Image Quality Assessment of Digital Scanners and Electronic Still Cameras

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Abstract

Performing image quality assessment of digital input devices often starts with the capturing of several targets or scenes. Scenes are usually excellent indicators of overall image quality, but are subjective measures providing little diagnosis of problems. By analyzing captures from specific targets, precise objective measures can be extracted. This data is useful for benchmarking devices, performing research and development tests, and for device manufacturing where specific tolerances must be met. Creating or obtaining targets and getting software to work in harmony with them can be a daunting task.

This work reports on a new suite of targets with complementary image quality analysis tools. This image quality package has helped several research and development teams throughout the product development cycle, provided invaluable third party assessment of both reflection and transmissive scanners, and is being used on manufacturing lines ensuring the efficient quality control of digital scanners and electronic still cameras. This talk will describe the target layout, along with the automated processing philosophy, and then give an overview of how each of the image quality tests are designed and executed.

Introduction

Reflection scanners, transmissive scanners, and electronic still cameras (ESC's) have three common characteristics: (1) they have unique image quality attributes, (2) these image quality attributes are often documented through various home-brew, off-the-shelf, and hybrid testing packages, and (3) they output digital images. This paper will describe a systematic method of performing automated image quality analysis on any digital capture device.

This analysis can be constructed from complex device characterization routines or simpler image quality verification routines.[1] The former is useful for research and development or device benchmarking work, while the latter is useful for manufacturing environments. Existing packages such as ImageXpert,[2] IPLab,[3] Image-Pro,[4] and QEA[5,6] have been applied successfully in the field, and may benefit from the strategies discussed in this paper.

While this report concentrates on digital capture devices, the methodologies can easily be propagated to non-digital capture devices or output devices. Non-digital capture devices (i.e., film and camera) can be analyzed by these procedures as long as there is some digital capture device capable of scanning the output of the non-digital system. When analyzing the film/camera system, the exposed and developed film can be scanned on a transmissive scanner. By backing out the scanner image quality characteristics, we are left with the camera/film/development image quality characteristics. In a similar manner, all output devices can be analyzed by scanning their output on a digitizing device and backing out the digitizing device characteristics.

Keys to Successful IQ Analysis

When adopting a strategy for performing image quality (IQ) assessment, four critical elements must be addressed: (1) test standardization, (2) targets, (3) characterization of targets, and (4) streamlined analysis.

Test Standardization

There are countless methods used to calculate signal-to-noise (S/N) ratios, device MTF, dynamic range, and flare. Decisions need to be made up front as to which methodologies work best, which are practical to implement, and which the community as a whole can adopt as a standard. A great deal of time should be spent researching and planning methods before implementation. Thought should not only be given to what algorithms to use, but how images are acquired, and what metric the analysis is ultimately performed in.

Targets

Every IQ test starts out with a target. A uniformity test may require a flat field target, a MTF test may require a sine wave target, and a veiling flare test may require a dark patch surrounded with a highly reflective/transmissive background. Certain targets are very difficult or expensive to create and should be avoided unless necessary. Often, when creating IQ targets, revisions must be made to improve test usefulness or to compensate for new capture device limitations. The target creation method should be flexible enough to accommodate changes quickly, but allow changes to be incorporated at minimal cost.

Characterization of Targets

Once targets are created, they need to be characterized. The characterization of targets identifies the particulars about the target. Each digital capture is a function of its input. Target characterization is the task of knowing what that input is. For MTF, it may identify the modulation and frequency of our sinusoidal patterns. For color tests, it describes the spectral properties of each of the color patches. If the target creation process is very tightly controlled, batch statistics can be generated, however, for critical tests, or tests of high precision, unique characterizations should be performed for each target.

Streamlined Analysis

IQ testing should be as efficient, error free, and user friendly as possible. IQ analysis should not be restricted to individuals mastering image science principles. Thought should be given to the environment in which the tests will be run. Inefficient process flow and/or human intervention are often the cause of slow IQ tests or error prone tests. If we can optimize the process flow and omit all human intervention, we will come a long way towards a streamlined analysis. Automatic IQ analysis through self-guided routines can resolve these issues.

Implementation Specifics

Fiducials and Relative Locations

The solution proposed requires a rather rigid image quality target generation procedure. Targets must obey two critical rules:

(1) Each target must have four fiducial marks, one in each corner. The exact location of these fiducials is not critical, but the four fiducials should define a rectangle. The examples in this report describe cross-hair fiducials, but any shape with an extractable centroid is acceptable, where the centroid is an estimate of the center of the fiducial mark.

(2) Each target must contain an identifying barcode, and the barcode must be in a specific location. This location is defined as a function of the fiducial centroids. For example, the barcode upper-left location can be 50% between the lower left and lower right fiducial centroids in the x direction, and equal to the lower left and lower right fiducial centroids in the y direction.

Key image quality sections of the target are also defined by specific relative locations to the four fiducials. For example, if we were to try and determine the dynamic range of a device, we would orient a set of tone scale patches on the target, where the upper left and lower right coordinates of the grid of patches (or each individual patch) is defined as a function of the four fiducial centroids.

By using this technique of relative addressing of all components on the target to the fiducial centroids, we devise a system that is not only resolution independent, but skew tolerant.

Barcodes

Barcodes play a critical role in automated testing and are to placed on each target. The relative location of the upper left and lower right corners of the barcode are defined as a function of the four fiducial centroids. The barcode data contains information required to proceed with the image quality analysis. Commonly recorded pieces of information include the target identification, the batch number (or individual target id), and information specific to the particular target, such as film/paper type, etc. The examples in this report follow the Interleaved 2-of-5 Format,[7] an international standard for which there are several commercial packages readily available for reading and writing. The format is simple enough that a user can write custom reading/writing software.

Careful attention should be given to barcode size. Barcodes typically have narrow bars and wide bars, where a wide bar is about 3 times as wide as a narrow bar. For robust automated barcode detection, a narrow bar should be at least 3 pixels wide. By calculating the lowest capture resolution, one can determine the physical size the barcode needs to be, such that a capture of that barcode will yield at least 3 pixels per narrow bar.

System Integration

By incorporating fiducial finding software, a standard barcode format, and barcode locations relative to fiducial centroids, the image quality software can determine the type of target scanned automatically. This software front end would first locate the fiducial centroids, calculate the upper-left and lower right coordinates of the barcode, extract the barcode, decode it, determine what target was scanned, and finally execute the appropriate image quality software. By knowing the fiducial centroids, and the contents of the barcode, the image quality software can find any specific predefined location on the target. Typically several locations are predefined on each target and extracted from the digital scan as the software is executed.

In a sense, the decoded barcode dictates what IQ routines will run. Setup files saved in predefined directories or environment variables define optional parameters for each test.

Effectively, once the target is scanned and saved to disk, one has only to supply the front end with the name and location of the digitized image. All extraction of pertinent data is performed automatically, all data is saved to disk, and all plots are sent to a printer/plotter, leaving the operator free to move onto the next scan or other tasks.

Using this system can make the physical capture and saving of the digital image the bottleneck of the IQ procedure. Scanner or ESC software drivers can be written to minimize this step. Once images are saved to disk, the IQ software can be running in the background, waiting for new images to appear in its *in-basket*. No user prompting is required for what test is to be run and no prompting is required for specific target characterization data files. No prompting means no user entry errors, no idle waiting periods, and a highly efficient and streamlined IQ test procedure.

Unfortunately, no matter how much thought goes into an IQ routine, custom modifications are sometimes needed. These could be as small as computing the IQ parameters in unique color metrics, selecting a specific printer queue, or as complex as implementing an alternative IQ algorithm. The IQ system described here incorporates parameter files with each installed version of the software. Flags in the parameter files customize the software to the unique requests of the customer.

Finally, when unexpected results appear, there is a need for more information. The IQ package should incorporate an interactive mode, where detailed IQ tools are available. This interactive mode should be as extensive as possible, with custom screens for each test.

Standard Tests and Targets

This section will review a sample set of IQ targets and tests already in production. It is organized by target type. Some targets perform a single IQ test, others can perform multiple tests. Following a brief target description there is a discussion of the IQ attributes tested and algorithms used in each test.

Tone Scale Target

Often the most important IQ attribute of any imaging system is the system tone scale. The tone scale target should test the neutral tone scale of the capture device. Neutral patches of varying density, from the darkest possible input to the lightest possible input should be present in the target. Figure 1 is a representation of one such tone scale target.

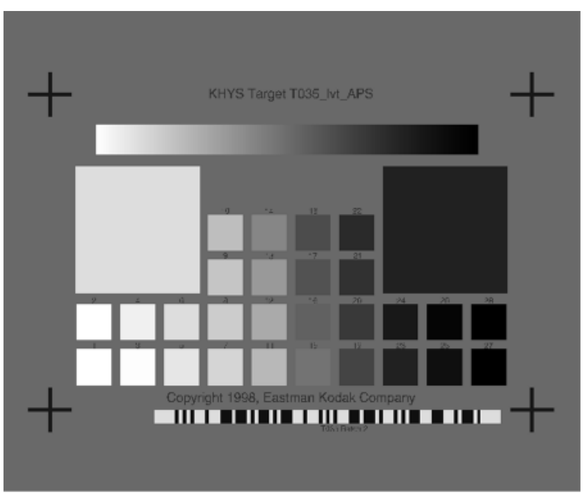

Figure 1 Sample tone scale target.

By interrogating the captured digital file, one can compute statistics at each patch site. The local mean, median, minimum, maximum, and standard deviation at each path are determined by extracting codevalues from the captured image at each patch location. By comparing these statistics against the input (target) measured density, one can determine system contrast, dynamic range, toe and shoulder roll-offs, neutral color balance, and noise as a function of density. Figure 2 shows a typical tone scale response for a sample reflection scanner. Figure 3 shows a plot of noise (standard deviation) vs density for a typical reflection scanner.

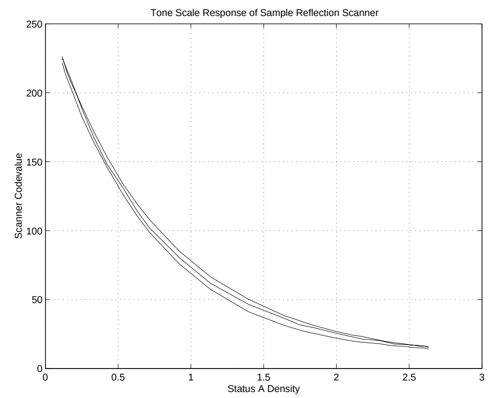

Figure 2. Sample reflection scanner tone scale response.

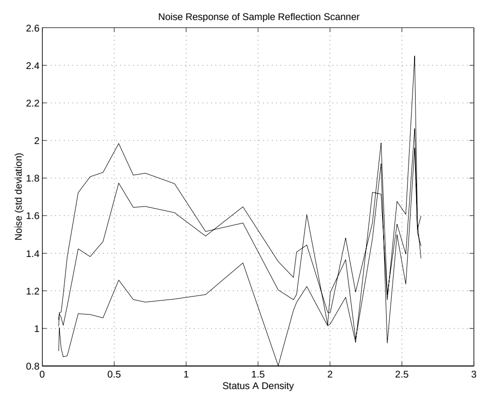

Figure 3. Sample reflection scanner noise profile.

In addition to the above, equations can be formed to report dynamic range of capture devices. While there are several methodologies for reporting dynamic range, two that have proven particularly useful are: (1) a flavor of signal-to-noise (S/N) ratio, and (2) a slope estimation with an estimation of noise. The dynamic range S/N ratio sees widespread usage in the electronic capture community. It can be calculated by:

$$SNR\ (dB) = 20\log(MaxWhiteCV / MinBlackRMS) \quad (1)$$

where:

MaxWhiteCV is the maximum codevalue delivered by the capture device. (The codevalue returned when the capture device is looking at white.)

MinBlackRMS is the standard deviation of the capture device when its input is pure darkness.

The second method, the slope estimation method, requires that a curve be fit through the original tone scale data. The derivative is then calculated. As the derivative approaches zero, the capture device essentially cannot tell the difference between one density to the next. A threshold slope is chosen, based on subjective experiments, such that when a tone scale curve approaches this slope, one can no longer distinguish any lighter or darker density patches input to the capture device. To be more critical, and take into consideration the noise of the capture device, we can also compare the noise at each measured tone scale patch in conjunction with the returned codevalue. Each successive patch must have a returned codevalue that differs from a previous patch by at least the previous patch codevalue plus one standard deviation.

MTF Target

Sharpness is the humanly observed sensation that predicts the sensation of clarity, or preservation of details, in an image. The modulation transfer function (MTF) is a measurement of a system's ability to reproduce detail as a function of frequency. Traditionally, various sine wave patterns of known frequency and modulation are captured by the device.[8] The resulting digital scan is analyzed and the corresponding modulation of each sine wave pattern is computed. By plotting the output modulation over the input modulation for each frequency, we are plotting the MTF response of the device. We can also calculate device MTF by capturing sharp edges, slanted edges, or square wave targets (each with known MTF response). Figure 4 shows a plot of the MTF for a film scanner. As frequency increases, the camera's ability to maintain modulation decreases.

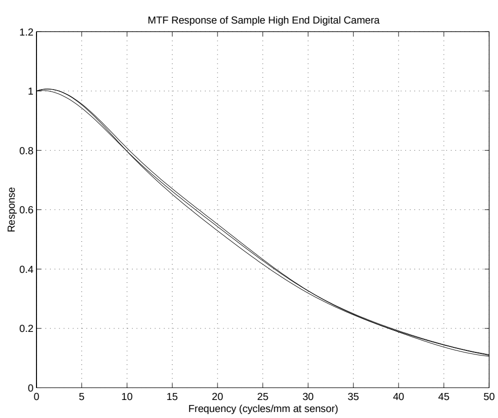

Figure 4. Sample RGB MTF output from an ESC.

Edge analysis relies on a clean trace across a knife edge or other sharp transition. The resulting cross section is differentiated to generate a line-spread function (LSF). This LSF is Fourier transformed, yielding an MTF curve. Capture devices with poor sampling resolution cannot use edge analysis because the procedure is shift variant. Slanted edge analysis[9-11] was developed to overcome the inadequacies of edge analysis. By tilting the edge anywhere from 7 to 30 degrees,[12] the edge profile intersects the sampling grid at several sampling positions. The edges can be aligned, then recombined creating a super-resolution edge trace. After sampling this super-resolution edge trace onto a fixed spaced grid, the derivative can be taken forming the LSF. The LSF is Fourier transformed, producing the MTF curve. Slanted edge analysis has proven so simple and robust to perform, that it is part of an international standard for digital camera MTF characterization.[13]

Periodic signals are useful in MTF analysis.[14] Square waves are particularly useful because digital devices reconstruct digital square waves exactly, they provide many useful harmonics in the frequency domain, and the input amplitudes do not have to be measured. Whereas square waves are made up of several edges, it can be argued that the noise in square wave analysis is reduced from that of slanted edge analysis. For lower resolution devices, slanted square waves can be used to create super resolution square wave trances, making the process shift invariant. By transforming square wave traces to the frequency domain and analyzing the odd harmonics of the Fourier spectrum, we can compute the device MTF. This method has been proven to be more efficient and easier to perform than the sine wave analysis method for digital devices. Figure 5 is a picture of a sample square wave target.

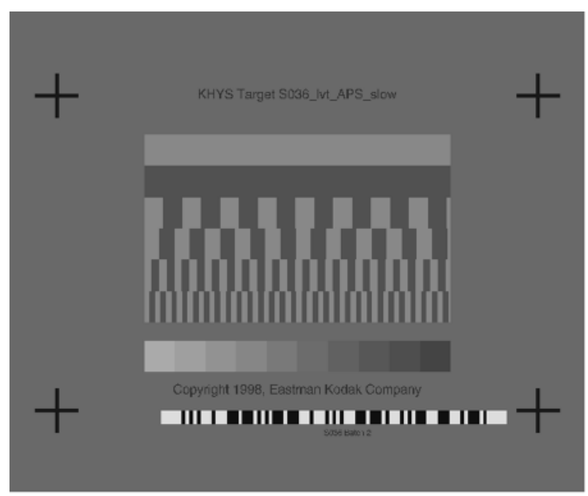

Figure 5. Sample MTF (square wave) target.

Uniformity Target

A capture device's ability to faithfully reproduce a fixed density as a function of position in the capture plane is an indication of uniformity. If a film frame that was perfectly uniform was placed in a scanning gate, all the pixel code values in the resulting digital image file should be very similar to one another (within the noise characteristics of the scanner). To the degree that they are not the same (after noise if factored out) is a measure of uniformity.

The toughest problem in performing uniformity analysis is generating targets with a uniform profile. For digital cameras and reflection scanners this can be done with reasonable accuracy, but for film scanners, this task has proven to be quite formidable. This, combined with the fact that no target is perfectly uniform, has driven the decision to accept the fact that targets are not perfectly uniform, and just compensate for this non-uniformity in the analysis. Figure 6 shows a sample uniformity target. The individual squares on the target indicate areas where the target is characterized and where the scanner will be characterized. All other areas on the target are ignored.

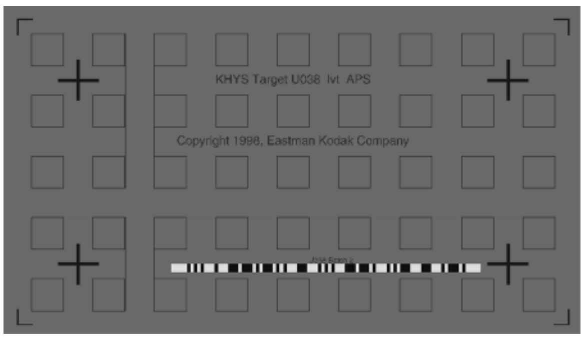

Figure 6 Sample uniformity target.

Uniformity analysis, like most IQ analyses, should be done in a fixed metric. The mean capture device codevalue inside each patch is calculated. Using the tone scale response of the device, determined by scanning the tone scale target, we can convert from mean codevalues at each patch to a fixed metric, such as density or CIELAB L*. Each patch also has a characterized measured value that is then subtracted. The resulting profile is an indication of the uniformity profile of the capture device. To accommodate for biases in measurement, the mean density or L* is subtracted from each resulting patch value, yielding a profile centered about zero. Patches above zero indicate areas of higher density or L*, patches below zero indicate areas of lower density or L*. Figure 7 shows a contour plot of the profile from a sample film scanner in density metric.

It should also be noted that the target in Fig. 6 has continuous areas in both the fast and slow directions for streaking (random streaks) and banding (periodic streaks) analysis.

Veiling Flare Target

A capture device's ability to reproduce dark densities when surrounded by lighter surrounds is a measure of flare. There are two types of flare, local and veiling flare. Local flare is a measure of blooming or ghosting around small dark objects surrounded by lighter backgrounds (black text on white is the most common situation). Veiling flare is the aggregate random reflection of stray light inside the capture device. To mimic a "worst case scenario", a dark patch is exposed in the center of a bright scene. When this scene is imaged onto our capture device, light from the bright surround scatters, and some of it reflects onto photosites that should record very little light because of the dark patch in the center. Figure 8 shows a sample flare target. This target has three flare patches, each at three different densities. This allows the flare analysis to be performed at three different densities on the tone scale.

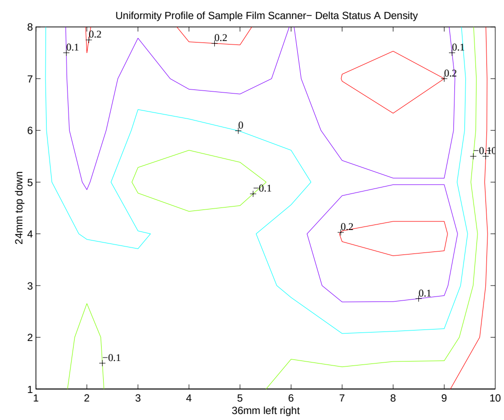

Figure 7. Sample film scanner uniformity contour plot.

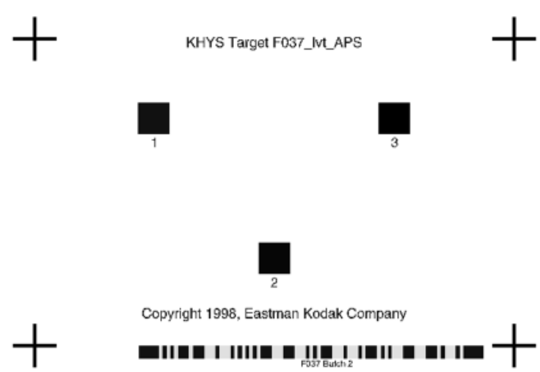

Figure 8. Sample veiling flare target with three different density patches.

Like all other targets, the flare target must be characterized. The white surround and dark patch is measured. A relationship between scanner code value and density is created via the tone scale target analysis. The mean codevalue of the dark patch(s) surrounded by white area is calculated. This mean codevalue is converted to density via the predetermined scanner codevalue to density relationship. The densities of the actual target white surround, actual target dark patch, and capture device dark patch (as the device saw it) are all converted to transmittance ($10^{-\text{Density}}$). Veiling flare is then[15]:

$$\text{Veiling Flare} = (T_c - T_k) / (T_w - T_k) \qquad (2)$$

where:

T_c is the capture device code value transformed to density, then to transmittance.

T_k is the measurement of the dark patch in transmittance.

T_w is the measurement of the white surround in transmittance.

Conclusion

When designing IQ targets and tools, it is critical to include four key aspects. These include: (1) test standardization, (2) target creation, (3) target characterization, and (4) streamlined analysis. It has been shown that using fiducials and barcodes allow the implementation of streamlined IQ analysis. Several IQ tests and sample targets have been shown which have been implemented successfully.

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