The Circular-edge Spatial Frequency Response Test

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ABSTRACT

A new method for testing the resolution of digital cameras has been developed. The new method is an extension of the ISO 12233 Slanted-edge Spatial Frequency Response test[1,2]. The new method computes the spatial frequency response along the edge of a circle. It is especially well adapted to inexpensive imaging systems with rotationally symmetric lens distortion. In addition to presenting the new method, a set of practical improvements is described which can be applied to both the slanted-edge and circular-edge methods.

Keywords: MTF, SFR, Slanted-edge, Modulation Transfer Function, Spatial Frequency Response

1. INTRODUCTION

One of the most important metrics of image quality is sharpness, or the ability to resolve fine features in a scene. Several different methods can be used to measure sharpness in digital camera images. The most direct method is to measure the contrast as a function of grating period for a chirped sine wave grating. Unfortunately sine wave gratings are difficult to generate and the interpretation of the contrast values is complicated by aliasing. Also, the sharpness of the optical system must be constant over a large field of view in order to accommodate a large chirped grating target, and the method is not amenable to automation.

The slanted-edge spatial frequency response test described in the ISO 12233 standard overcomes most of these difficulties. In the slanted-edge method, a test chart consisting of a single slanted-edge transition from light to dark is used. Even though the standard specifies a particular test chart, slanted edge transmission or reflection test charts are simple to create. In this method, samples along different horizontal (or vertical) scan lines are re-registered according to their estimated edge positions. The samples are then combined to obtain an estimate of the edge transition with enhanced resolution. The spatial frequency response is then obtained by performing a Fourier transform on the first derivative of the edge transition function.

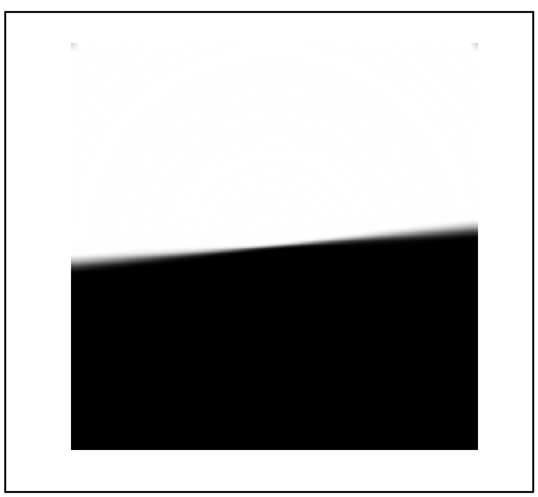

Figure 1. – Slanted edge with radially-increasing blur

One of the disadvantages of the slanted-edge method is that the sharpness must be constant, and the image must be free of distortion, over the region that is analyzed. Otherwise the transitions on different scan lines will have different widths and the transitions may not be located on a straight line. Practical camera lenses exhibit a number of optical aberrations that interfere with the slanted-edge method. Field curvature (the curvature of the true focal plane) causes the image sharpness to be a function of radius from the lens axis. Chromatic aberration (the variation in lens power with wavelength) causes a similar effect. Distortion causes the magnification to depend on the distance from the axis of the lens. All of these effects are significant in the compact lenses used inexpensive imaging modules. A common characteristic of all of these aberrations is that they are rotationally symmetric. In other words, the blur and distortion depend only on the radius from the optical axis. The effect of radially increasing blur on a slanted-edge is shown in Figure 1. The line spread function that results from applying the slanted-edge method to this target is compared to the true LSF at the center of the image in Figure 2. As the figure shows, the slanted-edge method is ineffective in this case because the blur isn't constant.

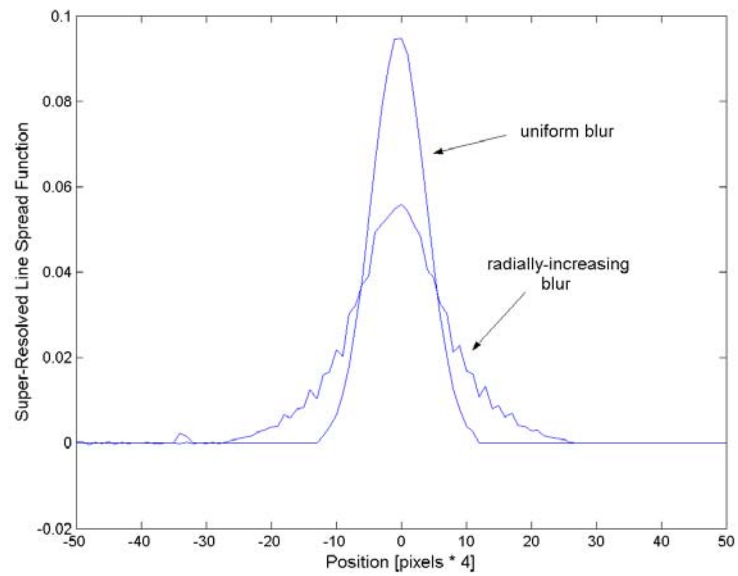

Figure 2. – Line Spread Function for slanted edges with uniform and radially increasing blur

The new circular-edge MTF method is designed to work correctly in systems with rotationally symmetric aberrations. In this method, a circular target is used. The center of the target is aligned with the optical axis so that the edge of the circle is a contour of constant blur and distortion. The samples from the circular edge transition are then combined to obtain a measure of the sharpness at a specific radius. The number of samples that are available is large because points along the entire circumference of the circular edge can be used. Targets of different diameter can be used to map out the variation of sharpness with radius. The new method is similar to the slanted-edge method, except that radial scan lines are used. It is described in detail in the next section.

Optical distortion, random noise and illumination shading all degrade the accuracy of the spatial frequency response estimate. Several techniques that can be used to improve the utility of the slanted-edge and circular-edge methods are described in the subsequent section. One technique is to accommodate distortion in the slanted-edge method by fitting the edge transitions to a higher-order polynomial, rather than a straight line. In the case of the circular-edge method, the edge transitions are fitted to a curve described by a Fourier series instead of a circle. Another technique is to fit the LSF to a Gaussian distribution, and to characterize it by the Gaussian line-width rather than computing the entire MTF curve. This method is very effective in practical imaging systems with Gaussian blur. Conclusions and recommendations for further research are presented in the last section.

2. The Circular-Edge Method

The new method is similar to the slanted-edge method, except that radial scan lines are used. The first step in the process is to calculate position of the center of the test target. Radial scans are then performed to estimate the edge position as a function of scan angle. The edge position estimates are the fitted to a circle and the original sample points are re-registered according to their estimated radial positions. The points are re-sampled in order to generate a super-resolved estimate of the edge transition. This estimate is differentiated to obtain the line-spread function (LSF). The Fourier transform of the LSF is then used to derive the MTF.

A circular-edge test target is depicted in Figure 3. The circular-edge test target consists of a light circle on a dark background, although the method can easily be extended to a dark circle on a light background. The target should be centered on the axis of the camera's lens in order to place the edge on a contour of constant blur and distortion. The target orientation should be normal to the axis of the lens in order to prevent the pattern from being distorted. As in the slanted-edge method, the contrast of the target should be between 40:1 and 80:1. If the contrast is too high optical flare may distort the edge transition. This method requires linear data. If the response of the camera is non-linear, then its OECF function must be measured, and this function must be used to correct the data. Other image processing functions, such as sharpening and compression, will affect the results and should not be used[3,4].

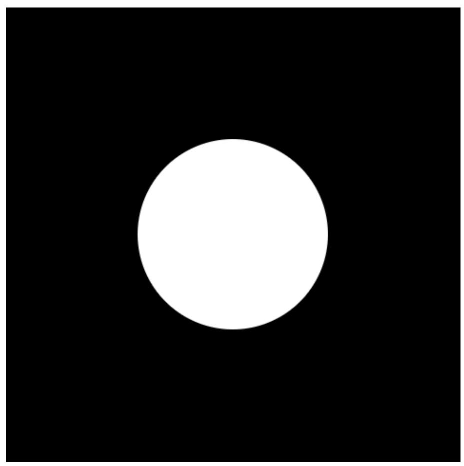

Figure 3. – Circular-edge resolution test target

2.1. Determining the center position

The first step in the procedure is to locate the center of the target in the image. This is accomplished by summing of all the rows and of all the columns in the image. The horizontal and vertical positions of the center are then determined by the computing the centroids of the row and column sums, respectively. The formulas for computing the position of the center of the target are shown below. In these equations, ROI(ix,iy) represents a region of interest of size NX, NY that includes the circular target:

$$S_{row}(ix) = \sum_{iy=1}^{Ny} ROI(ix,iy) \qquad Xc = \sum_{ix=1}^{Nx} (ix \cdot S_{row}(ix)) / \sum_{ix=1}^{Nx} S_{row}(ix)$$

$$S_{col}(iy) = \sum_{ix=1}^{Nx} ROI(ix,iy) \qquad Yc = \sum_{iy=1}^{Ny} (iy \cdot S_{col}(iy)) / \sum_{iy=1}^{Ny} S_{col}(iy)$$

The center position is estimated to sub-pixel accuracy. Consequently the center position is not generally located on the sampling grid (on the center of one of the pixels).

2.2. Estimating the radius

The radius of the target is determined by creating a set of radial scan lines that run outwards from the center. The accuracy of the radius estimate depends on the number of scan lines that are used. In these experiments, scan lines were generated every 10 degrees.

Along the horizontal and vertical axes, the sample spacing is one pixel period. Along the +/- 45-degree axes, the sample spacing is the square root of two times the pixel period. In addition, the scan lines do not generally intersect with the sampling grid, both because the scan angles are arbitrary and because center of the circle may be located off the grid. In order to obtain scan lines with a uniform spacing of one pixel period, interpolation is used to determine the scan line values. At any given position, the scan line value is determined from the nearest four points in the sample grid by using bilinear interpolation. The radial scan lines are depicted in Figure 4.

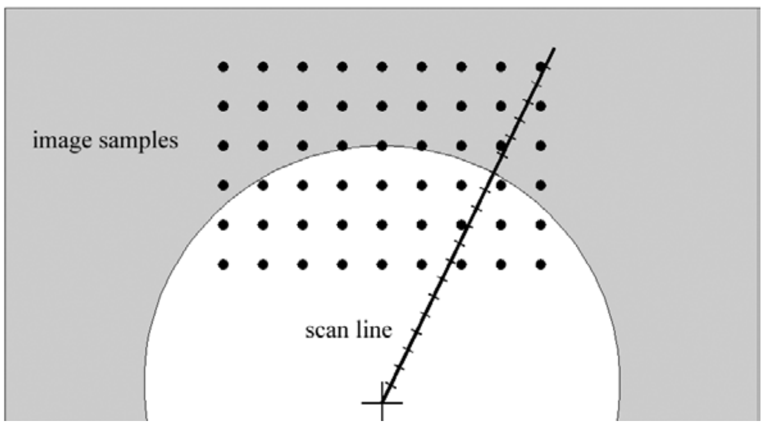

Figure 4. – Radial scan lines

The edge radius is determined by the same technique that is used in the slanted-edge method[5,6,7]. A derivative along the scan direction is computed for each scan line. The centroid of the peak of the derivative is used as an estimate of the edge radius. The radius estimates are then averaged to reduce the effect of noise, and increase the accuracy of the result.

2.3. Generating the super-resolved transition

Once the edge position has been determined, a super-resolved version of the transition can be obtained. Two methods can be used. The first method is similar to the slanted-edge technique, in that points from each scan line can be re-registered according to that line's edge transition radius. This method has two disadvantages. The first is that the samples will all fall on the same grid and super-resolution between grid points will not be possible. This problem can be overcome by using a slightly oval target. A more complicated procedure for estimating the edge positions is required. This procedure is described in the next section. The second disadvantage is that the points used to compute the super-resolved transition will have been obtained by interpolation. This will blur the edge transition.

The better (although somewhat computationally intensive) method to obtain the super-resolved transition is to resample the points in the original sample grid. In this method the radius from the center of the target to each point in the sample grid is computed. The position of the point is then re-registered according to the estimate of the edge radius. This method is illustrated in Figure 5. In the simple case presented here, the radius to the edge does not depend on angle.

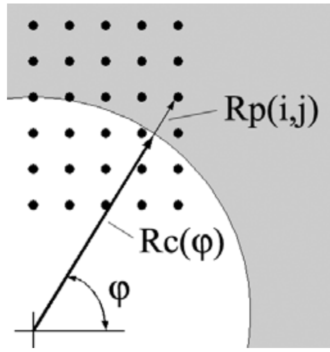

Figure 5. – Procedure for determining the distance of samples from the edge position

The relationship between the samples in the circular-edge image and the points on the edge transition is shown in Figure 6. Each sample in the circular-edge image can be mapped to a point on the edge transition. The x-axis location of a point in the edge transition plot depends on the distance between the point and the edge of the circle, while the y-axis location depends on the value of the sample. Because the sample points are distributed at different distances from the edge, the edge transition can be super-resolved without having to make the circle into an ellipse.

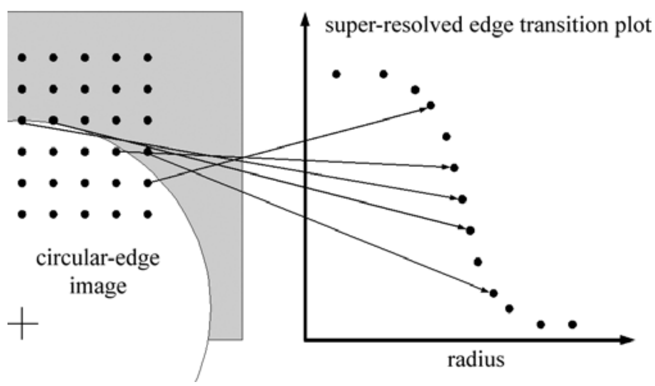

Figure 6. – Relationship between image values and edge transition curve

Once the grid points have been re-registered, they are averaged into bins to create an edge transition estimate. Because averaging is equivalent to applying a low-pass filter to the data, several bins per pixel period must be used[2]. In this work, four bins were used per pixel period. A scatter plot of the edge-spread function noise is shown in Figure 7. In this simulation a 3 pixel Gaussian blur was applied to the target, and 10% Gaussian white noise was added.

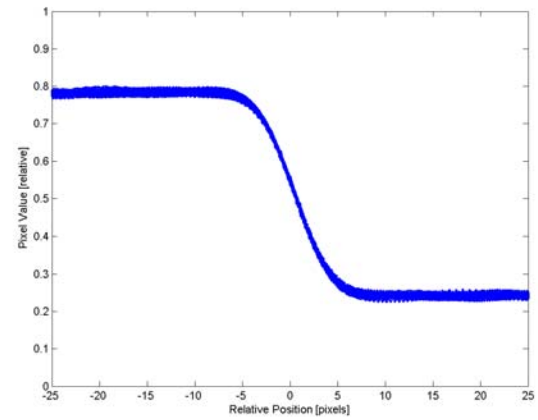

Figure 7. – Edge spread function

2.4. Calculating the line spread function

An estimate of the line-spread function is obtained by differentiating the edge transition estimate. Differentiation amplifies any high frequency noise that is present. A windowing function such as a Hamming filter can be used to reduce the noise at the edges of the LSF, where the value should be zero. An example of an LSF curve computed by this method is shown in Figure 8.

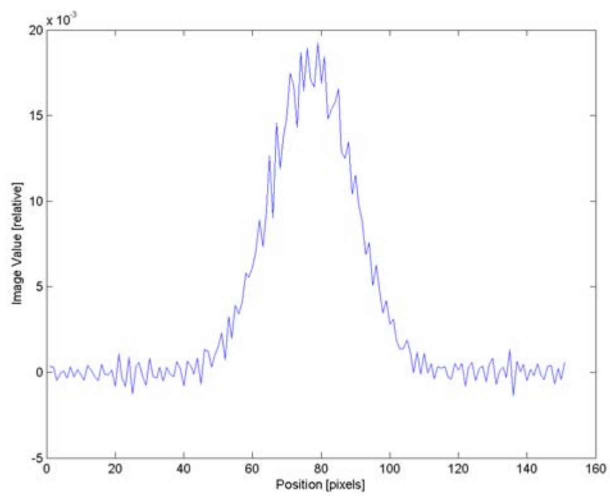

Figure 8. – Line spread function

2.5. Calculating the modulation transfer function

The modulation transfer function is computed by performing a Fourier transform on the LSF curve. The LSF must be multiplied by a windowing function first in order to prevent a discontinuity at the ends of the LSF record from contributing high frequency energy to the MTF curve (the Gibbs phenomenon). The MTF curve computed from the LSF curve in Figure 8 is shown in Figure 9.

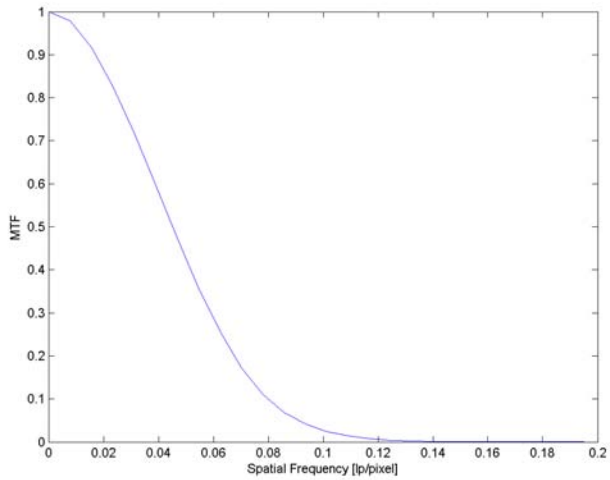

Figure 9. – Modulation transfer function

3. IMPROVEMENTS TO BOTH SLANTED AND CIRCULAR EDGE METHODS

In this section three improvements will be described that can be applied to either the slanted-edge or circular-edge methods. The first of these for the slanted-edge method is to fit the estimated edge positions to a polynomial rather than a line. The complementary improvement for the circular-edge method is to fit the edge positions to a Fourier series rather than a circle. The second improvement is to fit the LSF to a Gaussian function, rather than computing the entire MTF distribution. The last improvement is to apply shading correction to the image before beginning the resolution analysis.

3.1. Edge position estimation

The edge position in the slanted-edge method may deviate from linear because of lens distortion. This deviation can be accommodated by fitting the edge positions to a higher-order polynomial, rather than a line. The disadvantage of using a higher-order polynomial is that the edge position estimate will be more susceptible to noise. In this work, a polynomial fit of order 3 has been used. Once the coefficients of the polynomial are determined, the polynomial is used to re-register the edge positions.

In the case of the circular-edge method, optical aberrations may distort the shape of the circle. The target may also be elliptical rather that circular. Under these circumstances, the radius of the "circle" becomes a function of angle, as was shown in Figure 5. The first few terms of the Fourier series of the radius estimates can be used to describe this variation.

$$\mathrm{R}(\varphi) = c + \sum \left[a_i \;\sin(i \cdot \varphi) + b_i \;\cos(i \cdot \varphi) \right]$$

where the c, a_i and b_i coefficients are obtained by performing a Fourier transform on the set of edge estimates obtained from the radial scans.

If an elliptical target is used, it is also possible to compute the LSF by re-registering the scan line values, instead of re-sampling the original data points. In this case, the method becomes completely analogous to the slanted edge method. However the resolving power is limited because interpolation is used to compute the values on the scan lines.

3.2. Fitting the LSF to a Gaussian

From a practical standpoint, it is difficult to perform an accurate MTF measurement because of noise, shading and aberrations. Fortunately the optical blur in most digital cameras is almost Gaussian. Consequently a single number can be used to characterize the sharpness. Frequently the MTF at a specific spatial frequency or the spatial frequency at a specific MTF value is used. An equivalent description is the half-width of the LSF peak.

The advantage of fitting the LSF to a Gaussian is that it suppresses noise effectively. A Gaussian fit to an experimentally measured LSF curve derived from a slanted-edge target is shown in Figure 10. The optical blur is accurately described by a Gaussian.

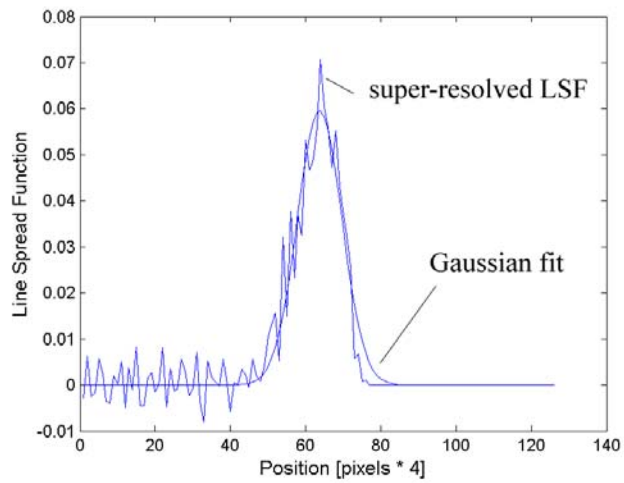

Figure 10. – Gaussian fit to super-resolved LSF

Some digital cameras use a birefringent blur filter to reduce color aliasing. In these cameras, the LSF can be fitted to a pair of Gaussian curves, offset by approximately one pixel period.

If a single MTF specification is required, it can easily be calculated from the half-width of the LSF. The following formula was obtained by applying the Fourier transform to the assumed Gaussian LSF:

$$\mathrm{MTF}(f) = \exp(-\frac{1}{2}\left[2\pi\, f\, \sigma\, \mathrm{w}\right]^2)$$

Where f is the spatial frequency [lp/mm], σ is the half-width of the line-spread function, and w is the pixel pitch [mm]. This equation can be used to solve for the MTF in terms of f, or f in terms of the MTF, given sigma from the slanted-edge or circular-edge calculation.

3.3. Shading correction

It is difficult to uniformly illuminate a test target. Non-uniformities in illumination result in shading across the image. Shading can occur in luminance, chrominance, or both.

The best solution to shading is flat-field correction. In this method, a separate image of a uniform target is collected under the same illumination. The pixels in the resolution test image are then normalized by the values in the flat field image.

If a flat-field image is not available, the pixels in the resolution test image that are far from the edge transition can be used to perform a shading correction. The horizontal and vertical shading functions can be determined by fitting a curve to the pixels values along the borders of the of the image. The shading correction significantly improves the MTF estimate for images that have both shading and additive noise.

4. CONCLUSIONS

The circular-edge spatial frequency SFR test method is superior to the slanted-edge method for cameras with rotationally-symmetric distortion and blur. It is not an appropriate method for cameras that have more complicated aberrations, such as astigmatism. The circular-edge method would have required too much computation to be practical at the time that the slanted-edge technique was developed. However it is well within the capabilities of modern personal computers.

The circular-edge method yields the SFR at a specific target radius. The method could be extended to provide SFR data at many different radii simultaneously using a bulls-eye target with many concentric rings.

Several improvements that apply to both the slanted-edge and circular-edge techniques were demonstrated. One of these was the fitting of a Gaussian to the LSF function, which improves the robustness and accuracy of the method. In most cases a description of sharpness in terms of a single parameter, the width of the LSF Gaussian, is entirely sufficient.

Shading correction is another improvement that was demonstrated. Shading is the variation in luminance or chrominance of the illuminant across the image. The problem can be avoided by applying flat-field correction. However the development of multi-pass SFR algorithms, that estimate the positions of edge transitions and then remove them to produce a flat-field for subsequent shading correction, appear to be a promising area for future research.

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