Hybrid Halftoning, A Useful Method for Flexography

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Most printing devices, such as laser and ink jet printers and many print presses, are restricted to very few colors. The contone images should therefore be transformed into binary ones before being printed. The techniques doing this transformation are referred to as halftoning methods. Halftoning methods can be divided into two main categories, namely AM (Amplitude Modulated) and FM (Frequency Modulated). Some printing methods, such as Flexography, are not able to produce dots sufficiently small in order to handle the highlights and the shadows of the original image by using just an AM halftoning method. In this article we propose a hybrid halftoning method that incorporates AM and FM technologies in order to overcome this problem. The strategy is to use an FM method in the highlights (and the shadows) of the image and an AM method in the rest of the image.

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Introduction

There are two main types of halftoning, AM (Amplitude Modulated) and FM (Frequency Modulated). In the AM technique the size of the dots is variable while their spacing is constant. The single dot within the halftone cell grows larger as the tone value becomes darker and smaller as the tone value becomes lighter. In the FM technique, contrary to the AM technique, the size of the dots is kept constant while their spacing varies. The number of micro dots within the halftone cell increases as the tone value becomes darker and decreases as the tone value becomes lighter. However, for non-conventional FM halftoning methods, such as Error Diffusion, it is not so accurate to use the term halftone cell. In these kinds of halftoning methods you use rather the term *dpi* (dots per inch), i.e., number of micro dots per inch, than the term *lpi* (lines per inch), i.e., number of halftone cells per inch. This means that a conventional method could be AM or FM depending on whether the dots within the cell are clustered or dispersed. It has also to be mentioned that all FM methods are not necessarily stochastic, although the terms AM and FM halftoning are sometimes replaced by conventional and stochastic halftoning respectively.

Flexography is a modified form of letterpress printing method that is commonly used in the packaging industry for printing on the most varied materials. The print quality in flexography is lower than that in for example offset printing. On the other hand, flexography is the only printing method that can print on very thin, flexible, and solid films, thick card boards, rough-surface packaging materials and fabrics.[1]

One of the problems with Flexography is that it can not produce the dots sufficiently small in order to handle the very light and dark parts of the original image by just using an AM method. Experience on AM and FM methods showed that both technologies have their advantages and drawbacks in the Flexographic printing. AM technologies are especially useable in the mid-tones because dot gain is lower than when a FM technology is used there. FM methods, on the other hand, perform very well in the highlights where the optimized dot positioning and the choice of the minimum dot size allow for a perfect match to the technical limitations of the printing process.[2] It also allows the rendering of halftone images with higher line rulings than traditional AM, because FM-based halftoning is used in the highlights and shadows.[3]

First in this article we review a number of works that have previously been done in the area. Second, the FM method used in the proposed hybrid halftoning method is briefly described. Third, the proposed hybrid halftoning method is described in detail followed by a section where we show the results of our real test prints and compare the result of the proposed method with that of the SambaFlex™ raster method. Finally an overall discussion is given in the last section of this article.

Previous Work

Since different halftoning techniques have their own advantages and drawbacks it has always been attractive to find hybrid methods that include the good properties of different halftoning methods. For example, in Ref. 4 the authors propose a hybrid method that incorporates error diffusion and ordered dithering methods. In Ref. 5 we introduce a hybrid halftoning method that

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uses a FM method for the details of an image and an AM method in the homogenous parts of it.

In this article, however, we focus on a hybrid method that could be useful for Flexographic printing method. The problem that has been mentioned earlier in this article has been addressed in many articles and documents.[2,3,6–10] All of them present the problem and mention that a combination of FM and AM halftoning techniques can resolve the problem. None of them, however, gives any detailed description on how the methods should be implemented. We did not find any other published studies that gives a detailed description of these kinds of hybrid halftoning methods. A short summary of the articles and documents that present the problem and suggest solutions is following.

In Ref. 2 the authors present SambaFlex screens and compare this technique with two other screen techniques, namely frequency modulated classic screening (also called quantum hybrid screening) and Hybrid Screening (mixture of stochastic and conventional screening). The FM classic screening is not a mixture of stochastic and conventional screening. Instead, it is conventional screening, where a portion of the highlight dots is left out depending on the dot percentage. According to the authors this method has two important drawbacks compared to their SambaFlex Screens[2]:

- The dot pattern is not stochastic anymore and shows visible artifacts,
- The transition between the frequency modulated part and the purely conventional part is very hard.

In the method that is called Hybrid Screening in Ref. 2 a mixture of stochastic and conventional methods is used. The classic screen is cut off at a density for which the screen dots have a certain critical size. The stochastic screen is made of screen dots with this critical size. To avoid a clear transition between the classic and the stochastic parts both the classic screen and the stochastic screen are mixed in an intermediate density range. According to the authors of Ref. 2 the appearance of the classic screen (typically at 5% and 95%) and the disappearance of the stochastic screen (typically at 10% and 90%) can result in a clear boundary in, for example, vignettes. The transition between a pure stochastic and a mixture between stochastic and classic screen is also problematic. The method we present in this article has some similarities to Hybrid Screening but there are some differences as well. In our method there is no mixture between stochastic and classic screen. In the highlights (and shadows) we use a FM method with the smallest possible producible dot (referred to as the critical dot in this article) and in the rest of the image we use an AM method (or classic screen). We are going to show that the performance of our proposed method is very much dependent on the FM method. In the SambaFlex screening method there is a gradual transition between stochastic and classic screens. In the highlights, the dot pattern does not follow any classic pattern. At 25% dots come nearer to the classic theoretical center, and one can see dots "dancing" around the classic centers. Finally, at 50%, the dots are fully on the classical grid.[2] The available literature does not, however, describe how this method is implemented. As will be illustrated by the experimental results later in this article the method presented in this article actually results in better dot structure in the highlights compared to SambaFlex.

In Ref. 6, Nexus™ Hybrid Screening, the problem is addressed, and again a combination of AM and FM is mentioned as the solution. Without going into any details in Ref. 6 two methods are described which have already been mentioned above. Quantum hybrid screening only uses AM dots. When the AM dot size reaches the minimum dot size the customer can hold on plate, AM dots will be randomly removed to obtain the lighter tone values.

In Ref. 7, PerfectBlend™ Hybrid Screening is presented, but no details are given. According to the images shown in this document they probably use a method similar to quantum hybrid screening described earlier in this section. It is also mentioned that by using hybrid screening offset printers can increase the line screens they use over the AM values, without increasing on press difficulty.

Blondal[8] defines various forms of FM, AM and hybrid screening technologies and evaluates their strength, weaknesses and behavior.

Bartels[9] provides an overview of the advantages and disadvantages of hybrid screening. It is shown how advantages of both AM and FM screening can be combined in hybrid screening that, according to this author, will be the screening technology of the future. Although the hybrid screening methods are discussed and described by words and a number of images are shown, this article does not give any detailed description of the hybrid screening techniques. In Ref. 3 this same author proposes a number of techniques that reduce the visibility of the tile-based pattern, again without describing of any specific hybrid screening technique.

We have also introduced our method[10] without going much into the details. In the following sections we are now going to thoroughly describe the method. Before describing the method however, we present the FM halftoning technique that is used in our hybrid screening method.

Very recently Lin and Allebach have introduced a hybrid screen method that produces a stochastic dispersed-dot texture in highlights, and a periodic clustered-dot pattern in mid-tones.[11] The experimental results show a very smooth transition from dispersed-dot texture to cluster-dot pattern. This method is, however, most suitable for electrographic devices that produce a very noisy rendering of mid-tone dispersed-dot texture.[11] As can be understood, the idea behind developing this method and its application is somewhat different from our goal, which is to introduce a hybrid halftoning useful for Flexography. The aim in Ref. 11 is to reduce the noisy impression in mid-tones introduced by dispersed-dot dithering, by using clustered-dot in these regions. These authors do not discuss the problem associated with Flexography, i.e., the dots cannot be smaller than a specific size (critical dot size), or how to overcome this problem. However, their method can probably be modified to be used in Flexography.

The FM Method

In this section we give a short description of the FM method that is used in the proposed hybrid halftoning technique. This method is thoroughly described in Ref. 12. In this method the initial binary image is supposed to be empty, that is there is no dot in the initial halftoned image. The problem of halftoning a grayscale image can easily be described as placing a number of dots on this empty initial image so that the final result "resembles" the original image. As the overall impression of lightness/darkness of the image is very important, the number of dots to be placed can actually be determined in advance. The sum of the pixel values in the original

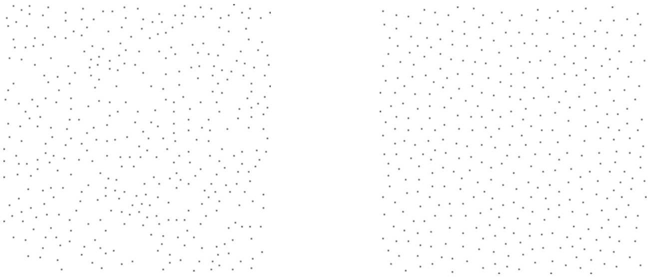


Figure 1. A constant image with a gray value of 1% is halftoned by the proposed FM method. a) The filter size is 11×11. b) The filter size is 21×21.

image rounded to the nearest integer gives us the number of dots that should be placed. Now when we know the number of dots to be placed the question is where to place the '1's, i.e., the black dots. In this method the dots are placed iteratively in order to decrease the difference between the original image and the halftoned image. Therefore, the first dot is placed at the position of the darkest pixel in the original image. By the darkest pixel we mean the pixel that holds the largest value, i.e., the position of the maximum in the original image. Since the human eye acts as a low-pass filter the difference of the low-pass versions of the two images should actually be decreased. Therefore the original image should be low-pass filtered prior to the method. Once the first dot is placed, the filtered version of the current halftoned image is subtracted from the filtered version of the original image. (This process will be referred to as the feed-back process in the following). Then the position of the maximum in this modified image is found and the second dot is placed there and the feedback process is performed again. This will continue until the predetermined number of dots are placed and then the final halftoned image is achieved. The low-pass filter used within the method has a great impact on the final result and therefore should be carefully chosen. In Ref. 12 we describe how this filter is designed.

According to our experiments the gray tones are not reproduced well for some images, especially in the highlight and shadow regions. To overcome this problem we choose to control the number of dots to be placed in a number of gray tone regions, and not only over the entire image. Since the highlights and shadows are more sensitive to changes in gray tones we use more control regions in these areas. We choose seven control regions between gray tones 0 and 0.1, i.e., [0, 0.01], [0.01, 0.02], [0.02, 0.03], [0.03, 0.04], [0.04, 0.06], [0.06, 0.08], [0.08, 0.1]. We choose another eight control regions between 0.1 and 0.9, i.e., [0.1, 0.2], [0.2, 0.3] and so on. We choose another seven control regions between 0.9 and 1, [0.9, 0.92], [0.92, 0.94], [0.94, 0.96], [0.96, 0.97], [0.97, 0.98], [0.98, 0.99], [0.99, 1]. Totally we have 22 control regions. Now the numbers of dots to be placed in each of these control regions are determined in advance by the sum of the pixel values in the corresponding region of the original image. The algorithm is now terminated when the predetermined numbers of dots are placed in all these 22 gray tone regions.

Now, the method works quite well for almost all kinds of images. However, the dots in the extreme highlights are not placed as homogeneously as one would expect. The reason is that the size of the filter should be chosen dependent on the gray tone. The lighter the gray tone, the bigger the filter. In Ref. 12 we describe how the size of the filter should be chosen for different gray tone regions. A constant image with a gray value of 1% is halftoned by the proposed FM method. For the image shown in Fig. 1(a) we used an 11×11 filter while a 21×21 filter was used for the image shown in Fig. 1(b). As can be seen the dots in the image shown in Fig. 1(b) are more homogeneously placed. This FM method has proved to perform very well for all kinds of images, and especially in the highlights (and the shadows). The fact that the proposed hybrid halftoning method uses an FM method in the highlights (and shadows) makes this FM method very attractive to be used as the FM method in the proposed hybrid halftoning method.

Hybrid Halftoning

Before going into details of the proposed hybrid halftoning method we give a short description of the terms *ppi*, *lpi* and *dpi*, as they sometimes seem to be confusing.

ppi, lpi and dpi

To be able to represent a photo in a computer it has to be digitized (or scanned). Images taken by digital cameras are of course already digitized. This is, however, done by measuring the gray tone or the color of the photo in a number of distinct positions over the entire photo or the scene. The term *ppi* (pixels per inch) is the (scanning) resolution and means the number of samples taken per inch when scanning or taking a picture by a digital camera. Therefore, the higher the *ppi* the better the quality of the digital image. On the other hand, the higher the *ppi* the bigger the memory that is needed to store the image in computer. Therefore *ppi* should not be unnecessarily high. The question of what *ppi* you should choose cannot be answered before you know how you are going to reproduce your digital image. For example if you want to show your image using a computer screen which normally has a resolution of 72 ppi it is just a waste of memory to scan the image with *ppi* >72.

In the conventional halftoning methods the original image is divided into small areas. Each small area is then represented by a halftone cell, which includes a background (white) and a black dot (or a number of black micro dots). The fractional area of each halftone cell covered with black represents the gray tone of the corresponding area in the original image. The number of halftone cells per inch is called line screen frequency and is denoted by *lpi* (lines per inch). There is a rule of thumb, which says that the scanning resolution (*ppi*) should almost be twice as high as the screen frequency (*lpi*) for better reproduction of the photo if the printed image is to be the same size as the original photo. For example, if the image is supposed to be printed at 100 lpi the photo should be scanned with a *ppi* of about 150 to 200. Choosing *ppi* higher than 2 *lpi* is unnecessary and does not lead to any higher quality of the printed image. Notice that if the scanning resolution (*ppi*) is twice as high as the screen frequency (*lpi*) each 2×2 pixel area in the digital image should be represented by a halftone cell.

Each halftone cell in the printers or the image setters consists of a number of micro dots. Two halftone cells, each consisting of 64 (8×8) micro dots are shown in Fig. 2. The halftone cell to the left corresponds to a gray level of 12/64 = 18.75% and the one to the right represents the gray value of 25%. The number of micro dots per inch is what we call print resolution and is denoted by *dpi* (dots per inch). The ratio (*dpi*/*lpi*) decides the size

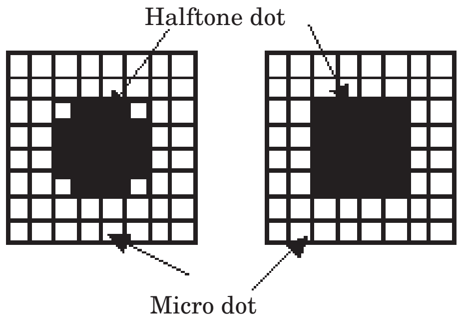


Figure 2. Two halftone cells are shown. The halftone cell to the left represents a gray value of 12/64 = 18.75% and the one to the right 16/64 = 25%.

of the halftone cells, which also decides the number of gray levels that can be represented. For example, the halftone cells shown in Fig. 2 can represent 65 ($8 \times 8 + 1$) levels of gray. Therefore the number of gray levels is equal to:

$$(dpi/lpi)^2 + 1 \qquad (1)$$

For example, a 600 dpi printer resolution combined with a 100 lpi halftone would only represent 37 levels of gray. Notice that, if the printer resolution cannot be increased then a higher *lpi* does not necessarily mean better print quality.

The Hybrid Halftoning Method

In our method access to software that does the AM halftoning is assumed. We use Adobe Photoshop™ in order to AM halftone our images. We further assume that 1 and 0 represent black and white, respectively. The method will be explained by both words and Matlab Pseudo codes. The only thing that needs to be known in advance is the critical dot (its size and shape) and the gray value for which the AM halftoning method produces this dot. By critical dot we mean the smallest possible reproducible dot. Our proposed method will be independent of the shape of the halftone dots, i.e., square, circular, elliptical, etc.; it is also independent of the halftone angle. In our illustrations in this article only the highlights are FM halftoned, but the shadows can be FM halftoned exactly the same way, if needed. Our original test image, *g*, is 600×600 pixels with *ppi* = 200, shown in Fig. 3. In the AM halftoning software (Adobe Photoshop) we choose *dpi* = 600 and *lpi* = 100, dot shape round, and the halftone angle 45°. We assume that the critical dot size is 2×2 micro dots, i.e., 0.085×0.085 mm. The gray tone that corresponds to this dot is 0.125. The number of gray levels presented here is only 37, see Eq. (1). We have chosen these data just to make the illustrations of the results more convenient. Note that a 2×2 dot in a 6×6 halftone cell means actually the gray value 4/36 = 0.1111. But since the halftone angles are normally not 0° or 90° then it is not easy to decide exactly the gray tone representing the critical dot size. It is not easy either to predict the shape of the critical dot. These are very much dependent on the halftone angle and the shape of halftone dots that are used in the AM halftoning method. Anyway, the critical gray tone should approximately be equal to the area of the critical dot divided by the area of the halftone cell. Note also that when the halftone angle is irrational, the size of the halftone cells is not constant; it can vary

Figure 3. The original test image. 600×600 pixels with *ppi* = 200 and printed at 200 dpi.

depending on position. However, the method presented here works independently of the halftone angle and the critical dot shape. As mentioned earlier only the critical dot size and the gray tone that corresponds to it need to be known in advance.

The original image is first AM halftoned by the available software or program, in our case Adobe Photoshop.

$$g_{AM} = AM\_halftone(g) \qquad (2)$$

Since $ppi = 2\, lpi$ and the halftone cell is 6×6, g_{AM} is 1800×1800 pixels. Since the critical dot size corresponds to 0.125 we build a mask using Eq. (3) in order to locate the highlights, i.e., the regions where the image is supposed to be FM halftoned.

$$mask = g < 0.125 \qquad (3)$$

Equation (3) means that *mask* is equal to 1 in positions where *g* is smaller than 0.125, and 0 elsewhere. Now *mask* is AM halftoned with exactly the same values as were used for AM halftoning the original image, see Eq. (4).

$$MASK = AM\_halftone(mask) \qquad (4)$$

MASK is now the same size as g_{AM}, i.e., 1800×1800. *MASK* is shown in Fig. 4. The parts in *MASK* that are black, or 1, are the parts of the image that are going to be FM halftoned. By using *MASK* we can now locate the parts of g_{AM} where the dots are bigger than the critical size, i.e., the dots bigger than 2×2 in our example.

$$g_{am\_mask} = \sim MASK \;\&\; g_{AM} \qquad (5)$$

where ~ means a “logical NOT” and ~*MASK* is a matrix whose elements are 1’s where *MASK* has zero elements,

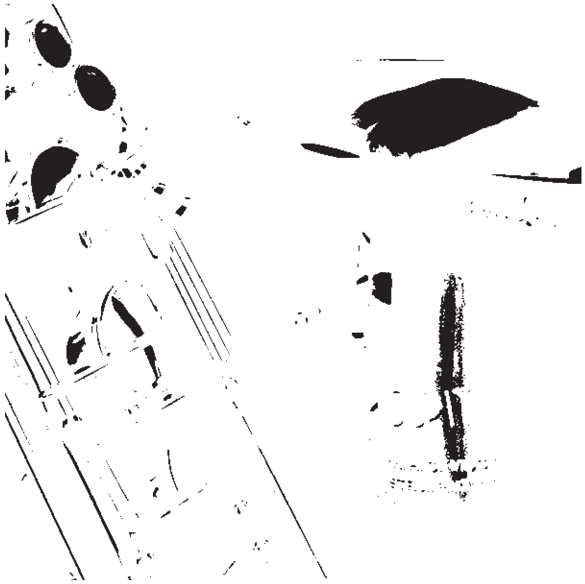


Figure 4. The mask printed at 600 dpi. The parts that are black, i.e., 1, are the parts of the image that are going to be FM halftoned. The parts that are white, i.e., 0, are being AM-halftoned.

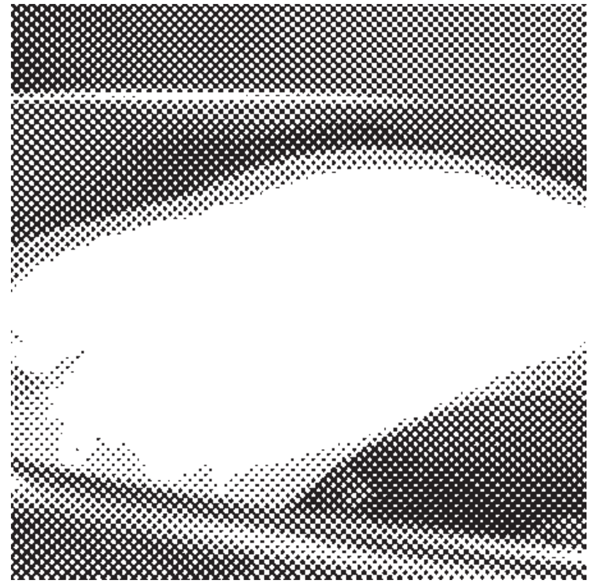


Figure 5. An enlarged version of a part of g_{am_mask} is shown. There are some dots in the transition area that have been cut and are smaller than 2×2. Apart from these unwanted dots, the image also shows an enlarged version of a part of the test image that would be obtained in print if the print press were not able to print the dots smaller than 2×2. This image is printed at 150 dpi.

and 0's where *MASK* has non-zero elements. & denotes the element-by-element "logical AND" between the matrices, in our example between ~*MASK* and g_{AM}. The transition area is the regions where *MASK* changes its value from 1 to 0, or vice versa. We would like all the dots in g_{am_mask} to be bigger than the critical dot size. But since the halftone angle could be arbitrarily chosen, 45° in our example, some of the dots bigger than the critical dot might be cut by *MASK*.

An enlarged version of a part of g_{am_mask} is shown in Fig. 5. As can be seen there are some dots at the transition area that have been cut and are smaller than 2×2. Although these dots are smaller than the critical dot size and probably would not be printed by the printing press they can still be problematic and impact the print quality. For example, these dots can later be connected to the FM dots and make them bigger and consequently affect the print quality. In this test image and under the printing conditions they are printed in the illustrations for this article, which is not exactly the same as in the aimed application (Flexography); the removal of these small dots has no significant effect on the quality of the final image. These dots might however cause problem for other images and in some applications there might be cases where they should be removed. In the next section we illustrate how these unwanted dots can negatively affect the final image and describe how these dots can be removed, if necessary. Apart from the unwanted dots, the image in Fig. 5 also shows an enlarged version of a part of the test image that would be obtained in print if the print press were not able to print the dots smaller than 2×2. If the unwanted dots are removed from g_{am_mask} the result is called G_{am}. We are now done with the AM halftoned part of the image.

In the FM part we should only use the critical dot, i.e., a 2×2 square dot in our example. The simplest way to do it is to first FM halftone the parts that should be FM halftoned as usual, and then double the size of the result. This will make every single dot be 2×2, the critical dot size. The original image is 600×600 and the double sized image will be 1200×1200, but the final result should be 1800×1800 pixels. Therefore the original image should first be resized to 900×900 pixels before being FM halftoned, i.e., it should be 1.5 times larger, see Eq. (6).

$$g_{new} = imresize(g,1.5) \tag{6}$$

where *imresize* resizes the image in both directions by the specified factor, i.e., 1.5 in Eq. (6).

It is critical that the number of pixels in both directions in the original should be a multiple of the size of the critical dot. In our example the pixel size in both directions should be an even integer. If this is not the case, it is necessary to add an arbitrary row or column to the original image, and then remove them from the final processed image.

Now g_{new} can be halftoned by the FM halftoning method, but observe that it is not necessary to FM halftone the whole image parts that should be FM halftoned, have already been specified by *MASK*. The only problem is that *MASK* is 1800×1800 and g_{new} 900×900. Therefore we halve the size of *MASK* to get a new mask.

$$mask_{new} = imresize(MASK,0.5) \tag{7}$$

As discussed before it is the areas of the original image that are black in the mask that are supposed to be FM halftoned; see Eq. (8).

$$g_{fm} = FM\_halftone(g_{new} \& mask_{new}) \tag{8}$$

This image is resized again, see Eq. (9).

Figure 6. Our test image and a grayscale ramp are halftoned by the proposed hybrid halftoning method. In the test image the parts that were black in *MASK*, shown in Fig. 4, are FM halftoned and the rest of the image AM halftoned. The FM method is non-modified Error Diffusion. Images are printed at 600 dpi.

Figure 7. Our test image and a grayscale ramp are halftoned by the proposed hybrid halftoning method. In the test image the parts that were black in *MASK*, shown in Fig. 4, are FM halftoned and the rest of the image AM halftoned. The FM method is the method presented in this article. Images are printed at 600 dpi.

$$G_{fm} = imresize(g_{fm}, 2) \qquad (9)$$

Note that every single black dot in g_{fm} has now become a 2×2 black dot in G_{fm}, which once again is 1800×1800 pixels.

Now when we are done with both AM and FM parts we just need to add them together to get our final hybrid halftoned image, as determined by Eq. (10).

$$G_{hyb} = G_{fm} \mid G_{am} \qquad (10)$$

where | denotes the element-by-element "logical OR" between matrices, in this case between G_{fm} and G_{am}. It must be mentioned here that since in G_{am} the unwanted dots at the border between AM and FM halftoned parts have been removed the FM and the AM dots will not overlap in G_{hyb}. Figures 6 and 7 show our test image and a grayscale ramp being halftoned by the proposed hybrid halftoning method. In the test image the parts that were black in *MASK,* shown in Fig. 4, are FM halftoned and the rest of the image AM halftoned. In images shown in Fig. 6 we used the non-modified Error Diffusion method as the FM method. In images shown in Fig. 7 we used the FM method presented in previous section as the FM method. All images are printed at 600 dpi. By looking at these images from some distance one can notice that the transition from AM to FM and vice versa is not disturbing at all, see also the discussion section. The FM dots are however much more homogeneously placed in the images shown in Fig. 7, since the non-modified Error Diffusion normally performs poorly, especially in highlights. Any "good" FM method could probably result in high quality hybrid halftoned images.

Therefore, the proposed hybrid method is not necessarily limited to the FM method presented in this article. But this FM method has a number of advantages that make it useful therein. The first advantage is that this method performs very well in the highlights (and shadows) because by changing the filter size, as discussed before, the dots can be homogeneously placed. Another advantage is that the number of dots being placed are controlled over a number of gray tone regions; therefore the gray tones are guaranteed to be represented correctly. Another advantage is that in this FM method the number of iterations is dependent on the number of dots being placed. Since a small number of black dots are placed in the highlights (and a small number of "white" dots are placed in the shadows) this FM method actually operates faster than might be expected. In fact this FM method halftones normal images (and not only the highlights) quite fast compared to the other iteration halftoning methods.[12] Another advantage of this

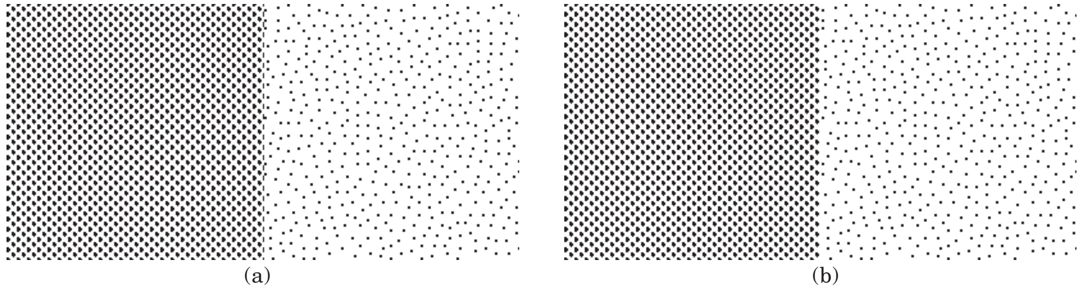


Figure 8. The left half of the images is AM-halftoned and the right half is FM-halftoned. (a) the unwanted dots are not removed, hence a visible vertical dashed-line structure is observed in the border between AM and FM patterns. (b) The unwanted dots are removed and the visible vertical dashed-line has disappeared.

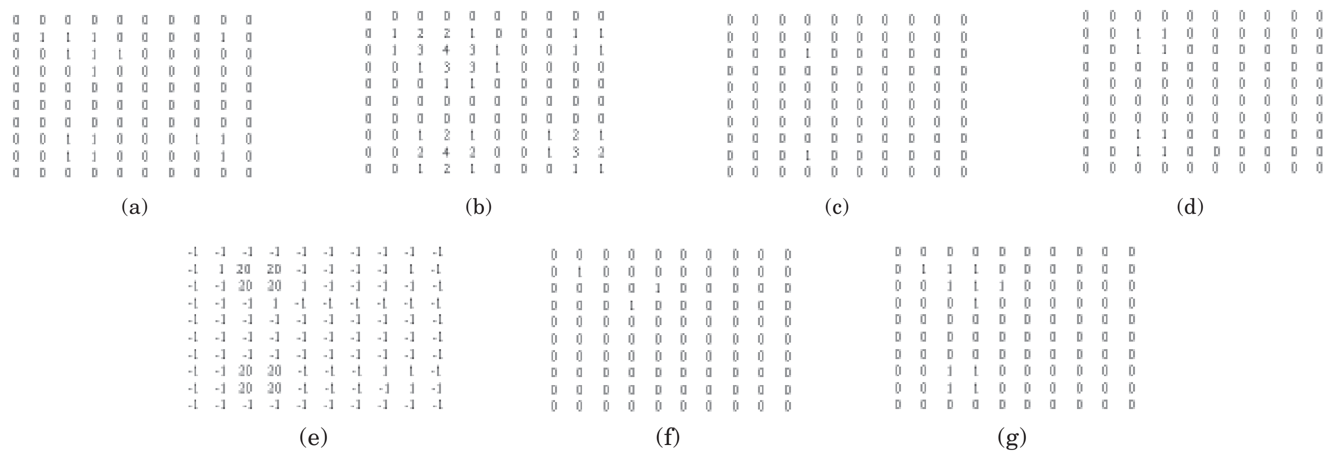


Figure 9. How to remove the dots smaller than 2×2. The two dots to the right in a are going to be removed. The other two dots will remain as they are. (a) The original, called a. (b) The image b in Eq. (11). (c) The image c in Eq. (12). (d) The image d in Eq. (13). (e) The image e in Eq. (14). (f) The image f in Eq. (16). (g) The final image a_{new} in Eq. (17).

method is that when halftoning a uniform image we add a very small amount of noise to the original to avoid having structure in the result.[12] Thus the first dot is placed "randomly", which also decreases possible distortion in the transition areas.

How to Remove the Unwanted Dots

As discussed earlier the removal of dots smaller than the critical dot size is not always necessary. For example, if these unwanted dots were not removed from our test image and the AM and FM images had been combined independently, the resulting image would not be any different. However, since there might be cases where these unwanted dots could degrade the quality of the final image; see Fig. 8, in this section we discuss how these dots can be removed. Figure 8 illustrates a simple example. The left half of each of the images is AM halftoned and the right half is FM halftoned. In Fig. 8(a) the unwanted dots are not removed, hence a visible vertical dashed-line structure is observed in the border between AM and FM patterns. Since the unwanted dots are removed in Fig. 8(b) the visible vertical dashed-line has disappeared.

In previous section we discussed that after using the mask on the AM-halftoned image in order to separate the AM part from the part being FM halftoned, there might be some dots in the transition area that are cut and consequently smaller than the critical dot. In this section we present a method that can remove these unwanted dots. There might be many appropriate methods, but here we present a method that uses only the convolution function, which is available in all image-processing toolboxes, including Matlab. We describe the method by words and Matlab pseudo codes. We assume that the critical dot size is still 2×2. Any dot smaller than 2×2 should be removed while the dots that are 2×2 or bigger should remain where they were. This method can easily be generalized to be used for any other critical dot shape.

We use a simple example to illustrate the method. Assume that the 10×10 image shown in Fig. 9(a) is the AM-halftoned image that has been masked. In our example, 1 means a black micro dot and 0 means no dot. Therefore, in the image shown in Fig. 9(a) the two black dots to the left should remain as they are and the two to the right should be removed. We call this image a. To locate the dots that are equal to the critical dot we convolute this image with a kernel that represents the critical dot.

$$b = conv2\left(a, \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}\right) \tag{11}$$

where *conv2* denotes the two-dimensional convolution and the matrix represents the 2×2 critical dot. If the critical dot has another shape than this one the kernel should be chosen accordingly. Note also that the convolution operator rotates the kernel 180° before operating so if the critical dot does not have a symmetrical shape, the kernel would be the rotated version of the critical dot. (In our example, however, the critical dot has a symmetrical shape).

Since our kernel is 2×2 the result b in Eq. (11) is 11×11. We can simply remove the last row and column in b without affecting the result, (depending on how the convolution operator is programmed). Here we assume that it is the Matlab operator *conv2*. Matrix b, after removing its 11th row and column, is shown in Fig. 9(b). The positions that hold 4 (the number of ones in the kernel, i.e., the number of black micro dots in the critical dot) indicate that there has been a dot equal or bigger than the critical dot size corresponding to that position, see Eq. (12).

$$c = (b == 4) \tag{12}$$

This operation means that the matrix c is equal to 1 in those positions where b equals 4, and equal to 0 elsewhere. Matrix c is shown in Fig. 9(c). As can be seen the dots smaller than the critical size has no indication in this image c. Now we rebuild our critical dot around the 1's in c. This is done by convoluting c with the kernel. The kernel again represents the critical dot. Note that in Eq. (13) the kernel should represent the critical dot, and not its rotated version even if the critical dot does not have a symmetrical shape.

$$d = conv2\left(c, \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}, 'same'\right) \tag{13}$$

where '*same*' makes the result d to be the same size as c. Matrix d is shown in Fig. 9(d). As can be seen in this image the critical dots are rebuilt in the positions where we had the dots bigger than or equal to the critical dot. The dots smaller than the critical dot are removed. There are now some black micro dots in the original image a that are missing in d, and we have to rebuild those. The black micro dots that exist in a and do not exist in d belong either to the dots bigger than or smaller than the critical dot. Those that belong to the dots smaller than the critical dot have no connection to any black micro dot in d. But those that belong to the dots bigger than the critical dot have connection to at least one black micro dot in d. We give the black micro dots that exist in a and not in d the value 1. The black micro dots that only belong to d are given the value 20 (or any other appropriate positive number). The remaining micro dots, i.e., the pixels that are 0 in both a and d, are given the value –1. See Eq. (14) and the image shown in Fig. 9(e).

$$e = (a \& \sim d) \cdot 1 + (d) \cdot 20 + (\sim a \& \sim d) \cdot (-1) \tag{14}$$

Now if we convolute this image e with a 3×3 matrix of ones we can find whether or not any 1's in e have a connection with any black micro dot in d. For those 1's in e that are connected to at least one black micro dot in d, the result of convolution in the 3×3 neighborhood is not smaller than 14. It is actually the case when a 1 in e is only connected diagonally with a black micro dot in d. In this case the result of convolution in the 3×3 neighborhood will be at least $20 + 1 + 7\,(-1) = 14$. For the 1's in e that have no connection to any black micro dot in d, the result of the convolution in the 3×3 neighborhood can not be bigger than 9, actually it is always smaller than 9, see Eq. (15).

$$m = conv2\left(e, \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}, 'same'\right) \tag{15}$$

Now the 1's in e that have a value bigger than 10 (or 11 or 12 or 13) in m are the black micro dots that are connected to at least one black micro dot in d, see Eq. (16) and the image shown in Fig. 9(f). The three black micro dots in this image are actually the ones we were looking for.

$$f = m > 10 \quad \& \quad e == 1 \tag{16}$$

Now an element-by-element logical OR between f and d gives the image we were looking for, see Eq. (17) and Fig. 9(g).

$$a_{new} = f \;\; | \;\; d \tag{17}$$

The image a_{new} is actually the final image, i.e., a_{new} is the image a where the dots smaller than the critical dot size have been removed.

As mentioned earlier in this section the operations presented here are not restricted by the shape of the critical dot. The shape should, however, be taken into account when choosing the kernels. The value 20 used in Eq. (14) was actually one of many possible choices. For bigger critical dots a number bigger than 20 should be used. To ensure that Eqs. (14), (15) and (16) will work independently of the dot shape, it is probably better to use a very big number instead of 20, say 1000. Then in Eq. (16), 10 should be replaced by, for example, 200. However, the choice of the number 20 here does not affect the generality of the operations presented in this section.

Critical Dots with General Shape

In the example taken up in this article we assumed that the critical dot is a square, but it does not need to be. According to our experiments if the critical dot is close to square one can still use a square dot, without any considerable effect on the final hybrid halftoned image. But the method can slightly be modified to make a critical dot shape that is not square. Assume that we want the critical dot to be the dot in the upper left of Fig. 9(a). This dot is a 2×2 dot plus another three black micro dots. We first assume that the dot shape is 2×2 and perform the method precisely as before. For simplicity assume that (g_{new} & $mask_{new}$) in Eq. (8) is a constant image with 1% coverage. This image is first FM halftoned and then doubled in size to get G_{fm} in Eq. (9). This FM halftoned image is shown in Fig. 10(a). As can be seen the FM dots are 2×2 but we want them to have another shape, i.e., the shape of the dot up to the left in Fig. 9(a). The new dot consists of 7 black micro dots. If now any 2×2 dot is replaced by this new dot, the coverage will be $7/4 \times 1\% = 1.75\%$. Therefore we cannot simply replace the 2×2 dots by the new dots. What we can do instead is that we can FM halftone ($4/7 * g_{new}$ & $mask_{new}$) instead of (g_{new} & $mask_{new}$). If we do so then we can replace every square dot with the new dot and get exactly the same coverage, i.e., 1%. In this example we should therefore first halftone the constant image with coverage (4/7)1%. Then we resize it as before in order to get the 2×2 dots. Assume that this image is called p. Now we can replace each 2×2 dot in this image by the desired dot.

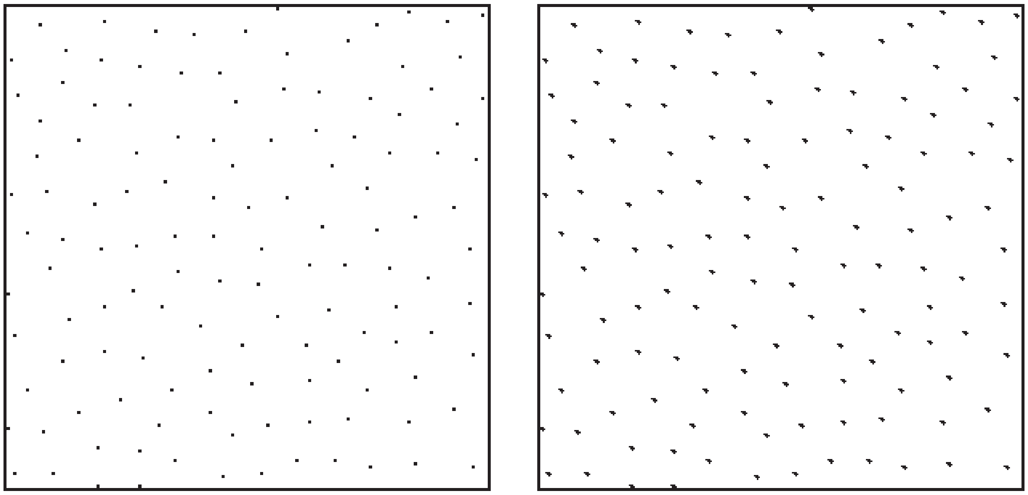

(a) (b)

Figure 10. (a) The dots are 2×2, and (b) the dots are the new critical dot. The fractional area covered with black dots is the same as in *a*.

First we perform a convolution to find the 2×2 dots precisely as before (Eqs. (11) and (12)), replacing a by p in Eq. (11). Now we have found the positions where we have 2×2 dots. Assume that the result is called c, as before (Eq. (12)). By performing the following convolution we can replace the 2×2 dot by the new dot, see Eq. (18).

$$q = conv2\left(c, \begin{bmatrix} 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}, 'same'\right) \tag{18}$$

Note that the kernel in Eq. (18) is actually the new critical dot that was supposed to replace 2×2 dots. Figure 10(b) shows the new image q, where the dots have the shape of the new critical dot. The number of dots in the image shown in Fig. 10(b) is of course less than that in the image shown in Fig. 10(a). The coverage on the other hand is 1% in both cases.

Discussion

As mentioned earlier the images shown in Figs. 6 and 7 have been AM halftoned with lpi = 150 and dpi = 600. The number of gray levels is therefore only 37, as discussed before. In a real print both the lpi and dpi are much higher, which makes the halftone dots smaller and also increases the number of gray levels. In our test images, however, we limited ourselves to smaller lpi and dpi in order to illustrate our method. One should consider these facts when looking at these images, it is therefore probably better to look at these images from some distance. The only part of these images that might be considered on closer inspection as disturbing is in the center of the saxophone above where you see the letter I in the text "JUPITER". One can easily distinguish the AM and the FM parts. We left this part as it is on purpose. This "disturbing" region is not disturbing in real prints. According to our test prints this transition from AM to FM is not at all as evident as it probably is in these images. However, since the quality of all halftoning methods are somehow dependent on the original images for real printing, it might be useful to first study the mask before preparing the halftoned image. If there are some parts that probably will give any kind of disturbing transition area, it is better to modify the original in order to change the mask a little, and thereby avoid the possible problems. We have tested our proposed method on many images, with different critical gray tones, and were unable to notice any situation that can give rise to unacceptable results.

Test Print

We have tested the proposed method for real printing. The test image, the same test image as in Fig. 3 but with ppi = 300, has been hybrid halftoned. The printing resolution was 2100 dpi and the screen frequency 150 lpi, thus 197 levels of gray. The halftone angle was 37°, which was required by the software that made the printing cliché. The critical dot was chosen to be 4×4. We asked the company that made the cliché to halftone the same image by their own method, which is actually SambaFlex™ as introduced in previous sections. The results of both methods show no disturbing artifacts in the transition area. The image halftoned by our method, which used the FM method presented in this article, actually looks better in the highlights because the FM dots are placed more homogenously. The FM dots in the other image sometimes follow the structure of the AM halftone grid. Since we do not have access to the digital image halftoned by SambaFlex we chose to scan both images. Figure 11 shows an enlarged version of a part of the printed test image halftoned by SambaFlex, here printed at 300 dpi. Figure 12 shows the same image halftoned by the proposed method in this article. An enlarged version of images shown in Figs. 11 and 12 are shown in Figs. 13(a) and 13(b), respectively. These images are printed at 150 dpi. As can bee seen in the highlights the FM dots are more homogeneously placed in the images shown in Figs. 12 and 13(b). Notice that images in Figs. 11 – 13 have been rescaled. These images in their original size are viewable at: www.itn.liu.se/~sasgo/Jist086/.

The test prints were shown to a number of observers who were told what aspects of the images are important to judge, namely, the transition area and the FM part. All of the observers agreed that there is no evident distortion in the transition area in any of the images

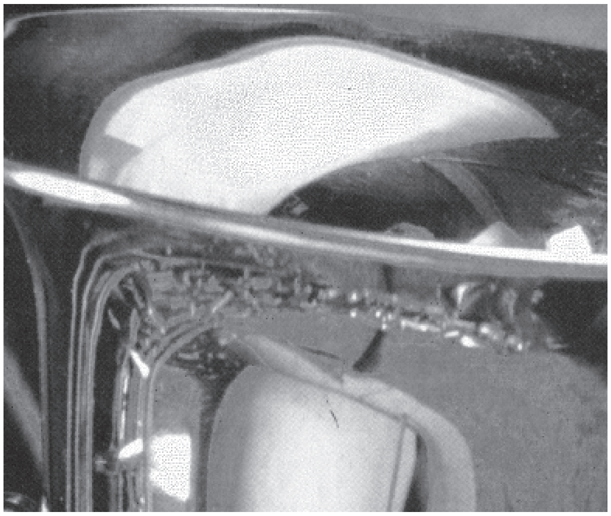


Figure 11. An enlarged version of a part of the test print, printed at 300 dpi. SambaFlex raster method was used.

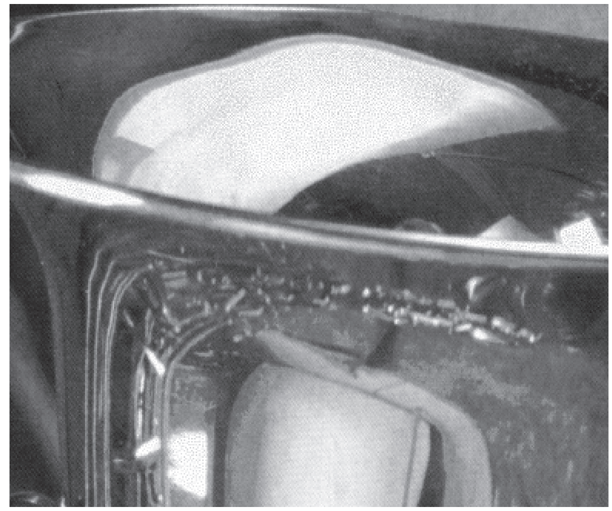
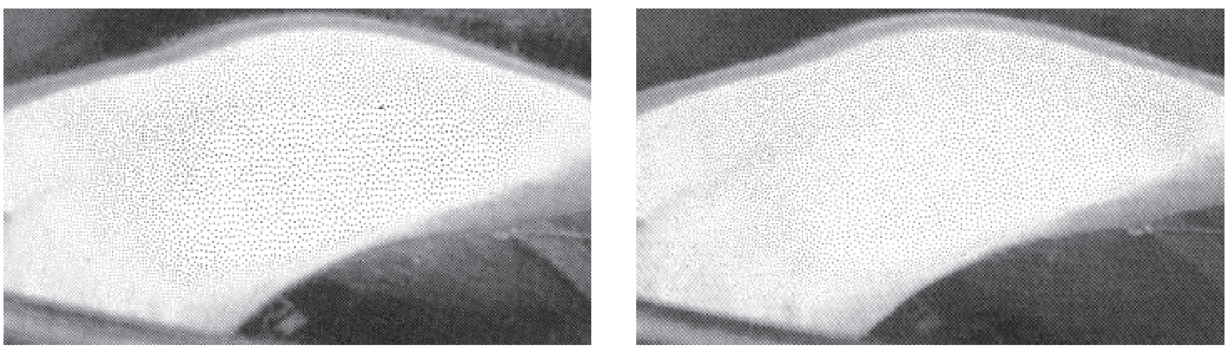


Figure 12. An enlarged version of a part of the test print, printed at 300 dpi. The hybrid method proposed in this article was used.



(a) (b)

Figure 13. (a) An enlarged version of a part of the image in Fig. 11, printed at 150 dpi. (b) An enlarged version of a part of the image in Fig. 12, printed at 150 dpi.

and also that the image halftoned by the proposed method performs better in the highlights. Please remember that these images shown here are scanned versions; the real prints are, of course, of much higher quality.

Discussions and Future Work

According to Ref. 2 a direct combination of AM and FM will suffer from some artifacts, especially in the transition area. According to our experiments, our proposed method which actually is a direct combination of AM and FM, does not suffer from any evident distortion in the transition area. We have shown that if these two technologies are combined properly, and if a "good" FM method is used, the proposed hybrid halftoning method works very well. The proposed method is actually very simple. If written in, for example, Matlab this method needs only 17 lines. (We considered the AM and the FM halftoning a one line code each.) In order to use this method a well performing FM method is essential.

Since the color extension of the FM method presented here halftones the color separations dependently,[12] we believe that an extension of this hybrid halftoning method to color can considerably increase print quality. We are planning to extend this hybrid method to color and do a number of test prints in color and compare this method with other commercially available methods.

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