Multiple Spatial Channel Printing

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1.0 Abstract

In the past, imaging has been achieved by varying the intensity or reflectance of otherwise nearly identical pixels. An alternative approach is to utilize pixels that have variable spatial characteristics. Large, diffuse dots can form the basis of a low-pass image channel that can be used in conjunction with a second conventional sharp-dot output channel to produce near continuous-tone image quality with fewer output states per pixel. A non-linear algorithm for splitting an image into two channels is described. This technique can produce nearly continuous-tone quality output with just two bilevel channels. Additionally, a 4-color process which uses blurred-dot C M and Y channels and a sharp-dot K channel is described that produces similar results for color images.

2.0 Introduction

Halftoning introduces undesirable visual noise, an example of which is shown in figure 2A. The noise can be eliminated through the use of higher resolution or multilevel output at the cost of additional complexity, bandwidth and memory requirements. With most common halftoning schemes, the noise is concentrated in the high spatial frequencies[1], and can hence be attenuated by an imaging process that renders a low-pass image. A process that produces large, overlapping, low-pass pixels will produce low-pass images, as shown in figure 2B. However, in addition to the noise this process will attenuate the high spatial frequency signal content of the image. For photographic images, some blur may improve the perceived quality, but for text or graphic areas of the image, the blur reduces image quality.

If an output device has the capability to produce conventional sharp pixels in addition to low-pass pixels, then it is possible to selectively suppress halftone noise without removing important signal. The two types of pixels form two imaging channels with different spatial characteristics. One channel is a low pass channel. The other channel can carry both high and low spatial frequencies. However, this channel suffers from noise. Here we describe how such a theoretical device could be utilized to generate near continuous tone output with only one output level per pixel location.

In this paper, we will first consider a hypothetical device that can produce two types of dots. Both dots are positioned on the same pixel grid, so they both have the same positional resolution. One of the dot types is just large enough to completely cover a cell in the pixel grid. This type of dot is a dark black circle. We call this type of dot a sharp-dot.

The second type of dot our hypothetical device can produce is a blurred version of the previous type of dot. That is, instead of each dot as a hard-edged circle, each dot is a translucent gray area that is also substantially larger than the pixel grid cell size, but it can be positioned with its center on any cell just as the solid black type of dot. Dots of this type that are near each other will overlap. This image channel has the same properties as the sharp-dot channel if it was then followed by a low-pass filtering kernel. If a dot in this channel is overlapped by another dot, it will be darker in the overlap area than it would be if it was not overlapped. We call this type of dot a blurred-dot.

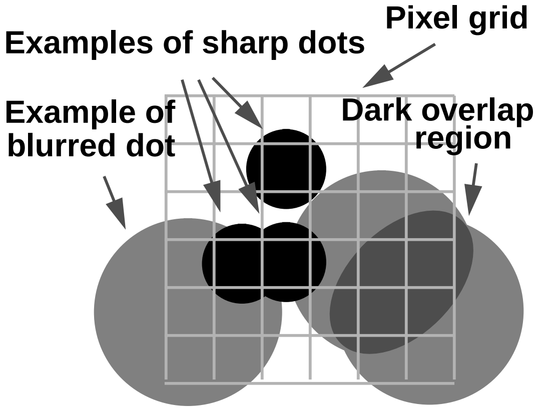

Figure 1.
Three example sharp dots and three example blurred dots on the pixel grid.

These two types of dots are illustrated in figure 1. Since the blurred-dot channel has the same properties as the sharp dot channel followed by a low-pass filtering kernel, we call this channel the L (low-pass) channel. The sharp dot channel can carry both high and low spatial frequencies, but it will inevitably contain some undesired high frequency content, so we call this channel the N (noisy) channel. Later in the paper, we will discuss a color variation of these types of dots, but for the first part of the paper we will restrict the consideration to black and white images.

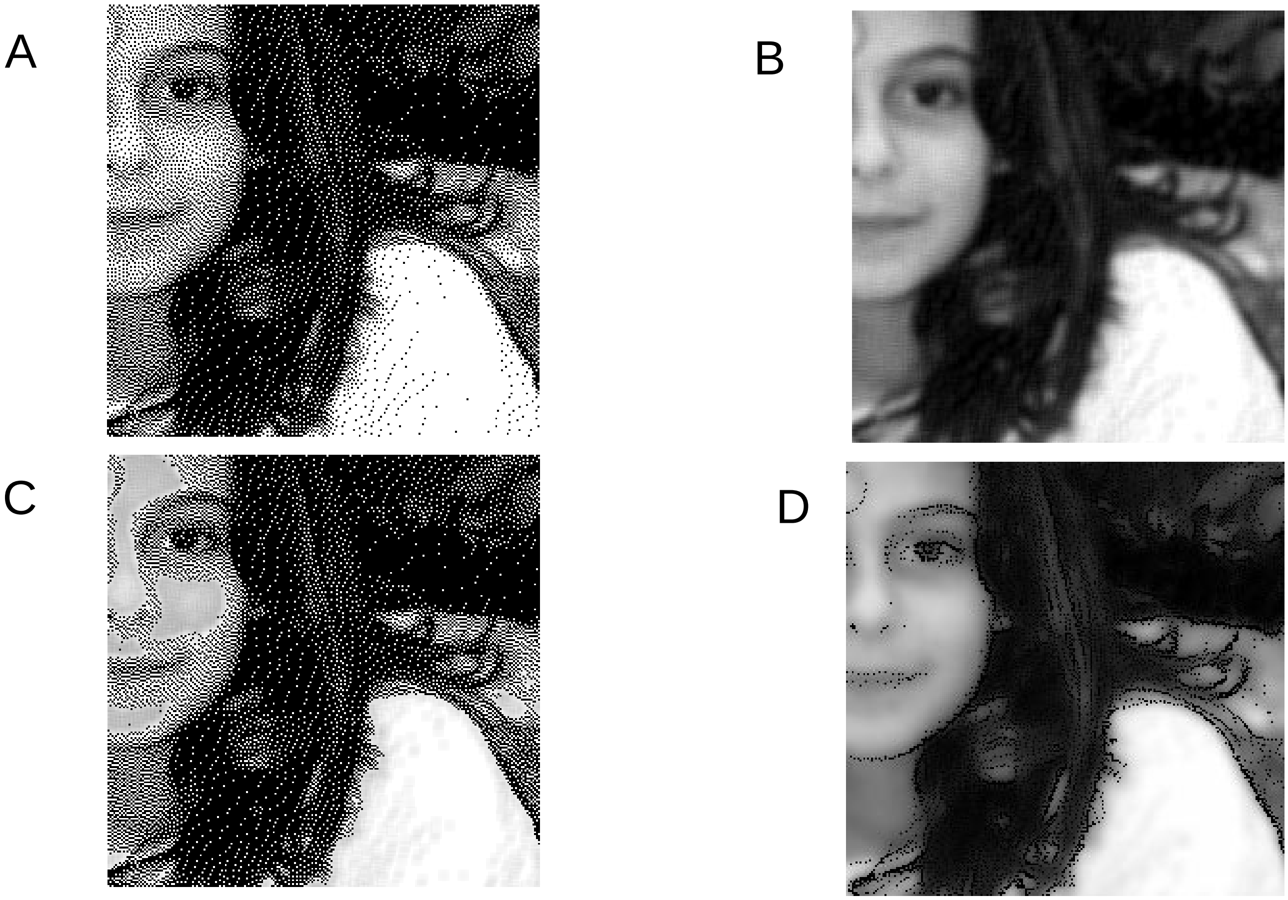

Figure 2.

A. Halftoning adds noise.
B. Using low-pass dots removes noise and signal
C.Using the blurred dots in the highlight areas only leads to contouring. How can a combination of sharp and blurred dots create a high-quality image?
D. Sharp dots used at the image edges.

It is not obvious how to best utilize the different dot types. As was mentioned earlier, printing an entire image with blurred dots removes much of the halftone noise, as is shown in figure 2B, but it also removes important signal as well. With the selective application of the two dots to different areas, it should be possible to improve image quality.

A straight-forward approach could be to utilize the blurred dots in the areas where the halftone noise is most visible. For example, in the light areas of a bi-level printed image, the dots are very widely spaced and are often very visible. The low pass channel could be used to print all of the light image areas. However, this will not result in improved image quality, as is shown in figure 2C. The edge between the image area printed with blurred dots and the area printed with the sharp dots will form a highly visible contour. A sharp boundary between an area with high frequency noise and an area with no high frequency noise results in highly visible low-frequency noise.[2]

Since we have one channel that is low-pass, and another that can carry high spatial frequencies, we might consider the application of linear spatial frequency decomposition to determine the inputs for the two imaging channels. This technique has had great success in applications such as image compression. However, in the case of these output channels, linear decomposition does not apply. Instead, we use a non-linear method to divide the image into low-pass regions and dark edges, that will be described, and is illustrated in figure 2D.

In this paper we are considering a hard-copy device for which, in violation of additivity, the total output is approximately the product of the output channels. For example, consider a printer that uses a dye that behaves as a filter that transmits 50% of the reflected light. A second application of the dye will filter out half of the light transmitted by the first application, thus creating a filter that transmits 25%, instead of 0%. Likewise consider a printer that uses fine particles of pigment that randomly cover 50% of the paper. Each particle from a second application covers light and dark areas of the previous layer with equal probability. After a second application, 25% of the area will not have pigment. By either of these means, the final image has a reflectance that is equal to the product of the two applications of colorant. Our hypothetical imaging device is given the property that the output image is the product of the N and the L channels.

With the property of multiplicative channels, we have developed an algorithm for splitting the image. Since the L channel has less noise than the N channel, it is used everywhere except where there is an edge with sufficiently high contrast. For high-contrast edges and lines, we use the sharp dot channel. The N channel's sharp dots are needed to carry the high-frequency image signal content. Although the sharp channel suffers from noise, the noise is strongly masked by the edge.

3.0 Procedure

We hypothesize a raster image output device with the following properties:

1. The device can produce a sharp-dot raster image, the N channel. The dots in this image do not extend far beyond the boundary of the raster cell where they are produced. At each pixel, either a sharp dot is printed or it is not printed. That is, this channel is binary.

2. The device can produce a blurred-dot raster image, the L channel. This channel is like the previous one if it were followed by low-pass filtering. In this paper we used a Gaussian kernel of limited support, but the exact form of this low-pass function is not very important. These dots are also binary, in that at each pixel, either a blurred dot is printed or it is not printed. However, these dots extend substantially beyond their raster cell boundaries.

3. The output image is the product of the N channel and the L channel.

To utilize this device, we first split the original image I into two images I_N and I_L. These images are halftoned to produce two binary images, and the binary images are output with the N and L channels, respectively to produce the images I'_N and I'_L which are combined as the output image I'. The splitting method we will describe has the following properties:

1. $I = I_N \times I_L$

2. $I'_N \approx I_N$

3. $I'_L \approx I_L$

4. $I' \approx I$

Where ≈ means approximately perceptually equivalent.

We used the following heuristic to motivate our function that splits the image I into I_N and I_L: The sharp dots should only be used where they are needed to render edges with significant contrast. Since the sharp dots are only dark, we can only use them to render the dark sides of the edges.

To extract the dark sides of the edges, we used dilation. The I_L image was produced by a morphological dilation operation[4]:

5. $I_{L(i,j)} = \mathrm{MAX}[I_{(i,j)}, I_{(i+1,j)}, I_{(i,j+1)}, I_{(i,j-1)}, I_{(i-1,j)}]$

And the L_N image was produced so equation 1 would be obeyed:

6. $I_N = I / I_L$

The dilation operation replaced each pixel with its brightest neighbor. This expands all of the light areas of the image, and removes the dark sides of all edges. The dark sides of all of the edges are stored in image I_N. This has the desired properties described in our heuristic.

After the images I_N and I_L were computed, we converted them into binary images. We used the Floyd-Steinberg[3] algorithm (*F*) to produce the L channel bitmap. The output image of the L channel I'_L was the low-pass filtered version of this. We used convolution (❋) with a rotational symmetric Gaussian kernel (*G*) with a 5 × 5 extent and a sigma of.5 pixels. Since the N channel image needs to contain only high spatial frequency image content, we used a Bayer dither *B* with a very small (2 × 2) kernel.

7. $I'_L = F(I_L) \circledast G$

8. $I'_N = B(I_N)$

Equation 6 can be refined if the blurring kernel is known in advance. Since $I_L \circledast G$ more closely approximates I'_L, equation 6 can be improved as:

9. $I_N = I / (I_L \circledast G)$

Equation 5 can also be improved by adding a threshold term, so only edges with sufficient contrast are dilated. Low contrast edges will then be rendered with the low-pass channel.

4.0 Example

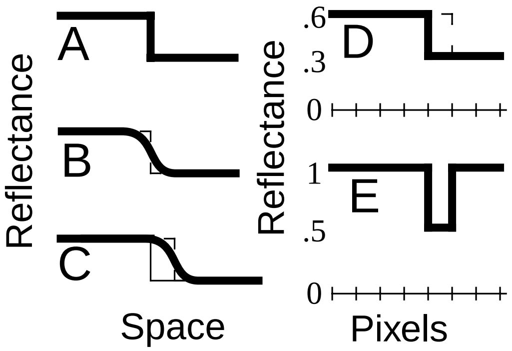

Figure 3
Reflectance profiles: A. Edge B. Low pass edge with positive and negative error. C. Low-pass dilated edge with only positive error. D. Dilated edge. E. Correction required for D.

Figure 3A is a diagram of an image edge. If it is rendered with a low pass hardcopy device, it will have the profile shown in 3B. To correct 3B back to 3A, it would require more dark ink to be added to the right side of the edge, and some light ink added to the left side of the edge. Figure 3C shows 3A after dilation as the dashed line, followed by low pass printing (the dark solid line). To correct 3C back to 3A, only the addition of dark ink on the right side of the edge is required.

Figure 3D shows the original edge as a solid line, and the dilated edge as the dashed line. Figure 3E shows the ratio of the dilated edge to the original edge. If 3D was dilated and printed, and 3E was printed on top of that, then the original image edge would be reconstructed.

5.0 Color

The simple way to extend this method to color images is to divide the image into a number of color output channels, such as cyan, magenta and yellow (CMY) and then to apply the same method to subdivide these channels further into C_N C_L M_N M_L Y_N Y_L. In fact, this method works well. However, this would require a very complicated 6 channel output device.

We have devised an alternative approach which uses only 4 channels, C_L M_L Y_L and K_N; cyan, magenta, yellow and black, respectively. C_L M_L Y_L are low-pass color channels, and K_N is a sharp-dot black channel. This approach has the tremendous advantage that it could conceivably be realized as a minor modification to a conventional printer.

It is well known that the visual system is less sensitive to defocus in chrominance than luminance, and therefore the chrominance of an image can be represented with less resolution[5]. With this process, the colored dots are all blurred, so high spatial frequencies chrominance signals can not be produced. This disadvantage is compensated by the improved luminance channel. There are two ways to create a luminance signal with this process; as low-pass composite black with C_L M_L Y_L, or as real black with the sharp-dot black channel K_N.

To utilize these four channels, we first start with an image represented in a luminance/chrominance space such as $L^*u^*v^*$. The luminance channel is further split into an N and a L channel as before.

10. $I_{L(i,j)} = \mathrm{MAX}[L^*_{(i,j)}, L^*_{(i+1,j)}, L^*_{(i,j+1)}, L^*_{(i,j-1)}, L^*_{(i-1,j)}]$

11. $I_N = L^* / I_L$

The L channel is then recombined with the color channels, and then converted into CMY channels. The N channel is used as a K channel. This way, the low frequency luminance components are rendered with composite black, and the N channel edges are rendered with real black.

12. $I_L\, u^* v^* \rightarrow C_L\, M_L\, Y_L$

13. $I_N \rightarrow K_N$

The final output channels C'_L M'_L Y'_L K'_N are the halftoned versions of these channels:

15. $C'_L = F(C_L) \ast G$

16. $M'_L = F(M_L) \ast G$

17. $Y'_L = F(Y_L) \ast G$

18. $K'_N = B(K_N)$

Figure 4 shows a demonstration of the process. 4A shows a conventional error-diffusion image with CMY sharp dot channels. 4B shows the C_L M_L Y_L channels we have described output together, without the K_N channel. This produces an image that is similar to the one that would be obtained by simply low-pass filtering 4A. 4C shows the sharp-dot K_N channel by itself, and 4D shows it when it is overlaid on 4B. 4D has the same positional resolution as 4A, and it has only two output states per location for each channel.

If you do not have a color print of figure 4, 4B will be the same as the low-pass channel described at the beginning, and in equation 7. 4C will be the same as the noisy channel

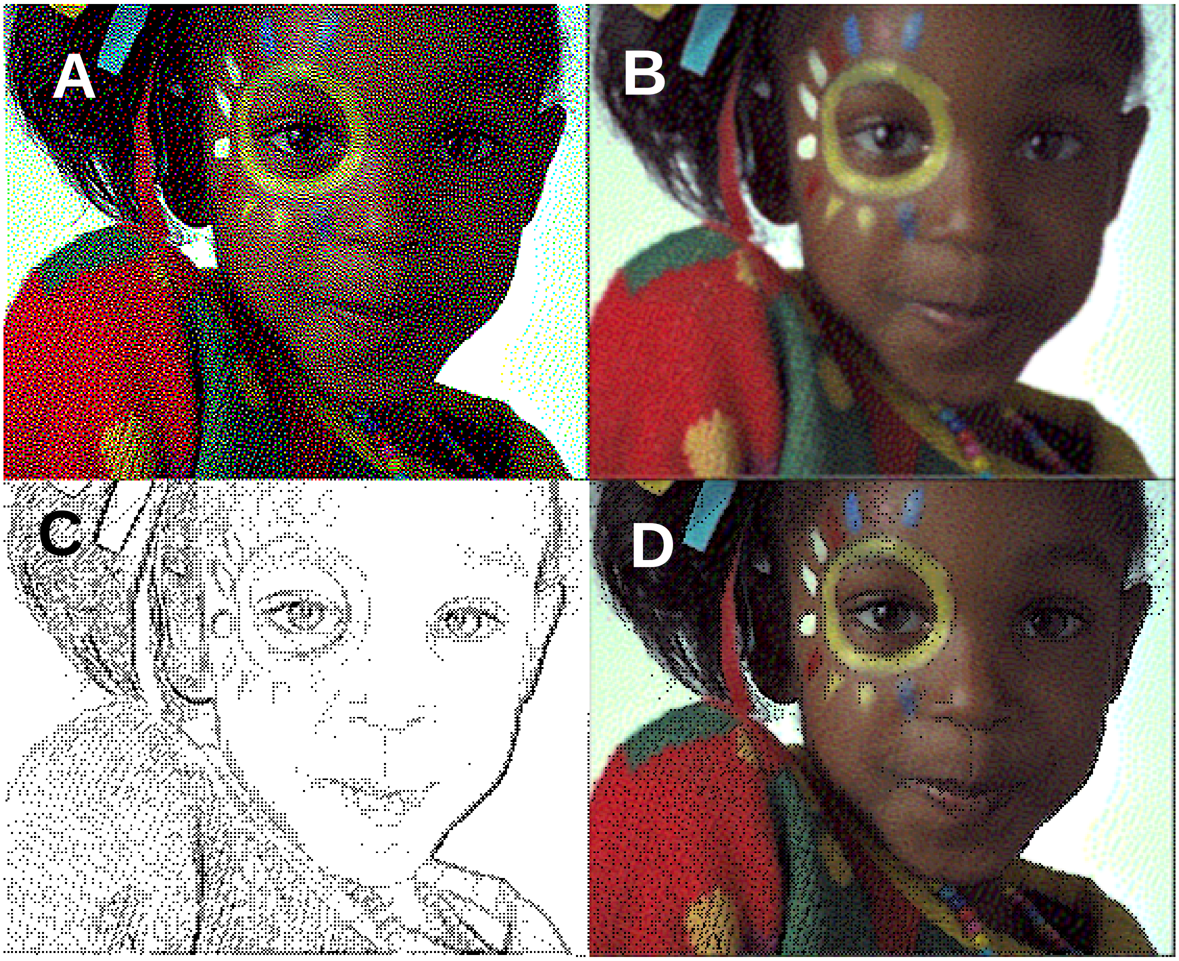

Figure 4.
A. Conventional CMY error-diffusion
B. C_L M_L Y_L channels output together.
C. K_N channel
D. C_L M_L Y_L and K_N channels output together (our process)

described in equation 8. 4D is the combination of the two channels. A color print will be sent to you on request.

6.0 Conclusions

The procedures described here can provide the basis for a new type of output device that takes advantages of human vision and image statistics. The images created with this method have greatly reduced halftone noise and are sharp. These improvements are achieved without using higher resolution or multiple levels per dot.

The algorithm is easy to implement and reasonably inexpensive to compute. The image channels have the additional advantage that they can be compressed efficiently. The low-pass channel has low entropy, and could be encoded compactly. The noisy channel is only used near edges, and hence could be efficiently run-length encoded.

7.0 References

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