Correction of High Frequency Smear in Thermal Printers

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Abstract

A new algorithm is introduced to combat high-frequency thermal smear. This algorithm has been shown to give an extra sharpness boost to thermal prints that is not achievable by traditional sharpening algorithms. This algorithm should be tuned in conjunction with traditional thermal smear and sharpening algorithms. It is possible to preconvolve the text-smear filter with the sharpening filter resulting in the ability to apply a single filter to the image. The single filter applies sharpness and text-smear correction in one step.

Introduction

Thermal dye diffusion printers using resistive printheads image one row of an image at a time. One of the big drawbacks of resistive printheads is that, despite sophisticated thermal conductivity designs, it takes time to heat up each resistor, and likewise, it takes time for each to cool down. This delay causes a blurring of the transfer of dye, which affects the MTF of the thermal print in the motion (slow, or down-the-page) direction. This delay is often referred to as "thermal smear." A thermal smear correction algorithm compensates for this artifact quite well. As printers are driven faster, the artifact becomes worse, and although the original thermal smear algorithms still do an excellent job correcting lower frequency thermal smear, a new technique is needed to compensate for thermal smear in the middle frequencies.

A new algorithm called "text smear" is introduced to solve this mid-frequency down-the-page thermal smear. The text-smear algorithm is a one-dimensional filter that operates in the down-the-page direction. This algorithm is excellent at restoring mid-frequency thermal blur from smear, and it gives thermal prints a sharpness boost above and beyond the capability of traditional sharpening.

Background

The MTF of the thermal printer can be obtained in both the fast (along the head) and slow (across the head or down the page) direction. Several techniques have been proven to be useful in characterizing the MTF of printing devices, including periodic signals and random noise. However, previous experiments have shown that in the slow direction, the MTF for rising and falling edges was quite different. Given that the periodic signals and random noise report the average of rising and falling edges together, slanted edges [1] were used instead. Slanted-edge analysis reports an average of the spatial frequency response, which is due to both the shoulder and toe of the trace. Mirroring techniques can be used to overcome this response.

A dark (2.4 Status A density) square (approximately 0.5″ × 0.5″) was printed on a gray (0.8 Status A density) background onto a thermal printer with a line time of approximately 1.0 msec/line. This printed black square was then scanned with the print tilted at 7° on a flatbed reflection scanner at 600 dpi. The resulting scans were read into MATLAB, (The MathWorks, Inc., Natick, MA), where the ISO slanted-edge analysis tool sfrmat 2.0 (http://www.i3a.org/downloads_iso_tools.html) was used to compute the MTF on each of the four edges of the square. The resulting MTF plots for the fast, or along the head direction, are shown in Fig. 1. The left edge of the square going from gray to black is solid; the right edge going from black to gray is dashed. As expected, the two MTF curves are quite close to one another. Any differences are assumed to be measurement error.

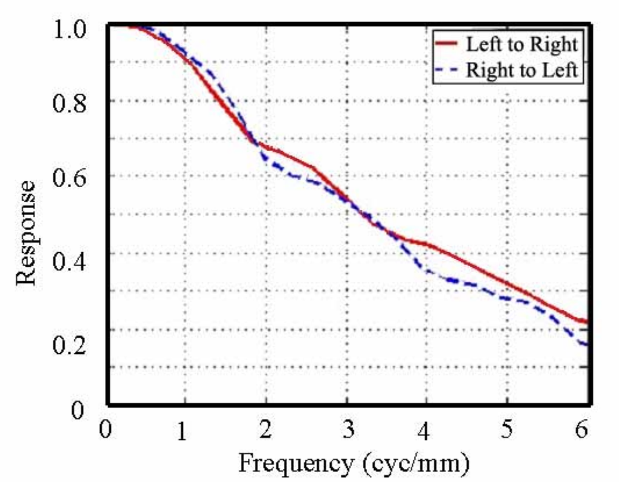

Figure 1. *MTF of the thermal printer in the fast, or along the head, direction*

Figure 2 shows the MTF of the slow (across the head) or down-the-page response of the same thermal printer. The top edge, going from light to dark is solid. The bottom edge, going from dark to light is dashed. The dark-to-light edge is much worse than the light-to-dark edge. Given that light-to-dark edges occur as we heat up the resistors, and dark-to-light edges occur as we cool down resistors, we can state that this particular thermal printer has a much better MTF on rising (or heating up) edges than it does for falling (or cooling off) edges. We can postulate that this is because of unique time constants for heating up and cooling off of the resistors. Figure 3 shows a density trace through this dark square on a gray background in the slow or down-the-page direction. Note how the rising edge is quite sharp and the falling edge is blurry—both whom support the MTF traces in Fig. 2.

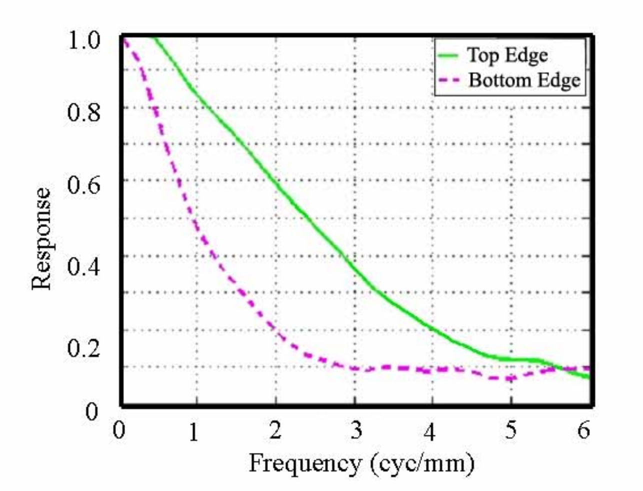

***Figure 2.** MTF of the thermal printer in the slow (across-the-head) or down-the-page direction*

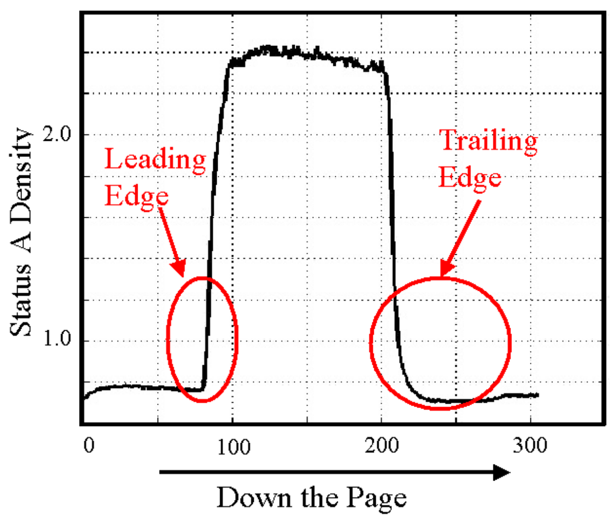

***Figure 3.** Density trace through a dark square on a gray background in the slow direction*

Upon closer examination, one can also see that the MTF of the slow direction for rising or falling edges is worse than the fast-scan direction. The physical tracking of the donor-receiver past the thermal head causes a motion blur, or thermal smear. This thermal smear is the delay in time that it takes each individual resistor to heat up or cool down—by the time the resistor heats up, the donor/receiver has moved past the thermal head.

Thermal smear algorithms try to compensate for this phenomenon, and they do quite well at correcting for low-frequency smear. These thermal smear correction algorithms typically model the heat buildup in the thermal head by keeping the statistics of the energy being sent to each resistor over time.

If we were to feed the printhead a constant code value, there would be a short period of time for the heaters on the printhead to come up to temperature, but once we arrive at temperature, the printhead would continue to get hotter as long as we continue to feed it the same level of constant energy. As the printhead heats up, more density is transferred from the donor to the receiver, yielding a nonuniform density transfer down the printed page. To compensate for this undesired nonuniformity, rising edges initially deliver the requested energy value, and then reduce this value to compensate for heat buildup. Falling edges initially deliver less than the requested energy value because excess heat needs to be shed quickly.

While thermal smear algorithms do an excellent job at compensating for this low-frequency heat-latency factor, it unfortunately has no capability to modify mid- to high-frequency edges. Sharpening algorithms can affect the higher frequencies, but generally they are either circular or elliptically symmetric. The concept of the text smear filter is to modify the slow scan system response by adding an extra boost only in the slow scan direction down the page to compensate for this mid-frequency thermal smear. The text-smear algorithm is a directional sharpening filter, where the sharpening is done in only one direction—that is down the page. For example, the simple filter in Eq. (1) sharpens only down the page.

$$f_d = \begin{bmatrix} 0 \\ 0 \\ 3 \\ -1 \\ -1 \end{bmatrix} \qquad (1)$$

These nonsymmetric filters are effective at boosting in only one direction—exactly what thermal printers need. To improve performance even further, we need to boost the falling edges higher than the rising edges. This is easily accomplished in conjunction with an edge-detection filter such as Prewitt, Sobel, or pixel-difference filters [2] such as the [1 0 –1 0 0] filter. To minimize noise, the [1 0 –1 0 0] filter can be preconvolved with a blur filter or expanded to form boxcar filters such as [1 1 1 0 –1 –1 –1 0 0 0 0] or truncated pyramid filters [1 2 3 0 –3 –2 –1 0 0 0 0]. The results from the edge-detection filter can be used to drive a gain factor on an unsharp mask, or it can be used to selectively pick one of many filters if we are performing direct sharpening.

Filter Design

There are many ways to implement directional filters. For example, the 9 × 1 FIR filter:

$$f1 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 3.046 \\ -0.957 \\ -0.809 \\ -0.347 \\ 0.067 \end{bmatrix} \quad (2)$$

will do no sharpening going up the page, but will sharpen going down the page with the filter response in Figure 4.

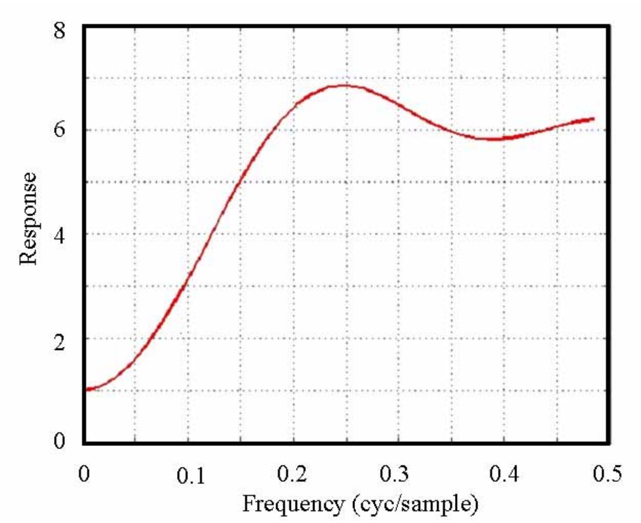

Figure 4. *Frequency response of filter f1*

If the thermal path only included a text smear filter, the down-the-page sharpness would be good, but the up-the-page and left-right directions would be too soft. Down-the-page sharpness boost filters should be used in conjunction with a typical sharpening filter. These sharpening filters are usually circular or elliptical FIR filters. The sharpness filter will boost the fast scan and slow scan directions with a baseline amount of sharpness. The text smear filter will then add an extra amount of sharpness down the page.

For purposes of discussion, an elliptically symmetric FIR filter, which has a 3.0 boost in the fast direction and a 3.5 boost in the slow direction, will be used. The frequency response of this filter in the horizontal (fast) and vertical (slow) direction is shown in Fig. 5. Filter f2 is shown below:

$$f2 = \begin{bmatrix} -0.143 & -0.300 & -0.143 \\ -0.240 & 2.653 & -0.240 \\ -0.143 & -0.300 & -0.143 \end{bmatrix} \quad (3)$$

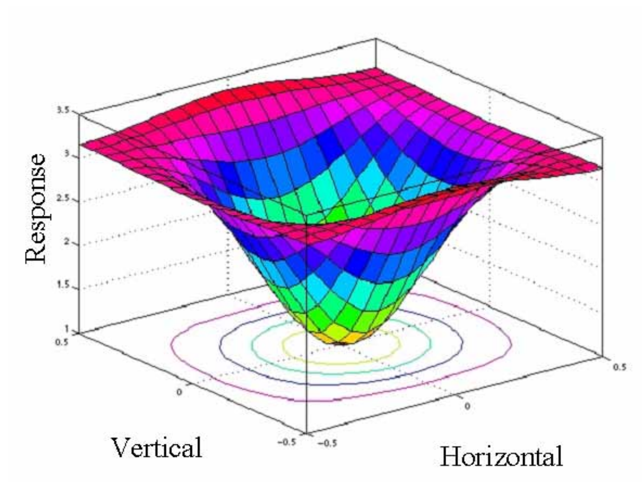

Figure5. *Frequency response of filter f2*

Filter f2 will give a baseline amount of sharpness to the thermal print and should be custom tuned for the particular printer. If we boosted less aggressively in the fast or slow direction, prints might appear blurry. If we boosted more aggressively in the fast or slow direction, over sharpening artifacts might start to appear. We can, however, still sharpen down the page. Filter f3 will accomplish this sharpening. The frequency response of f3 is shown in Fig. 6.

$$f3 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1.190 \\ 0.236 \\ -0.041 \\ -0.201 \\ -0.184 \end{bmatrix} \quad (4)$$

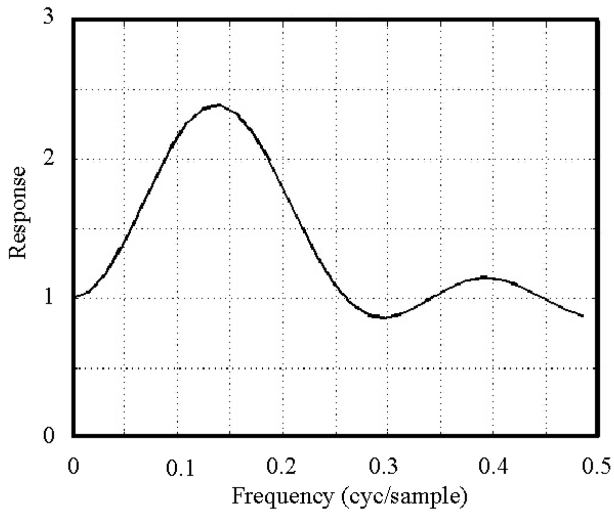

Figure 6. *Frequency response of filter f3*

We can preconvolve filter f2 with filter f3 to generate an 11 × 3 filter. It is mathematically equivalent to apply f2 followed by f3, or just applying the preconvolved single 11 × 3 non-symmetric FIR filter. The problem with the preconvolved filter is that in the 11 × 3 filter, all of the lower seven rows are fully populated as follows:

$$f2 * f3 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ -0.1705 & -0.3569 & -0.1705 \\ -0.3193 & 3.0855 & -0.3193 \\ -0.2213 & 0.2815 & -0.2213 \\ 0.0048 & -0.1185 & 0.0048 \\ 0.0804 & -0.4659 & 0.0804 \\ 0.0730 & -0.4279 & 0.0730 \\ 0.0264 & 0.0552 & 0.0264 \end{bmatrix} \quad (5)$$

In the spirit of creating filters that are more CPU friendly, we would like more zeros in that filter. One solution is to forgoe the circular symmetry. By extracting the horizontal and vertical responses of filter f2 and ignoring the diagonal response, we can speed things up. The resulting image quality loss is negligible owing to the fact that humans have a hard time seeing detail on diagonals. Not only that, we are still sharpening on the diagonals, just not in the proper amounts.

Taking the vertical portion of f2 we get:

$$f2\_V = \begin{bmatrix} -0.587 \\ 2.17 \\ -0.587 \end{bmatrix} \quad (6)$$

Taking the horizontal portion of f2 we get:

$$f2\_H = \begin{bmatrix} -0.527 & 2.05 & -0.527 \end{bmatrix} \quad (7)$$

Convolving f3 with the vertical portion of f2 yields:

$$f3 * f2\_V = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -0.6984 \\ 2.4431 \\ -0.1623 \\ -0.1089 \\ -0.3043 \\ -0.2813 \\ 0.1080 \end{bmatrix} \quad (8)$$

This combined response is shown in Fig. 7. The noise in the mid to high frequencies, while undesirable, is tolerable because in the down-the-page direction, there is very little frequency content past 0.2 cyc/sample for this particular device (see MTF plot in Fig.2). In addition, the human eye is not as sensitive to those frequencies; therefore, it is hard to tell if we are boosting by 2X or 3X at those frequencies. Of course, it would be preferable not to have the noise, but prints have shown human observers do not detect it.

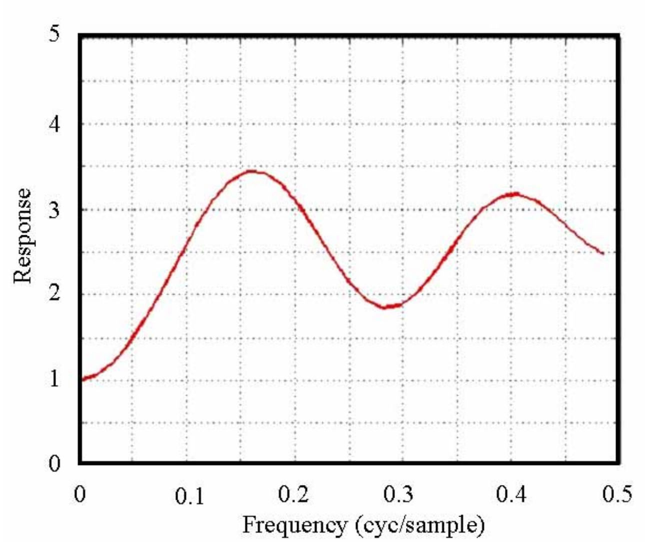

Figure 7. *Frequency response of filter f3 convolved with the vertical portion of filter f2*

If we now combine f3*f2_V with f2_H, we get filter f4. This filter combines both sharpening and text-smear sharpening in one convenient 11 × 3 FIR filter. Filter f4 is shown below:

$$f4 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -0.7012 & 0 \\ -0.5291 & 3.5115 & -0.5291 \\ 0 & -0.1629 & 0 \\ 0 & -0.1099 & 0 \\ 0 & -0.3053 & 0 \\ 0 & -0.2824 & 0 \\ 0 & 0.1084 & 0 \end{bmatrix} \quad (9)$$

In total, we have nine multiplies, which can be implemented as 1D LUTs, if desired. Two of the coefficients, or taps, are identical; therefore, we can combine two of the multiplies into an add plus a multiply. We ignore all zero terms.

To make things run a bit faster, we would like to remove all floating-point multiplies. A common technique is to scale the entire kernel by some integer factor, and then round all the coefficients to the nearest integer. After applying the convolution kernel to each pixel, we need to normalize the value so that for flat DC fields, there is no increase or decrease in signal. Because we are scaling all coefficients by an integer, we will have to divide by some value after the kernel is applied. If we scale the kernel by a power of 2, the divide operation can be by a power of 2 and be replaced by a bit shift operation.

For example, we can take filter f4, and scale it by 1024, giving us f5:

$$f5 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -719 & 0 \\ -524 & 3598 & -524 \\ 0 & -167 & 0 \\ 0 & -113 & 0 \\ 0 & -313 & 0 \\ 0 & -289 & 0 \\ 0 & 111 & 0 \end{bmatrix} \quad (10)$$

Filter f5 has the property that, if applied to a flat field or DC area of an image, it would boost the image by a scale factor of 1024. So, after applying this filter, we need to divide by 1024, or do a bit shift by 10 bits. Similar techniques can be used to turn all integer multiplies into bit shifts.

Conclusion

A new algorithm called "text smear" has been introduced. This algorithm can combat mid- to high-frequency thermal smear. This algorithm has been shown to give an extra sharpness boost to thermal prints that is not achievable by traditional sharpening algorithms. This algorithm should be tuned in conjunction with the traditional thermal smear and sharpening algorithms. It is also possible to preconvolve the text smear filter with the sharpening filter resulting in the ability to apply a single filter to the image. This single filter applies sharpness and text-smear correction at one time. As thermal printers print faster, thermal smear becomes exponentially worse, making the text-smear algorithm more valuable.

References

[1] P. D. Burns, Slanted-Edge MTF for Digital Camera and Scanner Analysis, Proc. PICS Conf. (IS&T, Springfield, VA, 2000) pp. 135-138.

[2] W. K. Pratt, Digital Image Processing., 2nd Edition (John Wiley & Sons, New York, 1991) pg. 503.

Author Biography

Ray Ptucha received his BS in computer science and BS in electrical engineering from the State University of New York at Buffalo (1988/1989) and his MS in imaging science from the Rochester Institute of Technology (2002). Since then, he has worked in the Research Labs at Eastman Kodak Company in Rochester, NY. His work has focused on the digital photofinishing algorithms, MTF, resampling, sharpening, digital cameras, scanners, and printers.