Image Quality of Digital Cameras

Edward M. Granger
X-Rite, Inc., Grandville, MI 49418

Abstract

Linear systems theory is routinely used to determine the behavior of imaging systems. The effect of smear, aberration, detector size, etc. can be characterized by a modulation transfer function (MTF). The individual MTFs can be multiplied together to compute the system MTF.

In sampled systems, as seen in CCD cameras, quantifying the MTF is not as easy. The effects of the aliasing and relative phase error require a new method of computing the MTF using statistical procedures.

The new MTF estimation method employs a simple edge target to sample the digital array. The edge measurements can then be converted to an average MTF using Second Moment statistics. This new image quality measure[1] is easily extended to predict the performance of color CCD cameras. In addition, the Second Moment can be used to predict the image quality of the displayed image when it's viewed at different magnifications.

Introduction

Linear systems theory is a valuable mathematical procedure for characterizing the behavior of imaging systems. The effect on the image by the optics, image motion, etc. can be determined from the Modulation Transfer Function (MTF) contributed by each element of the image train. The total system performance can be computed by multiplying the MTFs from each component that comprises the optical system to compute the total system performance.

Sampled imaging systems, such as those that use CCD detectors, are not linear shift invariant and, therefore, cannot be handled with Fourier analysis. The lack of spatial invariance results in the well-known image aliasing. This effect produces jaggies that are most apparent on sharp edges. This type of image error requires a different approach to find the equivalent MTF of the sampling elements.

This paper presents a simple method to determine an equivalent MTF for sampled images. The process employs an edge target to gather the required data and compute the average MTF for an array detector. A method of Second Moments is used to ascertain the equivalent MTF from the edge trace data. The equivalent angular averaged MTF can be calculated from the mean of Second Moments taken from two orthogonal edge traces.

The Sampling Problem

The nonlinear error associated with sampling is illustrated on figure 1. The figure shows a low frequency cosine wave that has been sampled on equally spaced centers. As can be seen on the figure, it is easy to find and assign a modulation transfer value for the low frequency cosine target.

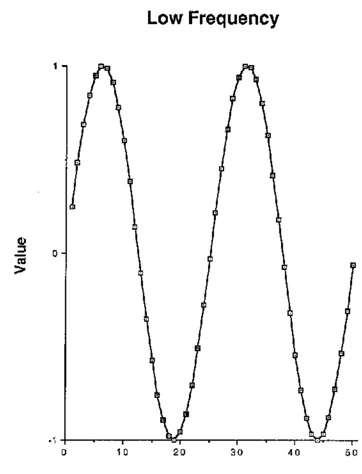


Figure 1

The error becomes more apparent for a medium frequency cosine shown on Figure 2. The phase error produced by sampling has made the determination of the MTF much more difficult.

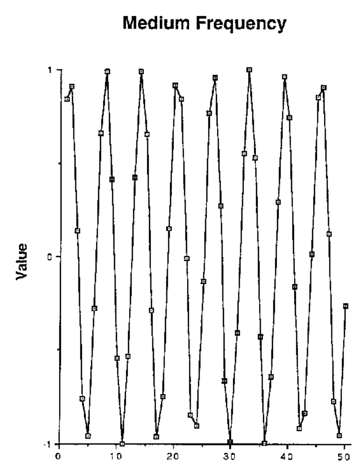
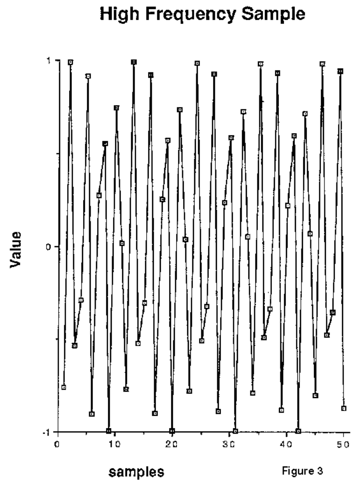


Figure 2

As the spatial frequency increases, the calculation of the MTF becomes nearly impossible as a shown on Figure 3. The problem is that the modulation has become a strong function of the phase of the cosine target relative to the sampling array.



The accuracy of determining the MTF by using a cosine or square bar target decreases as the frequency of the target increases. Figure 1 shows that at least 20 samples must be taken over the period of the target to get a good estimate of the MTF. The estimate that normally is used as the frequency limit of sampling, the Nyquist rate, would be most sensitive to the phase error. The sample rate of 3.5 samples for each target cycle shown on Figure 3 illustrates that the estimate of the MTF is difficult - at best, almost a factor of two from the Nyquist sample rate. In this case, the normal methods for computing the MTF do not work because the maximum and minimum are so scattered.

A Moment expansion of the Fourier transform has been used to approximate the modulation transfer function for point spread functions that are not symmetric. The MTF is given by the form:

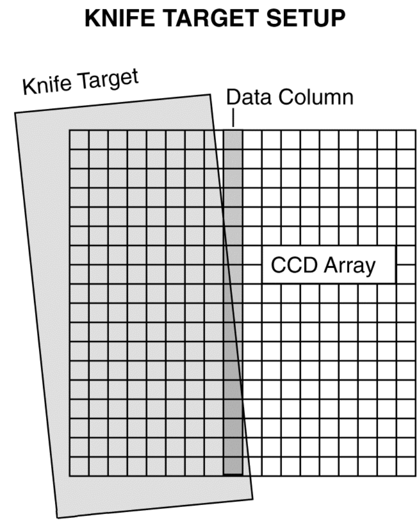
$$M(f) = e^{-2(\pi \bullet f)^2 \bullet \sigma} \tag{1}$$

where M (f) is the modulation as a function of the spatial frequency, f, and where s is the Second Moment of the image point spread function including the effects of the sampled array.

The Edge Test

Square or cosine targets are difficult to produce and control. The phase error makes it impossible to determine the MTF accurately at higher spatial frequencies. This reduces the use of these types of targets. What is required is a much simpler test to determine the MTF. The knife edge test, illustrated on Figure 4, is easy to construct. No special target calibrations are required to determine the Modulation Transfer Function.

The test uses a knife edge at a slight angle to the columns of the array, as is shown on Figure 4. It is recommended that the pitch of the knife edge relative to the column be at least ten to one. Therefore, the knife edge traverses 10 rows while crossing one column of pixels.



The edge, used in this manner, magnifies the line spread function. The data read from a single column has to cross ten rows in order to get a complete edge trace. Hence, the magnification of the spread function is ten to one. Higher magnifications could be obtained by changing the slope of the knife. A slope of 20 row crossings for one column crossing produces a magnification of 20. The next section explains how to convert the edge data taken along a column directly to a Second Moment. The Second Moment data can then be converted to the modulation transfer function and then to an image quality metric.

Second Moment

The edge trace developed in the previous section is usually converted to a line spread function by taking the derivative of the edge trace function. Normally the line spread function would be converted to a modulation transfer function by using a Fourier transform or the method of Second Moments[3] described above. This section develops a procedure to compute the Second Moment of the line spread directly from the edge trace function.

The relation of integration by parts is used as follows:

$$\int U \bullet \partial V + \int V \bullet \partial U = U \bullet V \tag{2}$$

The line spread function is represented by *l* (x) and the edge trace function by e (x). It is assumed in the following calculations that the edge trace has been scaled to lie between a minimum of 0.0 and a maximum of 1.0. The line spread function, *l* (x), is found by taking the derivative of the edge trace function, e (x).

Let U = x and V = e (x). Then the centroid of the line spread function, m, is:

$$\mu = \int_a^b l(x) \cdot x \partial x \tag{3}$$

From equation (2), the centroid can be found:

$$\mu = x \cdot e(x)_a^b - \int_a^b e(x)\partial x \tag{4}$$

The centroid can be approximated using the sampled edge data. Let Δx denote the distance between samples in the row direction as the data is being read in the column direction. Start the sampling index at 1. Assuming that N samples have been taken in the column, equation (4) can be rewritten:

$$\mu = N \cdot \Delta x - \sum_{i=1}^{N} e(i) \cdot \Delta x \tag{5}$$

The Second Moment of the line spread function can be computed in a similar manner as the centroid:

$$\sigma = \int_{a-\mu}^{b-\mu} l(x) \cdot x^2 \partial x \tag{6}$$

Using equation (2) again, the Second Moments can be found:

$$\sigma = x^2 \cdot e(x)_{a-\mu}^{b-\mu} - 2\int_{a-\mu}^{b-\mu} x \cdot e(x)\partial x \tag{7}$$

The Second Moment can be approximated:

$$\sigma = (N \cdot \Delta x - \mu)^2 - 2\sum_{i=1}^{N}(N \cdot \Delta x - \mu) \cdot e(i) \cdot \Delta x \tag{8}$$

The angular averaged MTF is computed by repeating the process outlined above for data being read in the row direction. This is best accomplished by building a knife edge test target with edges at right angles. The angular averaged Second Moment is determined from the Moment Theorem of mechanics as shown:

$$\sigma = \frac{\sigma_C + \sigma_R}{2} \tag{9}$$

where σ_C is the column Second Moment and σ_R is the row Second Moment.

Equations (5), (8), and (9) can be evaluated by setting up a spread sheet template and entering the edge values in the spread sheet. The 10 to 1 edge slope is recommended because it limits the amount of data entry but still yields adequate sampling of the edge. A value of 17 for N, the number of samples, usually gives enough extra samples to determine the limiting values on each end of the edge trace. A better statistical estimate of the system performance is obtained by averaging the Second Moment data from several adjacent rows and columns.

Color CCDs can be evaluated using the RGB signals for each element. The RGB signals are weighted to produce an equivalent luminance signal for each sample point. Typical weights for RGB are 0.3, 0.6, and 0.1 respectively. The luminance samples can be placed in the spread sheet template. This will give an excellent estimate of the color system performance.

Image Quality and Magnification

The output of the CCD is used as input to a rendering application. The resulting electronic image is printed at some arbitrary magnification. As the image is made larger, the quality of the resulting image degrades. Equation (1) reveals that the MTF at a given spatial frequency, f, is a function of the product of the frequency and the Standard Deviation, S, of the spread function. The magnification[2] is the ratio of the size of the pixel used in the evaluation of the Second Moment and the size of the pixel in the printed image.

The MTF can be expressed as a single parameter which is the product of S, the Standard Deviation of the image, and M, the magnification used to produce the printed image. Since the MTF can be defined using a single parameter, the image quality, SQF, of the printed image can also be plotted as a "universal" SQF template. Once the Standard Deviation, S, of the image is known, the SQF of the image is directly related to the magnification used to display the image. The universal template of image quality is plotted on Figure 5. The system SQF is shown as a function of the product of S and f..

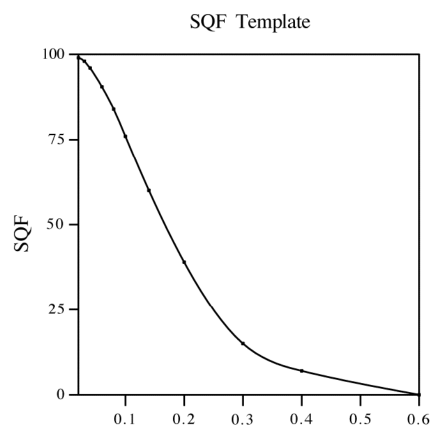


Figure 5

Conclusions

The method of Second Moments offers a single parameter estimate of the MTF. This method has two advantages. First, only simple computations are required to predict image quality. Second, the determination of a single parameter implies a large amount of noise averaging and hence improved system performance estimates.

The Second Moment method employs a knife edge and a simple numerical procedure that utilizes the edge data to evaluate the performance of an optical system. The knife edge is used to measure the image in two orthogonal directions. The Second Moments derived from the two edges are averaged to produce an estimate of the angular average MTF of the total system. This method is extendible to color images.

The Second Moment method has led to the definition of a "universal" image quality template. The SQF template is indexed by the product of the image magnification and the Standard Deviation of the optical system spread function. The SQF values produced by the template are accurate down to levels of SQF of 30. Below this quality level, the image is unusable.

The method of Second Moments has led to the development of a single parameter "universal" image quality template that allows rapid assessment of system performance. The template is very useful as an aid to the digital photographer in determining the maximum usable print size of the digital image.

References

1. E. M. Granger and K. N. Cupery, "An Optical Merit Function (SQF) Which Correlates with Subjective Image Judgment", *PS&E*, Vol. **16**, Pg. 221, 1972.
2. E. M. Granger, "Subjective Assessment and Specification of Color Image Quality", *SPIE*, Vol. **46**, Pg. 86, 1974.
3. E. M. Granger, " Visual Limits to Image Quality", *SPIE* Vol **528**,1985.