Edge-Raggedness Evaluation Using Slanted-Edge Analysis

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ABSTRACT

The standard ISO 12233 method for the measurement of spatial frequency response (SFR) for digital still cameras and scanners is based on the analysis of slanted-edge image features. The procedure, which applies a form edge-gradient analysis to an estimated edge spread function, requires the automated finding of an edge feature in a digital test image. A frequently-considered (e.g. ISO-13660, -19751) attribute of printed text and graphics is edge raggedness. There are various metrics aimed at the evaluation of the discontinuous imaging of nominally continuous features, but they generally rely on an estimation of the spatial deviation of edge or line boundaries, the tangential edge profile (TEP). In this paper, we describe how slanted-edge analysis can be adapted to the routine evaluation of line and edge quality. After locating and analyzing the edge feature, the TEP is estimated. The estimation of RMS deviation and edge spectrum are then described.

Keywords: edge raggedness, tangential edge profile, normal edge profile, slanted edge

1. INTRODUCTION

In printed images and documents the reproduction of edges is subject to various sources of degradation and error. In some cases, e.g., projection through a lens, the imperfect edges appear blurred. This can also be the case for discrete event-formed images when individual edge variations are minor or at high spatial frequencies. The analysis of the transfer of image detail information important to the perception of image sharpness has long been described by the modulation transfer function (MTF)[1] and corresponding spatial spread function. The measured edge spread function is sometimes known as the normal edge profile (NEP).

For systems that reproduce edge features with irregular boundaries such as electro-photographic and inkjet printers, under some conditions the edges can appear rough or ragged, rather than blurred. Figure 1 shows an example of a printed line with irregular edges. The perception of raggedness has been addressed for both threshold and super-threshold conditions.[2] Corresponding methods for measurement of physical correlates were also developed. Raggedness measurement is usually based on the variation of the edge as a function of position, known as the tangential edge profile (TEP). When various periodic edge deviations were introduced, the observed visual threshold was found to be insensitive to the various phase conditions for the sinusoidal deviation components. This finding supports the use of a frequency-based contrast sensitivity function (CSF) when predicting the observers' raggedness rating. A CSF weighting can also be used with a noise-power spectrum of the TEP, which provides a statistical description that is also insensitive to the phase of the edge deviation components.

It has been pointed out that for printed edges and lines, whether edges appear blurred or ragged will depend on the spatial correlation of the variation in edge location. This will often depend on the size of the imaging elements and the distribution of their position error with respect to a perfectly reproduced edge. Printed edges from systems with small imaging elements and large (normal to the edge) position errors are said to appear blurred.[3] For those with large events and relatively smaller normal position errors, a ragged appearance is thought to dominate.[4] Engeldrum[5] addressed this blurred-to-ragged continuum in a model of ideal dot-formed line images. He considered the case where the only source of edge variation was the size and overlap of the circular image-forming dots. For this model the dots size influences the spatial frequency of the edge variations, and the amount of overlap determines their relative amplitude. The result was a prediction of the size and overlap settings which would result in either a uniform blurred or discontinuous ragged appearance.

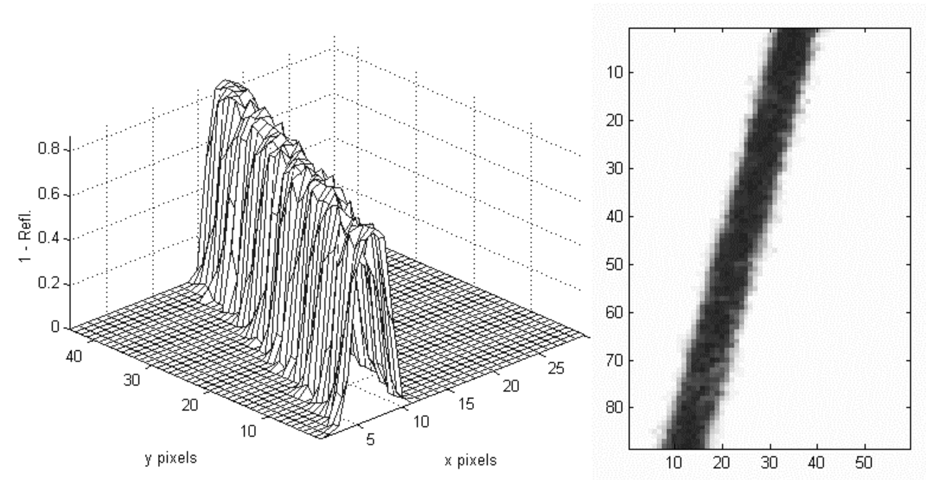


Figure 1: Example of edge deviations scanned at 600 pixels/inch (PPI), a sampling interval of 0.042 mm

The last few years have seen the development and adoption of several international standards for the evaluation of the imaging performance. The standard ISO 12233 method [6-8] for the measurement of spatial frequency response (SFR) for digital still cameras and scanners is based on the analysis of slanted-edge image features. The procedure, which applies a form of edge-gradient analysis [9, 11] to an estimated edge spread function, requires the automated finding of an edge feature in a digital test image. Since the ISO method is robust with variation in edge placement and angle, it is natural to consider adapting it to other attributes of edge and text quality.

As indicated above, a frequently considered (e.g. ISO-13660, -19751) attribute of printed text and graphics is edge raggedness, or edge roughness. [12] Originally the term raggedness referred to the visual impression of the edge or line feature. This usage is consistent with other nesses such as graininess and sharpness. Often, however, the term is used to indicate a physical quantity that is used to predict the visual impression. In this paper we make the distinction between the attribute (raggedness) and the measured quantities that are estimated in order to predict the level of visual sensation (e.g., tangential edge profile, RMS edge noise, edge spectrum).

There are various metrics aimed at the evaluation of the discontinuous imaging of nominally continuous features, but they all generally rely on an estimation of the spatial deviation of edge or line boundaries from the intended form. The edge boundary is usually described in terms of the measured tangential-edge profile (TEP). In this paper, we describe how the previously developed ISO method for slanted-edge analysis can be adapted to the routine evaluation of edge quality. After locating and analyzing the edge feature, the TEP is estimated. From the TEP the estimation of RMS deviation and edge spectrum can then be computed.

2. SLANTED-EDGE ANALYSIS

Edge-gradient methods have shown the advantages of target simplicity and a small test image area, but the disadvantages of alignment sensitivity and noise bias. The method, outlined in Fig. 2, usually calls for the scanning the image of an edge feature in a direction perpendicular to the edge. An edge profile is then derived from the data, often with noise reduction, such as by averaging edge traces. From this edge-spread function, a point-spread function is computed, either by a discrete first derivative or by a parametric fit to the data. The discrete Fourier transform of the point-spread function is then computed, with its modulus recorded.

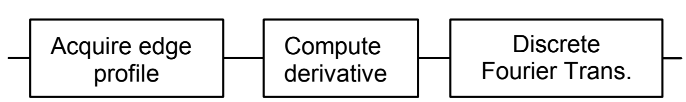


Figure 2: Edge-gradient analysis steps

If the input edge feature used is of sufficiently high optical quality, in terms of its edge modulation, then the above measured modulus can be taken as estimating the MTF of the system whose output provided the data. If this is not the case then the output modulation can be divided by the input target modulation frequency-by frequency to yield the system MTF. We refer to the result based on a single measurement as a spatial frequency response (SFR), and one corrected for the input modulation as an MTF.

The above edge-gradient method was modified [6-8] for application to digital camera and scanners, and based on image data rather than those acquired via a separate instrument. The use of a slanted, or skewed edge was proposed, in conjunction with corresponding data processing. The steps are show on the left-hand side of Fig. 3.

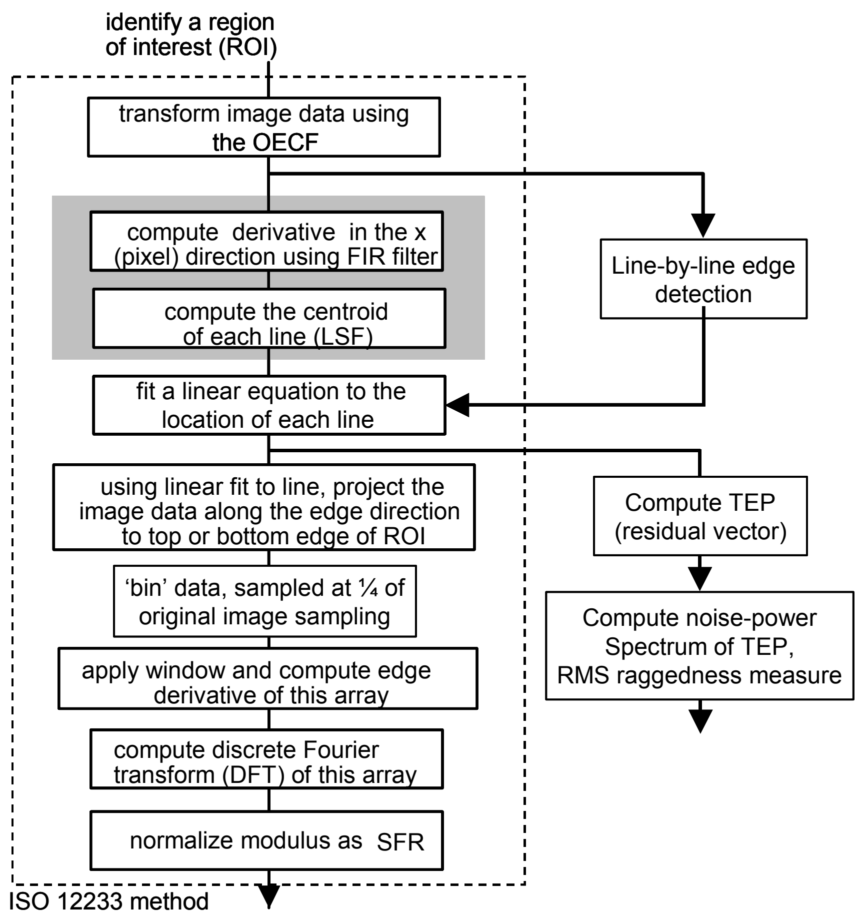


Figure 3: Outline of the slanted-edge analysis method (left-hand side), with additions for raggedness evaluation on the right. The sampled edge is assumed to be near vertical.

The region of interest surrounding the edge is selected and transformed to compensate for the camera photometric response. This is done via the opto-electronic conversion function (OECF). The edge location and direction are then estimated via a linear equation. This is found after taking a one-dimensional discrete derivative and finding the centroid for each data line. The image data for all pixels are projected along the direction of the edge to form a one-dimensional 'super sampled' edge-spread function. The four-times oversampling accomplished by this step reduces the influence of signal aliasing of the measured spatial frequency response (SFR). After application of a Hamming window, the discrete Fourier transform is computed. The normalized modulus is then taken as the SFR.

3. MODIFIED SLANTED-EDGE ANALYSIS

While there are several specific edge raggedness measurements used in the literature, they all start by finding the edge location variation along the edge. The ISO 13660 standard calls for scanning the edge at 600 PPI (24.5/mm) or more. From this data array the 60% transition between the minimum and maximum edge reflectance values is found for each location along the edge. These edge locations are fit to a straight line and the residual variations from the line make up the tangential edge profile vector. The standard deviation of these fluctuations is taken as the physical correlate of edge raggedness.

Fig. 3 also shows several steps that can be used to adapt the slanted-edge method to the routine measurement of edge raggedness. The first of these is an alternative to the line-by-line derivative and centroid calculation. The method, well established for low-noise and near continuous signals can give unstable results for some printed images. Fluctuations far from the edge can bias the centroid calculation. An alternative avoids the derivative filtering and applies a simpler edge thresholding step for each line in the test image array. It is usually best to process the data from low-noise (usually paper) area to higher noise, and apply a statistical outlier rejection step afterwards. The set of edge location data can serve as input to the linear fitting function, as show in Fig. 3.

The line-by-line difference between the edge location data and the fitted equation and yields the measured tangential edge profile vector. An example for an electrophotographic print is shown in Fig. 4. The equal (red, green, blue) test image was printed and this resulted in a single black toner being used.

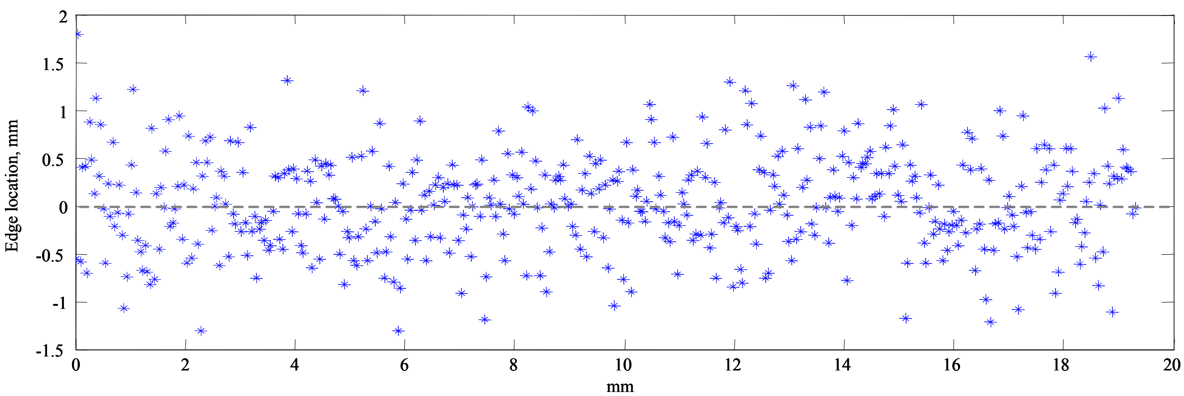


Figure 4: Example TEP for an electrophotographic printed edge

If a spatial frequency description of these fluctuations is needed, the noise-power spectrum of these data can then be computed, as indicated in Fig. 3. The noise-power spectrum (NPS) provides us with a statistical description of a stochastic process. In our case this process is the array of TEP fluctuations. The NPS is the Fourier transform of the spatial autocorrelation function and describes the fluctuations as a function of spatial frequency. Since, by Fourier transform properties, the integral of the noise-power spectrum is equal to the variance, we can also interpret the NPS as the spatial-frequency decomposition of the variance.

Although the ISO 13660 standard does not call for this NPS estimation step, this may be useful when comparing results from different testing facilities. For example, Briggs *et al.* [12] point out that the ISO standard only specifies a minimum sampling (600 PPI). For a range of print sampling settings, however, resultant variation in RMS TEP noise is observed. They suggest that an improved standard might include filtering the data to closely approximate the response of a (reference) 600 PPI scanner. This can easily be done in the spatial-frequency domain by weighting the NPS prior to computing the RMS raggedness measure. Alternatively, a visual weighting could be employed to achieve the result, with the added benefit of weighting the TEP fluctuations according to visual importance. The computation of a visually weighted RMS raggedness metric is as follows.

3.1 Computation of the Frequency-Weighted Raggedness Measure

For continuous edge data, the measure is taken is the square root of the area under (one-dimensional integral of) the visually-weighted noise-power spectrum. For discrete estimates based on sampled data, the integral is replaced by summation. Consider the NPS estimate in the form of an array,

$$n_i,\ i = 1 \ldots N \tag{1}$$

and a corresponding CSF,

$$c_i,\ i = 1 \ldots N \tag{2}$$

where the index corresponds to spatial frequencies, zero to the half-sampling frequency. The spatial frequency sampling of the estimate is determined by the original data sampling Δx and the size of the NPS estimate array,

$$\Delta f = \frac{1}{2\Delta x(N-1)} . \tag{3}$$

The CSF-weighted RMS edge noise is given by,

$$r = \left[\Delta f \left\{ n_1 c_1^2 + n_N c_N^2 + 2\sum_{i=2}^{N-1} n_i c_i^2 \right\} \right]^{0.5} . \tag{4}$$

Figure 5 shows the test region and resulting TEP spectrum with a typical visual weighting applied, for a viewing distance of 33 cm. The units of the TEP noise-power spectrum are variance per spatial frequency. Since the variance of the edge locations is in mm^2 and spatial frequency is in cy/mm (mm^{-1}), the spectrum units are mm^3. The computed RMS edge noise results are,

1.36 mm unweighted
0.63 mm with visual weighting.

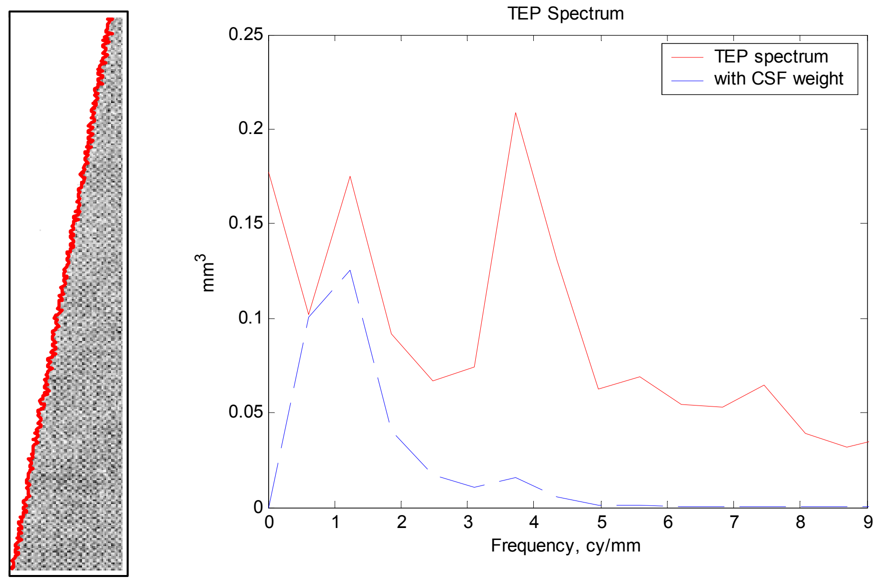
Note that the unweighted rms value can be either computed from the spectrum using Eq. (4), or via the usual sample standard deviation formula. Interesting features of the spectrum shown in Fig. 5 are the components at about 1.25 and 4 cy/mm. These can be attributed to the periodic nature of the digital halftone pattern. Replicate measurements indicated that these results were repeatable.

Results of a second example measurement, for an inkjet print, are shown in Fig. 6. All printer inks were used in this region of the print, and the analysis results are for the scanned green-record image. This presented a less ordered halftone pattern and, as expected, we see a relatively higher amount of low-frequency edge fluctuations. The corresponding RMS results are,

1.61 mm unweighted
1.07 mm with visual weighting.

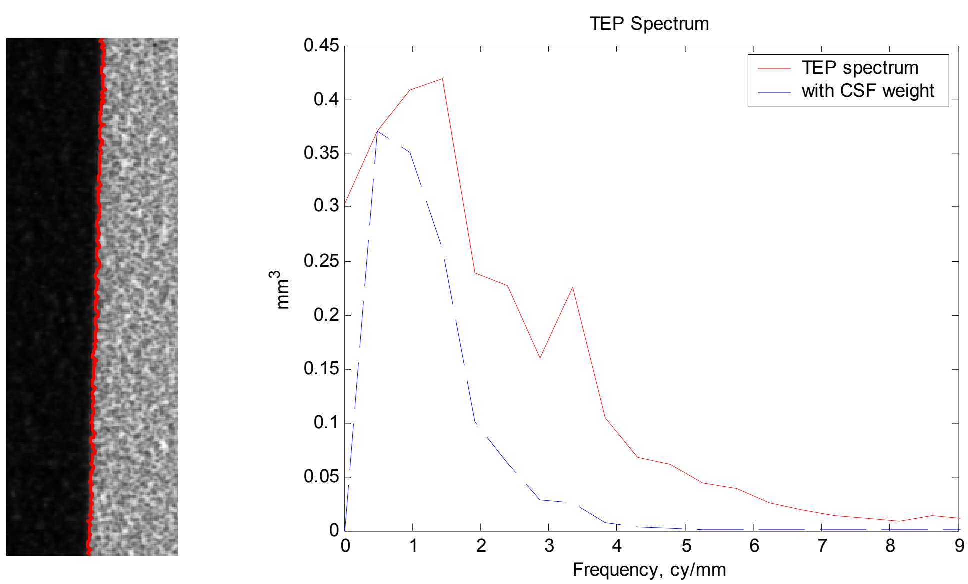
4. CONCLUSIONS

The well-established ISO slanted-edge analysis, first developed for resolution evaluation of digital cameras, can be adapted for edge quality evaluation of printed images and documents. The implementation described here included a modified edge finding method, calculation of a tangential edge profile, noise-power estimation and frequency-based raggedness measure. While various standards may differ on the exact details (e.g., spatial filtering vs. sampling specification) it is likely that this approach could be employed in routine edge quality evaluation in much the same way that the slanted-edge analysis is used for digital cameras and scanners. In particular, the accommodation of varying print-to-scanner alignment should be useful. In addition, if needed, it is possible to obtain both normal edge profile (for sharpness evaluation) and tangential edge profile (for raggedness) based on the same test feature and with in the same software tool.



a. *b.*

Figure 5: (a) Scanned electrophotographic print with detected edge added, and (b) TEP noise-power spectrum and CSF weighting for 33 cm viewing distance.



a. *b.*

Figure 6: (a) Scanned inkjet print with detected edge added, and (b) TEP noise-power spectrum and CSF weighting for 33 cm viewing distance.

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