blue, as well as for the subgroups, C_S, M_S and K_S, employed in multi-channel halftoning.

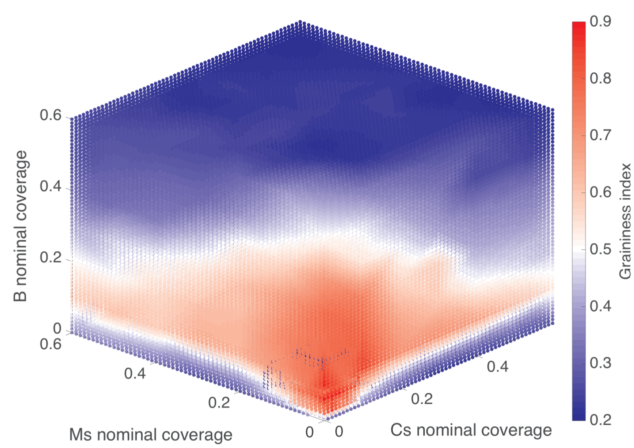

Figure 3. Graininess index, GI, for $C_SM_SB_S$ ink combinations.

Figure 4 shows individual ink coverages for 20 different ink combinations that can reproduce the target color L*a*b*=(70, 21, -30), within the just noticeable difference 1 ΔE_{94}, together with the resulting GI. Each column shows the relative coverage for paper, light cyan (lc), light magenta (lm) and photo gray (pgy), for one possible ink combination. The ink combinations are sorted after total ink coverage, which varies from 14% (left) to 53% (right).

Since this is a relatively light target color, the colorimetric redundancy is not very large, with only 20 possible ink combinations. Still, it is obvious that the resulting GI is strongly dependent on the selected ink combination, ranging from 0.48 to 0.86. It is also clear that the GI is reduced with total ink coverage, and when not using the blue ink.

If we compare ink consumption and graininess index as possible criteria for the color separation process, for this target color, the resulting combinations would be the one to the left (22% total coverage, GI=0.84) and the one to the right (53% total coverage, GI=0.48). Clearly, these different criteria are directly contradictory, selecting the two opposite extremes from the available ink combinations. The resulting printed and scanned patches for these two ink combinations are displayed to the left in figures 7 and 8.

Figure 5 shows the GI and the individual ink coverages for the ink combinations that can reproduce the target color L*a*b*=(56, 31, -42), within 1 ΔE_{94}, organized in the same way as in figure 4. Since this is a slightly darker color, the colorimetric redundancy is increasing, now giving 137 different ink combinations. The total ink coverage ranges from 27% to 122%, and the GI from 0.48 to 0.78. It is clear that the GI again decreases with total ink coverage and when replacing the blue ink with combinations of light cyan and light magenta. It is also noticeable that the GI drops when the total ink coverage reaches 100%, thus completely covering the paper. If ink consumption or GI would be used as criterion in the color separation, again the two extremes (outer left and right) would be the resulting printed patches (displayed to the right in figures 7 and 8). It is, however, worth noticing that the reduction in graininess by using lighter colorants comes with the cost of increasing the total ink consumption by 450%, compared to the most ink saving alternative.

Figure 6 shows the individual ink coverages for ink combinations that can reproduce the target color L*a*b*=(30, 15, -31). This is a darker blue color and the colorimetric redundancy is now large, with 8660 different combinations reproducing the target color within 1 ΔE_{94}. The graininess indices (not displayed) are all below 0.45, because of the high total ink coverage, ranging from 113%-224%. This figure illustrates how the multilevel halftoning algorithm handles the subgroups C_S and M_S, varying the individual ink coverage within each subgroup, up to totally 100%, thus avoiding ink overlap.

Figure 7 shows printed and scanned patches, corresponding to the target colors in figure 4 (left) and figure 5 (right). Magnifications of the same patches are displayed in figure 8. It is clear from figure 7 and 8 that the graininess can be greatly reduced (second row) by incorporating GI in the color separation. Reducing GI, however, comes with the cost of ink consumption as shown in figures 4 and 5. It should be noticed that even if the color of the patches using different ink combinations may not be identical when reproduced here, the color difference for the real printed patches are within 1 ΔE_{94}.

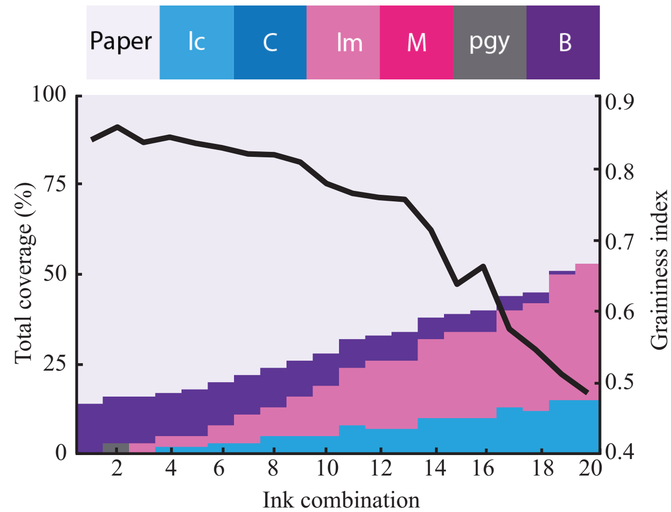

*Figure 4. Ink converges for 20 ink combinations, reproducing the target color L*a*b*=(70 21 -30), within 1 ΔE_{94}, together with the resulting GI.*

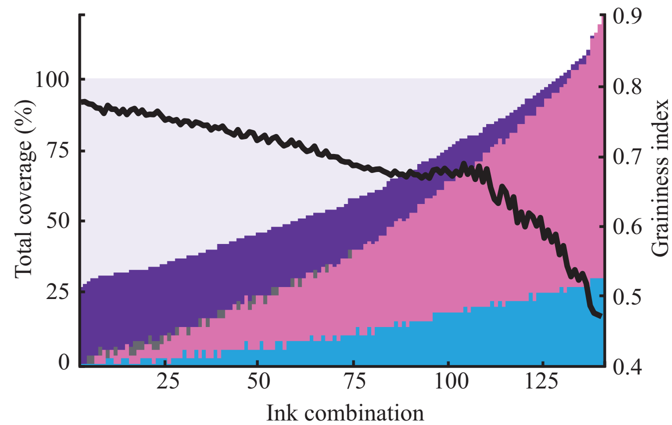

*Figure 5. Ink converges for 137 ink combinations, reproducing the target color L*a*b*=(56 31 -42) within 1 ΔE_{94}, together with the resulting GI.*

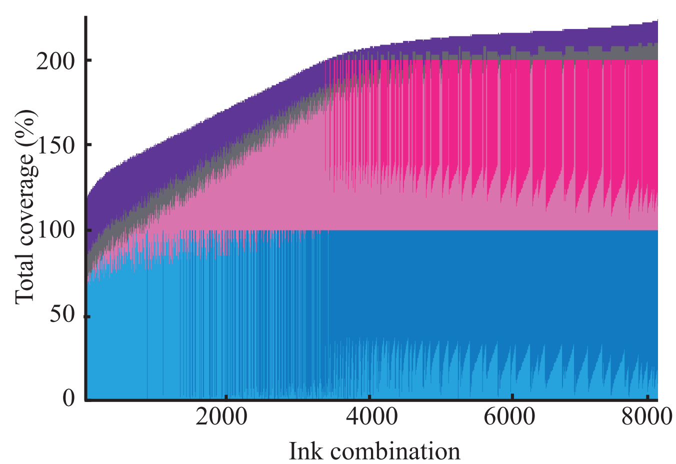

*Figure 6. Ink converges for 8660 ink combinations, reproducing the target color L*a*b*=(30 15 -31) within 1 ΔE_{94}.*

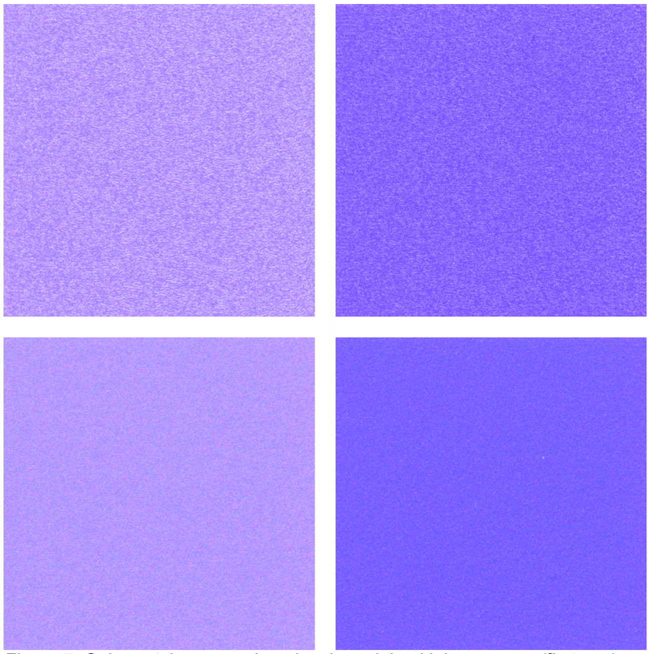

Figure 7. Color patches reproduced, using minimal ink coverage (first row) and minimizing GI (second row) as criterion in color separation.

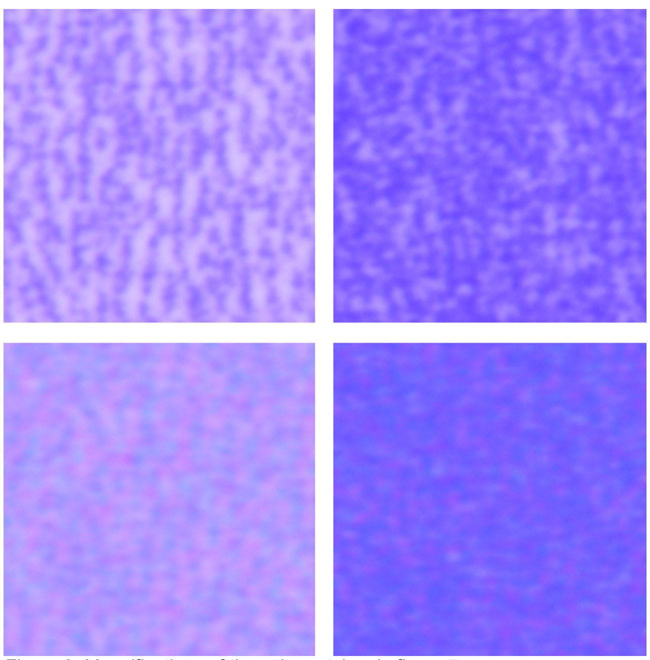

Figure 8. Magnifications of the color patches in figure 7.

Figure 9 shows continuous tone ramps, with slowly varying target colors. The upper ramp has been generated using only the closest colorimetric match to the target CIELAB values in the color separation. The lower ramp has been created using GI as an additional criterion in the color separation process. Clearly, the lower ramp has a less grainy appearance. When inspecting the resulting ink combinations for the two ramps it turns out that the lower ramp (incorporating GI) is reproduced completely without using the blue ink. In the upper ramp, the blue ink is partly used, which causes graininess in the low coverage, all in line with the previous results in figures 2-5.

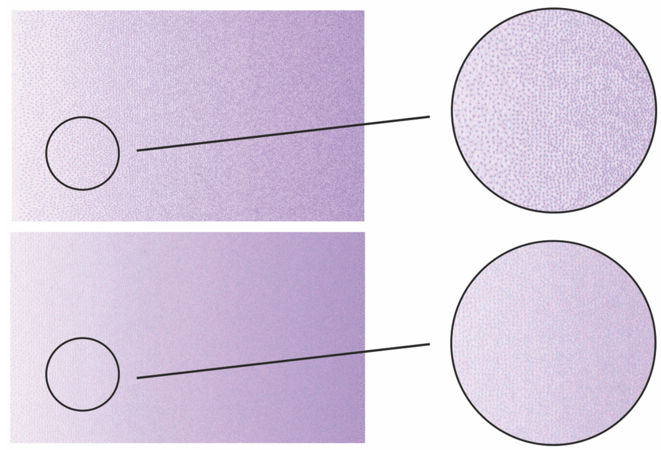

Figure 9. Continuous tone ramp reproduced using closest colorimetric match (top) and reducing GI (bottom) in the color separation.

It is known that the approach of dividing the printer gamut into multiple subgamuts for printer characterization can sometimes cause visual artifacts in the transitions between subgamuts [8]. Even though the focus in this study has been on analysis of the results for the $C_SM_SK_SB$ subgamut, it is important to verify that the approach used for gamut subdivision and color characterization is valid. The M_SYK_SR subgamut (red) has been characterized in the same way as the $C_SM_SK_SB$ subgamut, to test if the color separation can handle transitions between subgamuts. Figure 10 shows a continuous tone ramp with varying target colors, defined in CIELAB, ranging from light red to light blue. The GI has been used as an additional criterion in the color separation process. The magnification in the center, displaying the region where the transition between the two neighboring subgamuts occurs, does not contain any visual artifacts, or discontinuities.

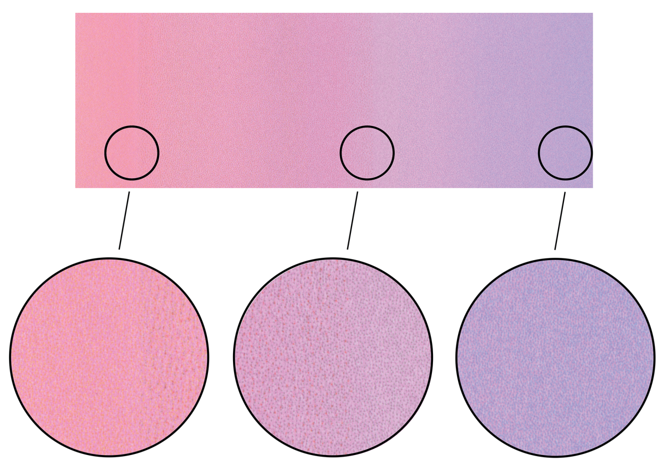

Figure 10. Continuous tone ramp showing the transition between the neighboring subgamuts M_SYK_SR (red) and $C_SM_SK_SB$ (blue).

Conclusions

Using multi-level halftoning, handling 11 individual colorants as 7 unique subgroups, greatly reduces the complexity of the color separation, as well as the colorimetric redundancy, by ensuring no overlap between inks within the same subgroup. Still, the results show that the colorimetric redundancy is extensive, especially for dark colors, where numerous different ink combinations can be used to reproduce the same target color. However, the graininess is generally low for dark colors with high ink coverage, since the paper is then fully covered. Thus, if image quality in terms of graininess is of importance, special attention must be given the lighter colors in the color separation.

Using the secondary colorants does contribute to expand the gamut of reproducible colors, and to save ink consumption, but will inherently increase graininess if used in light areas. However, when also employing light inks (naturally increasing ink consumption), the main focus is typically image quality and reduced graininess, not ink saving. Thus, when combining both lighter and complementary inks, special attention should be given the usage of the complementary inks. The results in this study, focusing on the "blue" sub-gamut, clearly show that employing the blue ink most often increases the graininess, thus lowering print quality. For lighter colors, the "same" target color (at least within the just the noticeable difference) can be often reproduced by combinations of primary and lighter inks, without visible graininess. Thus, if print quality and low graininess is of importance, the usage of the complementary inks (in this case blue), should be "handled with care", and only be used for the dark and saturated colors, or where no other ink combination can be found.

The extensive amount of data collected for this study provides valuable insight into the relation between ink combinations, total ink coverage, and the resulting graininess. To select a unique ink combination in the color separation process, additional constraints must be used, because of the colorimetric redundancy. The result will be greatly affected by the criterion used, where ink saving and low graininess generally are directly contradictory. In an extended study, the data and the results have been used further, to propose a color separation model, expressing GI, color accuracy and ink consumption, as cost functions [14]. By letting the user define the relative importance of the colorimetric accuracy, graininess, and ink usage, the model will select the optimal ink combination, handling the colorimetric redundancy in 11-ink color separation.

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