On the Density-dependence of Sharpness in Thermal Print Media

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Abstract

In direct thermal print media where image dyes are formed in a layer structure, edge sharpness is observed to be dependent on density, and to be related to internal scattering and reflection. To study the effect quantitatively in various digital print media, a one-step scanner-based methodology was developed to measure MTF and SQF sharpness as a function of density and contrast on a single continuous density edge target. This was used to confirm that a previously described multi-resolution algorithm successfully corrected the density-dependent sharpness loss in direct thermal media.

Introduction

Sharpness is one of the most important image quality parameters when evaluating digital photo print systems. Achieving sufficient sharpness is a key goal when designing digital photo print hardware and media. In thermal printing, sharpness is affected by both the printer hardware and the print media. Important sharpness-limiting hardware characteristics are print head resolution, lateral thermal diffusion in the print head, color registration, print velocity, and thermal history. Internal scattering and reflection also contribute to reduced sharpness. A sharpness measurement tool should meet the following objectives:

1. The metric should correlate well with the visual perception of image sharpness.
2. Sharpness characterization over the entire range of print densities and contrasts is a novel way to better quantify media and hardware performance.
3. It should be an efficient measuring tool, based on a single test target and a one-step measuring process.

Sharpness is the psychovisual (subjective) response to the lateral spread or 'blur' of the image information. In complex images with spectral, spatial, and density components sharpness is correlated with a weighted average over all wavelengths of the spectral range, all visually relevant spatial frequencies, and all image densities. The appropriate weighting functions are modeled on the human visual system – photopic spectral luminous efficiency V(λ) for spectral frequency weighting, human contrast sensitivity function E(f) for spatial frequency weighting.

The dependence of sharpness on mean edge density and contrast is usually omitted and approximated by measuring sharpness on low-contrast edges printed above and below a mid-tone density of 0.75. For conventional thermal imaging methods such as dye or wax transfer where the image dyes are deposited in a thin layer on the surface of the receiver and no change of sharpness with density or contrast can be perceived this approach delivers reasonably accurate estimates of perceived sharpness. However, for direct thermal media where the image dyes are formed in separate layers there is a noticeable decrease in sharpness in low-density details. Since the sharpness of edges over a wider range of densities and contrasts govern the perception of sharpness in complex scenes, an objective measuring method for edge sharpness as a function of mean edge density and contrast is needed.

The initial approach was to measure edge MTF on an array of edges at a number of different mean edge densities and contrasts. Although such a print target can easily be composed of adjoining step wedges,[1] and conventional scanner-based edge sharpness measurements applied to each individual edge,[2] in practice this approach was cumbersome, especially for large-scale testing and calibration of adaptive sharpening algorithms as previously described.[1] Therefore it was desirable to develop a measuring method that delivers the distribution of MTF and sharpness over a range of densities or contrasts from a single print target and scan. It should also automatically exclude edge regions where the contrast is too small to allow reliable measurement, and discard outliers from the sharpness over density distribution.

The success of using CCD image scanners for measuring the MTF of films[0] suggested the suitability of high-end flatbed scanners for evaluating print quality. Flatbed scanners offer a low-cost, fast, user-friendly alternative[4,5] to automated microdensitometers.

Based on the success of measuring granularity vs. density on a continuous wedge target,[6] a novel scanner-based method was developed to measure MTF and SQF for edges with continually changing mean density and/or contrast that are composed of adjoining continuous density wedges.

Experimental

Measuring sharpness for a continuous edge requires separating the edge signal perceived as image sharpness from the gradual change of density along the edge. The described method subdivides the scanned edge image into segments for which the change of density can be considered to be small, and calculates the edge MTF for each segment to estimate SQF sharpness as a function of density and contrast.

Print Targets

The two basic types of continuous edge targets shown in Figure 1 are both composed of adjoining continuous density wedges. The first has locally varying mean edge density $\overline{D}(y)$ with a constant density difference ΔD, while the second is reversed with constant $\overline{D}$ and locally varying $\Delta D(y)$.

$$\overline{D}(y) = \frac{(D_2(y) + D_1(y))}{2} \qquad (1)$$

$$\Delta D(y) = D_2(y) - D_1(y) \tag{2}$$

Although ΔD is often referred to as contrast, the definition of contrast is actually

$$C(y) = \frac{(D_2(y) - D_1(y))}{(D_2(y) + D_1(y))} = \frac{\Delta D(y)}{2 \cdot \overline{D}(y)} \tag{3}$$

Practical print systems often deliver targets where ΔD and $\overline{D}$ change simultaneously, and the MTF and SQF data can be organized as a function of either mean edge density or contrast. The following discussion considers data organized as a function of mean edge density *MTF(D)* and *SQF(D)*.

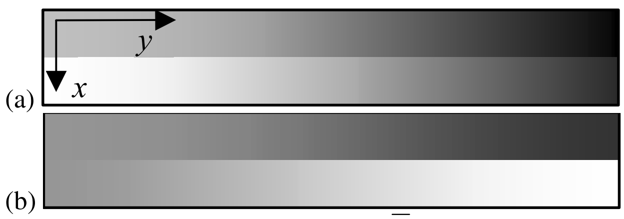

Figure 1. Continuous edge targets: (a) varying $\overline{D}$ and constant ΔD, (b) constant $\overline{D}$ and varying ΔD.

Scanning and Pre-Processing

The printed continuous edges are scanned at 1200dpi, using linear scanner settings at 42bit grayscale resolution. The pre-processing algorithm automatically detects the orientation of the edge, truncates the image, then flips and/or rotates the image to an orientation of horizontally increasing mean density or contrast. Pre-processing concludes with the calculation of either photopic visual or monochrome cmy densities. The subsequent steps of sharpness-density analysis are segmenting, edge scanning, and removal of halftone and granularity noise before calculating MTF and SQF for each segment. This results in distributions of *MTF(D)* and *SQF(D)* as well as an estimate of SQF for a midtone density. The algorithm is designed to deliver robust sharpness estimates when tilted and curved edges, halftone patterns, print grain, or uniformity defects are present.

Segmenting and Scanning of Edge Profiles

The scanned continuous edge is divided into segments, each having a density range of about 0.05, i.e. small enough for the density dependence of MTF and SQF to be assumed constant. Mean edge density $\overline{D}_n$, mean density difference ΔD_n, MTF, and SQF are then calculated for each segment *n*. Pixel merging simulates slit scans thus delivering edge density profiles $D_n(x)$ for each segment. Halftone patterns present a challenge for edge detection especially at low contrast, but the edge coordinates can be reliably detected in a temporary copy of the image where the halftone signal has been filtered out. If the edge is slanted, the slit length *l* is shortened so that blur is effectively eliminated, and the segment subdivided into bands with the dimensions $l \cdot N$ (Figure 2). Keeping a minimum slit length prevents ragged edges from being effectively straightened, which would result in the blurring effect of edge raggedness being underestimated.

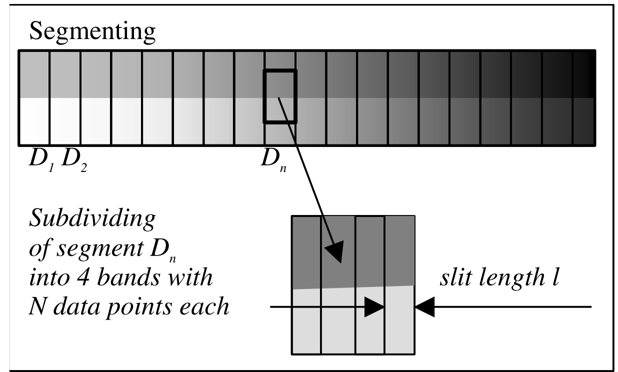

Figure 2. Segmentation of the edge image, and an example of subdividing each segment into scan bands.

The normalized edge profiles of all bands within each segment are averaged after aligning their centers. Those segments where an edge cannot be found due to insufficient contrast or to print defects are excluded from the analysis. A smoothing algorithm with a variable filter window, centered at the edge, then effectively removes granularity and halftone signals without degrading edge sharpness.[0] As an added bonus, the relative positions of cyan, magenta, and yellow edges in tri-chrome prints are a precise measure of color registration. For each segment the Line Spread Function (LSF) *L(x,D)* is calculated by differentiation of the edge profiles. Finally, MTF is calculated from the LSF via FFT,

$$M(f, D) = \left| \int_{-\infty}^{\infty} L(x, D) e^{-2\pi i f x} dx \right| \tag{4}$$

Sharpness Analysis

Most MTF-based sharpness metrics perform an eye weighted integration of MTF over spatial frequency, and integration over a log frequency gives less weight to the less visible higher frequencies.[8] Eye weighted integration over the log spatial frequency range of 0.5 to 2.0 cy/mm approximates the filtering by the human eye function *E(f)* and delivers an equivalent of Granger's Subjective Quality Factor (SQF),[0]

$$SQF(D) = 100 \frac{\int \left(\frac{E(f)}{f} \right) M(f, D) df}{\int \left(\frac{E(f)}{f} \right) df} \tag{5}$$

The final step is median analysis to remove outliers from the *SQF(D)* distribution.

The density-dependence of MTF, and of the perception of image modulation have not yet been considered in the image quality model; instead the SQF of a low contrast gray edge with a mean density of about 0.75 is assumed to be a good metric for image sharpness in print systems where the distribution of SQF over density is flat. The new continuous edge method is an effective tool for studying the dependence of print sharpness on density and contrast.

Results

When tested against conventional step-edge measurements the new continuous edge algorithm was found to be in excellent agreement. Figure 3 shows an example of a direct thermal print with characteristic low-density sharpness loss. Furthermore, the continuous edge method provides much higher density resolution than that obtainable from a step edge target of the same area.

Comparison of Thermal Photo Print Systems

The distributions of sharpness vs. $\bar{D}$ and C in turn were measured for a variety of digital photo print systems: direct thermal with separate color forming layers in thick and thin layer structures, thermal ink transfer ("OPAL"), and thermal dye transfer (D^2T^2). Experimental thermal printers were used to study the print processes without interference from digital sharpening.

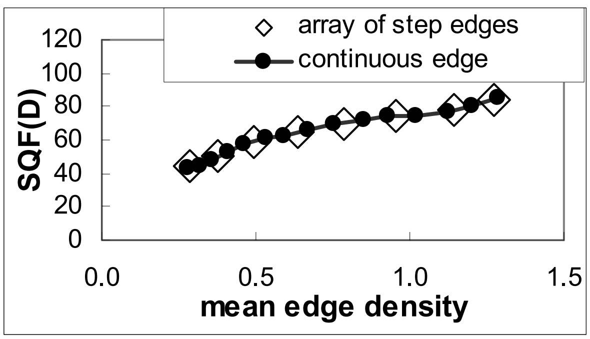

Figure 3. Comparison of continuous vs. step edge SQF measurements on a direct thermal print.

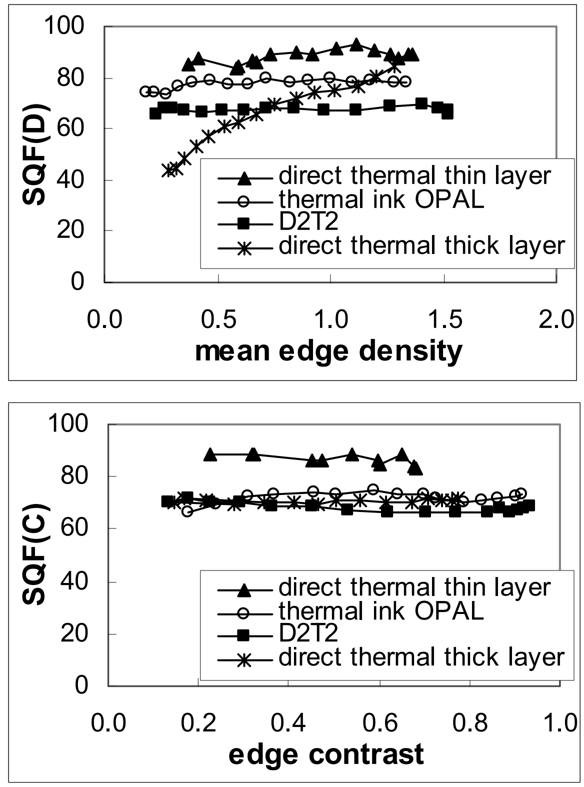

Figure 4. Distributions of SQF over mean edge density (above) and edge contrast (below) for a variety of experimental printers.

The curves only show larger variations in *SQF(D)* for the direct thermal media where the imaging layers are distributed in a 'thick' structure where internal spread, scattering and reflection all have a measurable effect on sharpness. All the other systems have mainly flat sharpness distributions, confirming midtone density SQF as a good sharpness metric for these systems. Interestingly, varying edge contrast at constant midtone $\bar{D}$ did not lead to a significant change in SQF for any of the investigated thermal print systems. This shows that density not contrast is the main parameter for sharpness loss due to internal scattering.

Adaptive Sharpening Calibration and Verification

The continuous edge method was used as an efficient tool to provide calibration data for a multi-resolution adaptive sharpening algorithm[1] on direct thermal media.

Internal scattering and light diffusion in opaque layers blur the edge profiles and cause them to extend into long ramps. These effects increase with decreasing density, thus severely lowering the SQF (Figure 5). The adaptive sharpening algorithm effectively removes the low-density blur and visually improves the sharpness of the direct thermal prints.

Conclusion

The scanner-based method described here measures the characteristics of sharpness versus mean edge density and edge contrast for thermal photo print systems using a single continuous density edge. The method has been used to study different thermal photo print systems. It revealed that light diffusion and scattering in direct thermal media reduces sharpness at lower densities, and was then used to provide calibration data for a compensating adaptive sharpening algorithm. This efficient and robust method has become an indispensable tool when optimizing thermal print media and hardware.

Acknowledgements

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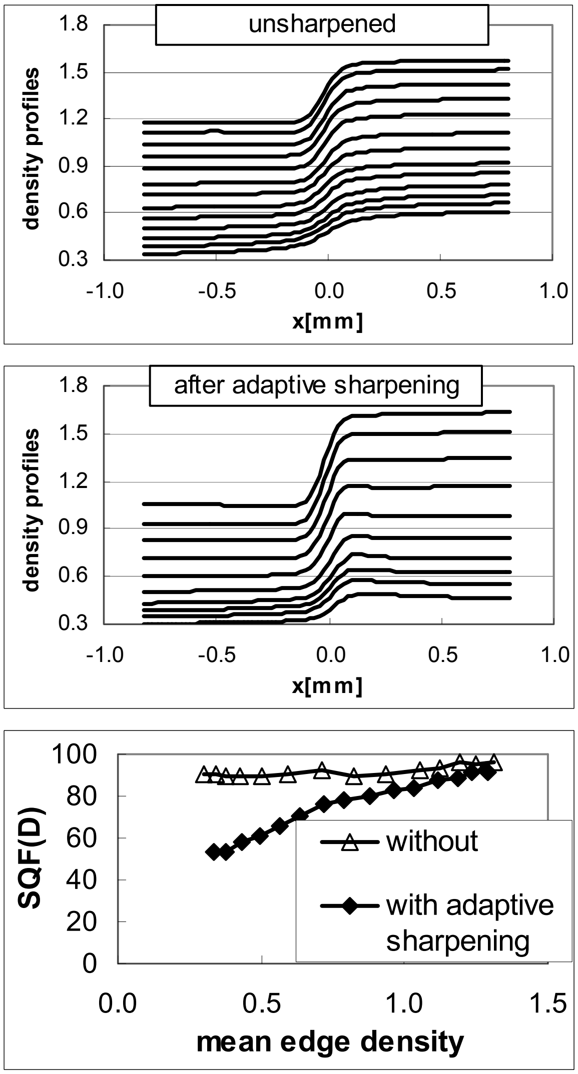

Figure 5. Removing the low-density sharpness loss by adaptive sharpening: above – unsharpened edges, middle – after sharpening, below – SQF(D) curves.

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Author Biography

Dirk Hertel received his degree in physics (1979), and a Ph.D. (1989) for research work on image quality from the Technical University Dresden (Germany), where he subsequently worked as researcher and assistant lecturer in imaging science. Since joining Polaroid Corporation in 1998 he focused on developing scanner-based print evaluation tools and on optimizing image quality in digital print media and hardware. He is a member of the IS&T, and the German Society for Photography (DGPh), and the Colour Group (Great Britain).