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# Multi-channel dot-off-dot halftoning compensating for slightly chromatic gray inks

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**Abstract**

Printing using more than four ink channels visually improves the reproduction but causes challenges with the ink layer thickness that could lead to ink bleeding and color inaccuracy. A color image is commonly prepared for print by first being separated into the colorant channels the intended print device utilizes. The separations are usually halftoned independently, resulting in random dot overlap with possible spots where all colorants are printed. A multilevel halftoning algorithm that processes each channel so that it is printed with multiple inks of the same hue value has already been applied to three achromatic inks – photo gray, gray, black – in a real paper–ink setup. Results proved a successful multilevel halftone implementation workflow using multiple inks while avoiding dot-on-dot placement. However, in this approach, the gray inks were assumed to be neutral and lighter versions of black, an assumption that may cause a $\Delta E^*_{ab}$ color difference as high as 5. In the present paper an alternative approach, based on dot-off-dot halftoning avoiding dot overlap, is proposed and applied to the same three inks. A look-up table driven separation procedure of the original image into the three channels is also proposed, which, combined with dot-off-dot halftoning, results in a $\Delta E^*_{ab}$ color difference not larger than 1.8. Results show that the dot-off-dot halftoned images are visually pleasant without any artifacts in tone transitions. The proposed approach has three main advantages to the commonly used independent halftoning. One being that dot overlap between different inks is completely avoided, i.e. photo gray, gray and black in the present work. The other one is that the results are less grainy compared to independent channel halftoning. The third one is that dot-off-dot halftoning consumes less ink than independent halftoning when reproducing the same color.

**Keywords:** multilevel halftoning, dot-off-dot halftoning, dot gain compensation, multi-channel printing, graininess

## 1. Introduction

In color reproduction, the original image to be printed is firstly separated into the colorant channels that the print device utilizes. Traditionally, the channels used are cyan (C), magenta (M), yellow (Y) and black (K), but in the interest of reducing graininess and augmenting the color gamut for high quality color printing, additional channels are introduced (Jang et al., 2005). These additional channels can be light cyan (Lc), light magenta (Lm), gray (GY), photo gray (PGY), red (R), green (G), blue (B), orange (O), etc. Introducing additional channels is a solution to achieve high quality prints in many printing technologies.

In color print, after the original image is separated, each channel is commonly halftoned (transformed to a bitmap) independently of the other channels. The separated channels are halftoned because of 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 dots and if the printed dots are small enough, the human eye that acts as a low-pass filter perceives the printed image as being continuous tone.

Once the channels are halftoned, the printing system transfers the corresponding channel's ink (C, M, Y, K, etc.) onto the media substrate. A certain light–ink–paper interaction then happens, known as dot gain or tone value increase, which causes the printed image to appear darker than the original digital image. Dot gain is the reason that there is a differentiation between the ink coverage value sent to the printing system (reference coverage) and the resulting printed coverage, called effective coverage (Namedian and Gooran, 2011). That is why, before halftoning, the initial image is accounted for dot gain so that the printed image has the intended effective ink coverage. One of the models used to account for dot gain is the well-known Murray-Davies model based on the measurement results of a number of printed halftone patches (Murray, 1936).

As mentioned, multi-channel printing (printing with more than four channels) increases the gamut and improves the overall image quality. Nevertheless, a high number of colorants imposes new computational 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 color inaccuracy (Zeng, 2000). Certain halftoning algorithms can help to overcome these issues. One of them is channel dependent halftoning or dot-off-dot halftoning, which can be applied to two or more channels simultaneously and dependently, avoiding dot overlap as much as possible, see Section 2.2.

In Zitinski, Gooran and Nyström (2014) another approach, multilevel halftoning, was applied aiming at avoiding dot overlap when several colorant channels with the same hue values (e.g. magenta and light magenta) were used, see Section 2.1. This approach was applied to three achromatic inks – PGY, GY and K – using an inkjet printer. Besides the method's simplicity, one of the main advantages of this approach was that no dot overlap occurred, resulting in more homogenous prints. In addition, compared to the case using single black ink K, the proposed multilevel halftoning method resulted in increased print image quality in terms of graininess and detail enhancement (Zitinski, Gooran and Nyström, 2014). However, in the proposed multilevel halftoning approach, the gray inks PGY and GY were unjustifiably assumed to be neutral in color and considered to be lighter versions of K halftone with almost the same hue value. For instance, the $\Delta E^*_{ab}$ color difference between fulltone PGY and the closest halftone of K is a non-negligible 4.2. In the present paper, an alternative dot-off-dot halftoning approach is proposed with the main goal of avoiding dot overlap in the digital bitmaps while keeping the color difference between the three-inks print and the single K ink print within an acceptable range. A look-up table driven separation procedure of the original image into the three channels is proposed.

## 2. Previous work

### 2.1 Multilevel halftoning approach

In Gooran (2006), a multilevel halftoning method was proposed. Its implementation to achromatic inks in multi-channel printing was described and examined in Zitinski, Gooran and Nyström (2014) and is summarized in this section.

Most multi-channel printers utilize multiple inks with almost same hues but with different lightness/intensities or saturation. Multilevel halftoning algorithms are therefore becoming more important as the capabilities of the printers improve (Xujie et al., 2012). For instance, many printers use black and one or two gray inks, cyan and light cyan, magenta and light magenta. Since in this paper the focus is only on the achromatic inks, let us limit the discussion to the case with black (K) and two gray inks, photo gray (PGY) and gray (GY), PGY being the lightest one. The common method to use all three inks is to first separate the original image into its PGY, GY and K channels and then bi-level halftone the three channels independently. Nevertheless, assuming the gray inks to be lighter versions of black, the original achromatic channel could instead be multilevel halftoned and then separated to the PGY, GY and K bitmaps, with the advantage of no dot overlap.

The first step in applying multilevel halftoning is to identify the gray levels each of the lighter inks represents. The darkest ink at fulltone coverage, K, is represented by 1 or 100 %, and the paper by 0. In order to find the gray level for the other two inks, their CIE $Y$ values at 100 % coverage are compared to those of the printed K patches at different reference coverages. According to the measurement results in our paper–print setup, 100 % PGY and GY correspond to 42 % and 62 % coverages of K, respectively. The original image is therefore multilevel halftoned to four levels, i.e. 0, 0.42, 0.62 and 1, and separated into three PGY, GY and K bitmaps. This is done by setting all pixel positions where the multilevel halftoned image holds e.g. 0.42 to 1 in the PGY bitmap and to 0 in GY and K bitmaps. Similarly, GY and K bitmaps are created. Since the pixels in multilevel halftoned image only hold one of the values 0, 0.42, 0.62 and 1, there will not exist any pixel position set to 1 in more than one bitmap, guaranteeing no dot overlap. For more details, interested readers are referred to Gooran (2006) and Zitinski, Gooran and Nyström (2014).

### 2.2 Dot-off-dot halftoning

Many instances of dot-off-dot halftoning algorithms exist. Lau, Arce and Gallagher (2000) introduce green-noise halftone patterns designed to avoid, when possible, ink overlap between multiple channels. Bernal et al. (2014) introduce a clustered stochastic halftoning algorithm in which both the dot shape and dot placement are controlled. They also introduce an extension of the algorithm to produce dot-off-dot structures, enhancing the texture smoothness and increasing the gamut while reducing ink consumption. Kawaguchi et al. (1999) propose a method based on the vector error diffusion, taking into account the reflectance spectra and therefore improving the spectral image quality.

In multi-channel printing, the channels of the original image are commonly halftoned independently, leading to possible spots where multiple inks are printed. In

Gooran (2004), a color halftoning method was proposed that halftoned the color channels dependently, maximizing dot-off-dot. As a result, dot overlap is avoided when the sum of coverages of the channels is less than or equal to 100 %. When the sum exceeds 100 %, minimum dot overlap occurs. For example, dot-off-dot printing of two channels with coverages of 80 % and 60 % will give the minimum overlap of 40 %.

The color halftoning method used in this paper is based on Iterative Method Controlling Dot Placement (IMCDP), an iterative halftoning algorithm for grayscale images, proposed in Gooran (2004), where the dots are placed iteratively with the goal of reducing the difference between the original and the halftone image. The creation of the halftone image starts with a blank image of the same size as the original. The total number of dots to be placed in the halftone image is known beforehand, as it is dependent on the original image's overall lightness/darkness. Starting with a blank image, in the first step, the algorithm finds the position of the darkest pixel (the pixel holding the maximum value) in the original image and places the first dot at that location in the halftone image. In the next step, the low-pass filtered version of the halftone image is subtracted from the low-pass filtered version of the original image. The low-pass filter used is Gaussian filter with standard deviation 1.3 truncated to 11 × 11 pixels. This operation is addressed in Gooran (2004) as the feedback process. Subtracting the filter from the image around the found pixels reduces the pixel values in a neighborhood of that pixel, meaning that the chance of the neighboring pixels to be picked as the next maximum is reduced. Then, the location of the maximum pixel value of the subtracted image is found and at that location on the halftone image the next dot is placed. The process continues until the known number of dots is placed, and the final halftone image is achieved. Due to the nature of IMCDP, it is easily extended to a color halftoning method utilizing dot-off-off as much as possible. Since in this paper the dot-off-dot strategy will only be used to halftone two channels, e.g., PGY and K, let us for the sake of simplicity explain the method on these two channels. The algorithm starts with two blank images representing PGY and K. It finds in advance the number of dots to be placed in PGY and K, respectively. The algorithm starts with finding the position of the maximum pixel value in the two channels; say it is found in the PGY channel. Then, that pixel in PGY is set to 1; the feedback process is performed as in IMCDP, not only on PGY but also on K as well. Consequently, the pixel value at this position in K is also reduced, making this position in K skipped as maximum until all other pixels are set to 1. By using this strategy, dot-off-dot is ensured if the sum of the coverages in PGY and K doesn't exceed 100 %. Since the dot-off-dot halftoning method is described in detail in previous publications, the interested reader is referred to Gooran (2004).

The only concern regarding the proposed approach is its computational speed. The separation is performed using a look-up table, created once, resulting in a swift separation procedure, see Section 3. The only possible time-consuming part is the dot-off-dot halftoning. The dot-off-dot halftoning in this paper is based on the approach explained, creating different threshold matrices for different separations (Gooran and Kruse, 2015). These threshold matrices are created once and stored. The halftoning process is therefore reduced to comparing each pixel value in each separation with a threshold value in the corresponding threshold matrix. This means that the halftoning process is as fast as it can be. To give an indication of the processing speed, a 1536 × 1536 pixel image was halftoned by IMCDP and thresholding. The former one took 196 seconds while the latter one only took 0.03 seconds in Mathworks Matlab (2011b) using the same computer. How to generate the threshold matrices is out of the scope of this paper and the interested reader is referred to Gooran and Kruse (2015).

## 3. Channel separation based on dot-off-dot halftoning

From now on in this paper, capital letters (e.g. PGY) denote an ink or colorant, while the subscript "ref" (e.g. $PGY_{ref}$) will indicate the ink's reference coverage.

As discussed in Section 2.1, in the multilevel halftoning applied to achromatic inks the thresholds are chosen based on the CIE *Y* value of the black ink at different area coverages. For example, in our print setup the black ink K halftones at 42 % and 62 % have the closest CIE *Y* values to fulltone PGY and fulltone GY, respectively. The multilevel halftoning approach would work perfectly if the PGY and GY inks were as "neutral" as the K halftones. According to our measurement results presented in Section 4 and 5, the $\Delta E^*_{ab}$ color differences between fulltone PGY and GY and K halftones at 42 % and 62 % are 4.2 and 4.57, respectively. Hence, although fulltone PGY has almost the same CIE *Y* (or CIE *L**) value as 42 % K, the color difference between them is 4.2, which is not acceptable in many applications. The proposed dot-off-dot approach copes with this issue by adding K inks in regions where K was not used in multilevel halftoning approach. In addition, contrary to the multilevel halftoning, in the new proposed approach the image is first separated into three different channels, PGY, GY and K, and then halftoned dependently by the dot-off-dot printing strategy described in Section 2.2.

Despite the differences, two of the main goals of the new approach are the same as those of the multilevel approach. One of them is to reduce the image graininess, compared to using only one K or to independently halftoning the PGY, GY and K channels. The second common goal is to completely avoid dot overlap. The new approach in addition aims to reproduce the same neutral colors as halftones of K. Notice that in this paper we refer to the colors reproduced by a combination of K inks and paper, i.e. K halftones, as neutral colors.

As the separation of an image into its PGY, GY and K channels represents the main challenge of this approach, it is described in this section for a given pixel value in the original image (or reference coverage of K) into three channels with coverages $PGY_{ref}$, $GY_{ref}$ and $K_{ref}$. In order to do that, a number of test patches has to be printed: single ink PGY, single ink GY, single ink K, PGY and GY (PGY&GY), PGY and K (PGY&K) and finally GY and K (GY&K). Notice that since one of the goals is to completely avoid dot overlap, the sum of the coverages of the two involved inks should not exceed 100 %. In the next step, the printed patches are measured and interpolated.

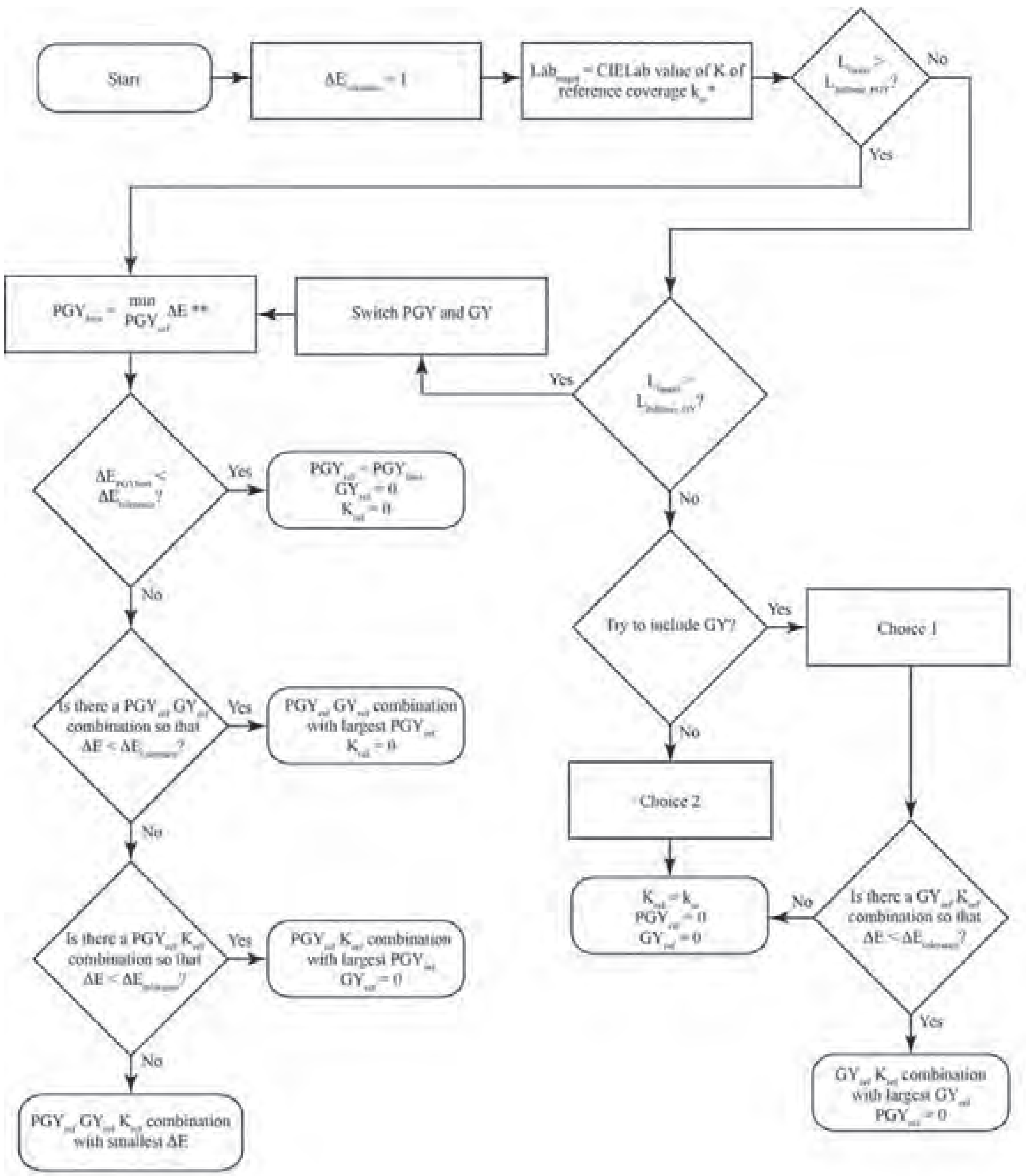


*Figure 1: Channel separation workflow (ΔE stands for $\Delta E^*_{ab}$ and L for L*)*

Table 1 shows the ink combinations considered in the three different regions in the proposed separation model. The separation approach is performed after collecting the measurement data and performing the interpolations, displayed as flowcharts in Figure 1.

*Table 1: The ink combinations considered in each region*

| Region number | 1 | 2 | 3 |
|---|---|---|---|
| Region interval | [0, 0.42] | [0.43, 0.62] | [0.63, 1] |
| Region ink combinations | PGY<br>PGY&GY<br>PGY&K | PGY&GY<br>GY<br>GY&K | GY&K<br>K |

In Figure 1 the input reference K coverage (or the pixel value) is denoted by $k_{in}$. The outputs are $PGY_{ref}$, $GY_{ref}$ and $K_{ref}$, which are the pixel values at the corresponding pixel position in the separated PGY, GY and K channels, respectively.

The tolerance for $\Delta E^*_{ab}$ color difference is chosen as 1 in this paper. Marked by * in Figure 1, for each given input pixel value, i.e. $k_{in}$, the CIELAB value of the K halftone corresponding to the reference coverage of $k_{in}$ is found by using the interpolated CIELAB measurement results for the printed K halftones. This is then used as the target CIELAB value denoted by ($L^*_{target}$, $a^*_{target}$, $b^*_{target}$).

Marked in Figure 1 by **, the $\Delta E^*_{ab}$ between all the interpolated CIELAB values for PGY (single PGY) and the target CIELAB value are calculated and the $PGY_{ref}$ that minimizes $\Delta E^*_{ab}$ is found and denoted by $PGY_{best}$.

## 4. Experimental setup

In order to be able to verify dot-off-dot printing in the used print setup and to find the channel separations, a number of patches is printed and measured. The measurement results are dependent on the ink combination, type of substrate, halftoning method and print resolution. The following specifications were applied:

For single ink prints, patches with 0 to 100 % reference ink coverage, in steps of 10 %, were printed for all three inks, yielding 11 patches for single printed PGY, 11 patches for single printed GY and 11 patches for single printed K, totally $3 \times 11 - 2 = 31$ single ink patches. The value 2 was subtracted because 0 % patch was included three times.

For two ink combinations, as marked in Figure 2 with gray, the following three specifications were applied.

PGY&K: 28 PGY&K patches were printed (dot-off-dot and no overlap), with $PGY_{ref}$ ranging from 30 to 90 %, with a step of 10 %, and $K_{ref}$ ranging from 10 to 70 %, with a step of 10 %. For $PGY_{ref}$ values smaller than 30 % it is not necessary to involve K to get close to the target color. $K_{ref}$ larger than 70 % means dark tones where PGY is obsolete. Observe that the condition of no dot overlap should be fulfilled, meaning $PGY_{ref} + K_{ref} \leq 100$ %. Therefore, only combinations marked with gray in Figure 2 fulfill this condition, making the total number of needed patches 28.

PGY&GY: 28 PGY&GY patches were printed (dot-off-dot and no overlap). $PGY_{ref}$, ranging from 30 to 90 %, with a step of 10 %, and $GY_{ref}$ ranging from 10 to 70 %, with a step of 10 %.

GY&K: 42 GY&K patches were printed (dot-off-dot and no overlap). $GY_{ref}$, ranging from 10 to 90 %, with a step of 10 %, and $K_{ref}$ ranging from 10 to 70 %, with a step of 10 %.

The total number of the printed patches is therefore 129. Notice also that the patches are printed, measured and then interpolated, creating a look-up table. This results in a swift separation where the right combination in the look-up table is obtained given an input pixel value $k_{in}$.

All prints were made using an inkjet 12-channel printer Canon ImagePROGRAF iPF6450. All samples were printed on 170 g/m$^2$ matte coated paper at a resolution of 600 dpi. Nevertheless, the same workflow can be

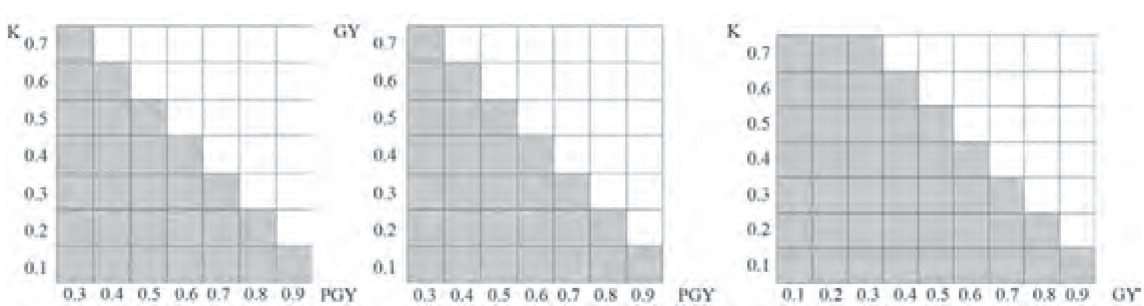


*Figure 2: Ink combinations of printed patches; only combinations marked with gray are printed*

applied to other media substrates and other printing resolutions. The CIEXYZ and CIELAB values of the printed patches were measured using the spectrophotometer BARBIERI electronic Spectro LFP RT, illuminant D50 with 2° standard observer. The data were then linearly interpolated with a step of 0.001. Cubic interpolation was also tested but it had no considerable impact on the results. Therefore, due to simplicity and calculation speed, we recommend the linear interpolation when, as in this case, the coverage steps are up to 10 %. Cubic interpolation may cause oscillating polynomials that could result in errors when no measured data is available for the parts of the created table usually filled with constant default values.

## 5. Results and discussion

The first important task for the multilevel halftoning approach is to localize the thresholds. The thresholds for the above experiments were found to be 0.42 and 0.62. Each interval is separated into three regions, as shown in Table 1.

In all calculations, the tolerance for the $\Delta E^*_{ab}$ color difference was set to 1. One of the interesting results was that the single GY and the PGY&GY combination never produced a colour difference smaller than 3, meaning a significant discrepancy of these ink arrangements from neutral for this type of digital printers and inks. Therefore, from now on they can be discarded from the alternatives, thus reducing the number of needed printed patches for future characterization to 91.

5.1 Color difference

For the sake of comparison between the proposed approach and multilevel halftoning approach, suitable multilevel halftoned patches were printed, measured and interpolated.

In order to verify the dot-off-dot halftoning approach proposed in Section 3, the reference K value ($k_{in}$) was varied from 0 to 1 with a step of 0.01. For each $k_{in}$, the corresponding steps in Figure 1 were performed and the achieved $\Delta E^*_{ab}$ was calculated. The same was done for the multilevel halftoning approach. Figure 3 shows these calculated $\Delta E^*_{ab}$ for both multilevel and dot-off-dot halftoning approaches versus $k_{in}$. For the dot-off-dot approach, the separation according to both, choice 1 and choice 2, shown in Figure 1, was used.

As seen in Figure 3, the color difference is much higher for multilevel halftoning, reaching $\Delta E^*_{ab} = 5$ for some $k_{in}$ (dotted curve). The color differences using the dot-off-dot halftoning approach are always low, sometimes exceeding the chosen tolerance of 1 (solid and dash-dot curves).

Let us analyze the color difference of dot-off-dot approach in the three tonal regions. In region 1, there is an interval (between 0.1 and 0.42) at which it was not possible to find any combination giving a color difference smaller than the tolerance, i.e. $\Delta E^*_{ab} = 1$. However, the maximum color difference is around an acceptable 1.8 (occurring at $k_{in} = 0.19$).

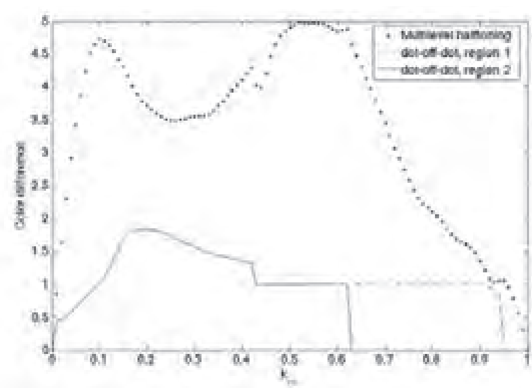


*Figure 3: $\Delta E^*_{ab}$ color difference for multilevel and dot-off-dot halftoning approaches based on interpolated CIELAB values*

In region 1 the lightest tone values were possible to reproduce with PGY, while for the tones between 0.16 and 0.42 the algorithm always found the best combination among PGY&K.

In region 2 the color difference is always less than the tolerance. In region 3 the color difference using choice 2 in Figure 1 is, as expected, always zero. In the case of dot-off-dot printing using choice 1, the color difference is always lower than the tolerance, being zero for tones darker than 95 %, as there the single K was chosen as the best alternative.

It is worth mentioning a reference to chroma. Since in the multilevel approach the CIE $Y$ (or CIE $L^*$) is used to find the coverage of PGY and GY inks, the $\Delta L^*$ between K and its corresponding PGY and GY separations is equal to zero. This means that the absolute value of the chroma difference, $|\Delta C^*_{ab}|$, is always smaller than or equal to $\Delta E^*_{ab}$ (dotted curve in Figure 3). Nevertheless, for the dot-off-dot approach, the CIE $L^*$ values between K and its corresponding PGY, GY and K separation are very close but not necessarily equal, resulting in very small $\Delta L^*$ even in this case. Therefore, $|\Delta C^*_{ab}|$ is smaller than or equal to the $\Delta E^*_{ab}$ values shown in Figure 3 (solid and dashed curves).

An important point is that the GY&K combination was not considered in region 1. The error is however acceptable and this combination can easily be added if one would aim on reducing the error further.

The graphs shown in Figure 3 were computed using the measured and interpolated CIELAB values for 129 patches. In order to verify the graphs shown in Figure 3, patches with coverage $k_{in}$ ranging from 0 to 100 % with a step of 2 % were created and halftoned in three different ways. First, they were halftoned by a bi-level algorithm and printed with single K ink. Then they were multilevel halftoned and printed with PGY, GY and K. Lastly, they were separated by the approach proposed in Section 3 (choice 1 was used) and the PGY, GY and K separations were halftoned by the dot-off-dot halftoning method.

The CIELAB values of these $3 \times 51 = 153$ printed patches were measured and the $\Delta E^*_{ab}$ values between each patch and the corresponding K patch were calculated and are shown in Figure 4. As seen, the color differences based on the measurement results are very similar to those shown in Figure 3, proving a successful characterization with low error.

5.2 Graininess

One of the main advantages of adding PGY and GY inks is graininess reduction (Zitinski, Gooran and Nyström, 2014). A graininess evaluation measure is the standard deviation of the pixel values of the halftone. For this purpose, patches with coverage ranging from 0 to 100 % with a step of 1 % were created and halftoned by three halftoning methods, bi-level (with single K), multilevel and dot-off-dot (with PGY, GY and K). The standard deviations of the pixel values of the halftones were then calculated and shown in Figure 5. As seen, the graininess for multilevel halftoning (dash-dot curve) is mostly lower than the other two. The reason the standard deviation is zero at the thresholds is that at these coverages the patches are represented by fulltone PGY and fulltone GY, respectively. Figure 5 also shows that the dot-off-dot halftoning approach (solid curve) always results in less grainy halftones than when only using single K ink (dotted curve).

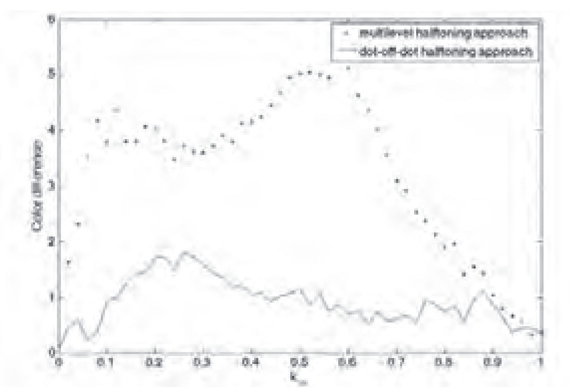


*Figure 4: $\Delta E^*_{ab}$ color difference for multilevel and dot-off-dot halftoning approaches based on measurement results*

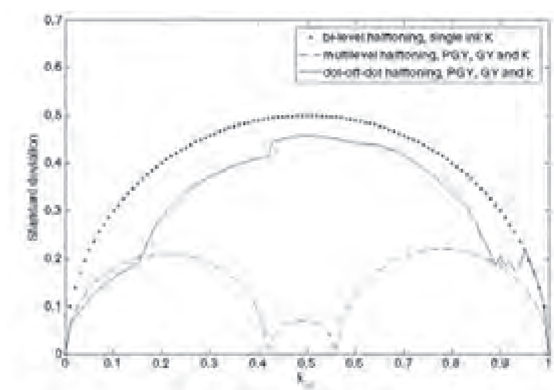


*Figure 5: Standard deviation of the pixel values of patches halftoned with bi-level, multilevel and dot-off-dot halftoning*

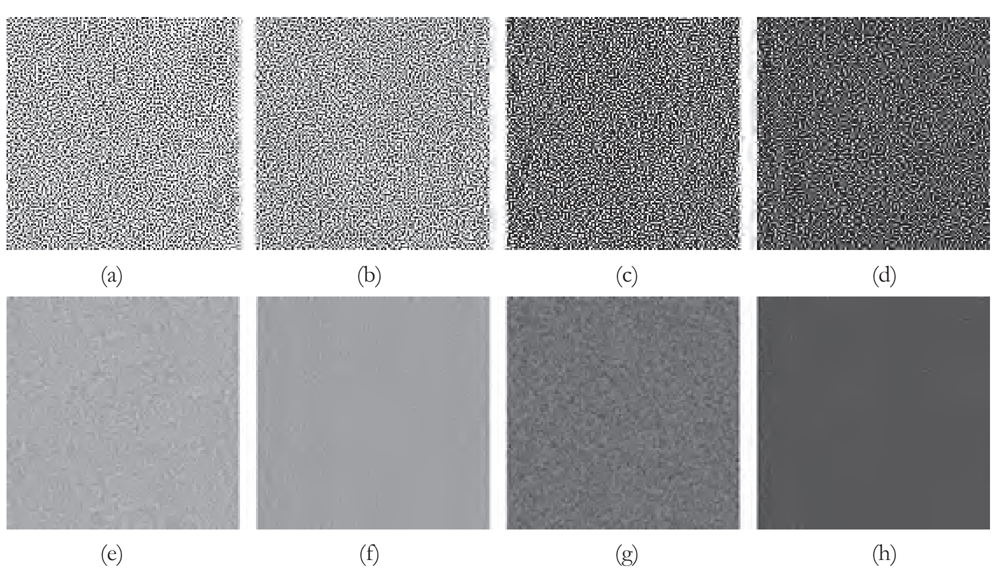


*Figure 6: Two patches representing K at 40 and 80 % reference coverage were separated to PGY, GY and K channels; the channels were halftoned by a) and c) independent halftoning, b) and d) dot-off-dot halftoning; a), b), c) and d) are enlargements of e), f), g) and h), respectively*

(a)

(b)

(c)

*Figure 7: Scanned versions of the printed gray scale ramp with reference coverage ranging from 0 to 50 % – a) bi-level halftoning, only K is used; b) multilevel halftoning, PGY, GY and K are used; c) dot-off-dot halftoning, PGY, GY and K are used*

The reason dot-off-dot reduces graininess more than multilevel between 0 and 0.16, despite using the same PGY ink, is the increased coverage necessary to approximate K.

Dot-off-dot halftoning approach has at least three advantages compared to independent halftoning of PGY, GY and K channels, i.e. less graininess, less ink consumption due to the smaller area covered by ink and no ink overlap. In order to demonstrate these, two patches were halftoned independently and with dot-off-dot corresponding to 40 and 80 % of K (i.e. $k_{in}$ = 0.4 and 0.8). The dot-off-dot separation approach separates these patches into ($PGY_{ref}$ = 0.3 and $K_{ref}$ = 0.28) and ($GY_{ref}$ = 0.28 and $K_{ref}$ = 0.59), respectively. Assume that a separation for an independent halftoning would give the same coverages. The digital representations of the resulting halftones are shown in Figure 6, demonstrating less grainy results with dot-off-dot halftoning. The standard deviations for images shown in Figures 6b and 6d are 0.41 and 0.33, while those for the images in Figure 6a and 6c are 0.43 and 0.44, respectively. In order to show the halftone structures, the images e to h in Figure 6 were enlarged 3 times and are shown in a to d. The images in Figure 6b and 6d look darker than the correspondent one using independent halftoning because the channel separation was performed for dot-off-dot halftoning and not independent halftoning. If the same original images were separated for independent halftoning they would surely result in larger coverages for PGY and K separation, resulting in even larger standard deviations and grainier results. It would also require more ink to reproduce the same tones. In the images shown in Figure 6a and 6c, there is 0.3 × 0.28 = 8.4 % and 0.28 × 0.59 = 16.5 % dot overlap, respectively, while in the images shown in Figure 6b and 6d no dot overlap occurs.

### 5.3 Tonal transition smoothness

One of the biggest challenges when involving several inks is to attain smooth transitions between tonal values. The best image to verify the smoothness with is a gray scale ramp with a continuous transition from 0 % to 100 % coverage.

Such a ramp was created, separated with the proposed approach and dot-off-dot halftoned. The ramp was also halftoned by a bi-level and multilevel halftoning. All three ramps were then printed at 600 dpi. Unlike in Section 5.2, the simulation of the results cannot be a good representation of the printouts, because the separation process for dot-off-dot halftoning approach is dependent on the printer, resolution, paper and inks. The chosen way to illustrate the results was to scan the printouts at 600 ppi, shown in Figure 7. Higher resolution was not applied, since the overall impression of the printouts was of interest rather than the halftone structure. In order to more clearly illustrate the transitions, only the tonal values between 0 % and 50 % are shown, as the other half of the ramp is too dark, moreover, since no dot gain compensation has been made at this point. As seen in Figure 7, the tonal transitions of all the ramps are smooth and without any tonal discontinuities. Possible visible discontinuities in the three images are a result of the scanning distortions. It can also be seen that the multilevel halftoned image is the least grainy one and that the bi-level halftoned one using only K is the grainiest one.

### 5.4 Dot gain compensation

One of the main challenges in any printing workflow is to achieve full control over dot gain. Here, we describe how an image can be compensated for dot gain, performed during the separation from $k_{in}$ to $PGY_{ref}$, $GY_{ref}$ and $K_{ref}$. The only difference is the calculation of the target CIELAB value. When no dot gain compensation was involved, the target was the CIELAB of K halftone at the input reference coverage $k_{in}$. This target is what differs when performing dot gain compensation.

First the relationship between the effective coverage ($a_{eff}$) and the reference coverage ($a_{ref}$) has to be found for K by Murray-Davies formula, Equation 1,

$$a_{eff} = \frac{Y - Y_p}{Y_{ink} - Y_p}, \qquad [1]$$

where, $Y$, $Y_p$ and $Y_{ink}$ are the measured CIE $Y$ values for K patches with $a_{ref}$ = 0 to 100 % with a step of 10 %, the CIE $Y$ value for paper and the CIE $Y$ value for fulltone K, respectively. By using the interpolated data for single K halftones, the reference coverage ($a_{ref}$) giving the effective coverage $a_{eff} = k_{in}$ is found, denominated $k_{new}$. The CIELAB value of K halftones that corresponds to reference coverage $k_{new}$ is found and used as the target CIELAB value.

Therefore, in order to carry out dot gain compensation for linear dot gain response, the calculation of the CIELAB target value in Section 3 is modified as follows. Find the relationship between $a_{eff}$ and $a_{ref}$ for K. For each given pixel value, i.e. $k_{in}$, find the corresponding reference coverage, $a_{ref} = k_{new}$ giving $a_{eff} = k_{in}$. Then find the CIELAB value of the K halftone that corresponds to reference coverage $k_{new}$ and use it as the target CIELAB value ($L^*_{target}$, $a^*_{target}$, $b^*_{target}$). The rest of the separation remains unchanged.

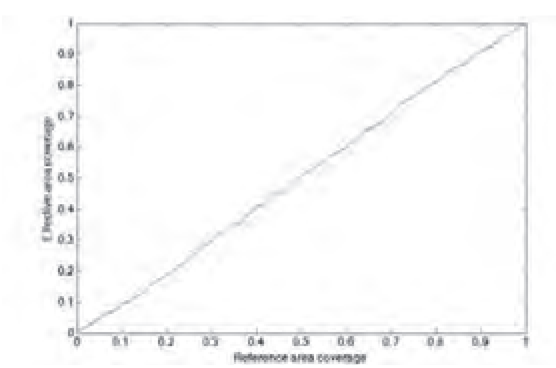


*Figure 8: Effective versus reference area coverage for dot-off-dot halftoning approach, compensated for linear dot gain response*

In order to verify the linear dot gain response, patches with reference coverage ranging from 0 to 100 % with a step of 2 % were created and separated to their PGY, GY and K channels as described. The separated patches were then halftoned by dot-off-dot halftoning, printed and measured. Figure 8 shows the effective area coverage versus the reference area coverage. As seen in Figure 8, the plot is a straight line, proving a successful dot gain compensation and dot gain control. Notice that the plot shown in Figure 8 was found by using CIE $Y$ values. Nevertheless, CIE $X$, CIE $Z$ and the reflectance spectra were also used to find the curve, demonstrating identical results.

5.5 Printing with only PGY and K

After compensating for dot gain, it was noticed that the GY&K combination was only used for reference tone values between 89 % and 100 %. This along with the fact that the single GY and the PGY&GY combination were never among the best choices led us to the possibility of using only PGY and K inks, disregarding GY. The separation process would be the simplified version of the separation approach explained in Section 3. For region 1, lighter than 42 %, two possibilities exist, PGY or PGY&K. For regions 2 and 3, darker than 42 %, PGY&K or K are contemplated. Excluding GY further reduces the number of needed measured patches to 49. Figure 9 shows the calculated $\Delta E^*_{ab}$ for dot-off-dot halftoning approach only using these two inks. As seen in this figure, the color difference peaks at around 1.8. Therefore, GY can be ignored if the linear dot gain response is required or a slightly larger color difference between 42 % and 82 % is tolerated (compare Figure 9 with Figure 3).

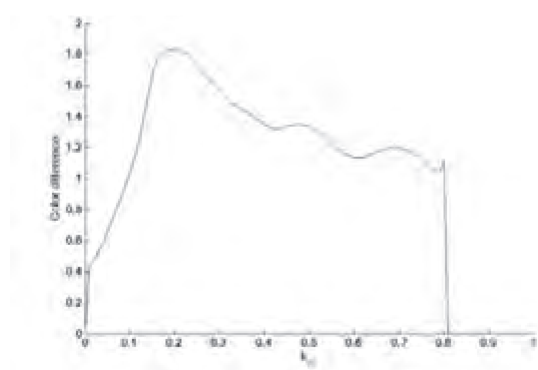


*Figure 9: $\Delta E^*_{ab}$ color difference for dot-off-dot halftoning approach using PGY and K inks based on interpolated measurement of CIELAB values*

## 6. Conclusions and future work

Dot-off-dot halftoning approach has been implemented in multi-channel printing using three different inks – gray (GY), photo gray (PGY) and black (K). This approach was suggested as an alternative to the multilevel halftoning approach, proposed in Zitinski, Gooran and Nyström (2004), as a way to neutralize the PGY and GY inks. The separation approach from a given reference K value (pixel value) to PGY, GY and K separations was described. The calculations were based on the measurement results of a total of 129 printed patches. As it was verified, some ink combinations can be excluded from the measured patches in future characterization of similar print setups, making the total number of needed patches 91. The results have shown that the dot-off-dot halftoning approach is able to reproduce all tones of K with a maximum error of 1.8, without ink overlap. It was also shown that dot-off-dot halftoning not only results in less grainy halftones but also requires less ink than both single K prints and independent halftoning. The smoothness of tonal transitions was also verified by printing a gray scale ramp. The dot gain compensation procedure was described in detail and the plot of the effective versus reference area coverage shown in Figure 8 verified that the proposed dot-off-dot halftoning workflow for the printer, inks and substrates used was successfully controlled and can be applied to other frameworks.

The proposed approach has the potential to be applied to multi-channel printing using other inks besides PGY, GY and K, such as C, Lc, M, Lm and Y. If the proposed dot-off-dot halftoning approach is to be used, providing that only the graininess is the concern and not the expansion of the color gamut, the original image only needs to be separated to four channels, C, M, Y and K. The K channel itself is halftoned using PGY, GY and K with no ink overlap, as described in this paper. The C and M channels are halftoned using C and Lc and M and Lm, respectively, with no ink overlap, in a workflow similar to the one described in this paper. Finally, the Y channel is halftoned for itself. This way, there will not be any spot with more than four inks involved and most of them can be replaced by one ink or two inks on top of each other.

In order to be able to reach a larger gamut than CMYK can offer with the proposed approach, coverages whose sum exceeds 100 % need to be included, resulting in some ink overlap. However, the overlap will occur only when necessary for reaching a specific CIELAB target outside CMYK gamut.

The separation can be done similarly to what was described in this paper, yielding dot-off-dot halftones with minimum ink overlap. The benefits of reduced graininess and ink consumption will remain. Since, in this case, increased coverage of the lighter colorants, i.e. PGY, GY, Lc and Lm, is involved, the difference in graininess and ink consumption between the two methods will be more evident.

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