Standard Reference Fulfillment Environments for the Management of Spatial Image Characteristics

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Abstract

Most digital imaging products aimed at the open desktop market are designed to produce and accept image data in the sRGB color encoding. sRGB is defined with respect to the tone scale and color response of a reference CRT display, and, therefore, has the advantage that color conversions are not ordinarily needed to display the image on a typical CRT. Thus, sRGB simplifies the workflow for soft copy-based viewing, editing, and/or image sharing. One intent of sRGB is to standardize the way in which images are stored and communicated in consumer digital imaging systems, thereby improving the interoperability of these systems. While the sRGB standard addresses some of the tone scale and color interoperability issues, one important area, not addressed, is the appearance of spatial image characteristics. It is common for spatial image characteristics such as resolution, sharpness, noise, and compression to vary significantly from one sRGB image to another. While these differences can result from intentional variations (for example, user-selected differences in sharpness level), a portion of this variability can also be attributed to the fact that different vendors optimize their device performance for different applications. For example, one vendor may optimize digital camera performance to produce a 4 x 6-inch image on a 102-dpi CRT monitor viewed at a distance of 20 inches. Another vendor may optimize digital camera performance to produce optimal image quality for 8 x 10-inch prints from a 333-dpi hard copy printer viewed at a distance of 14 inches. The different fulfillment/use assumptions that may be built into imaging products can make it difficult to produce optimally printed images without using a fulfillment path that is tuned for each distinct image source. For example, some digital cameras are very aggressive with the amount of digital sharpness enhancement applied and others are quite conservative. If a print path were optimized to produce a desired level of sharpness for some nominal input image source, images from other sources may appear to be soft or over-sharpened. This paper will propose an approach to this management problem, which entails defining desired spatial image appearance relative to a reference fulfillment environment. Once this reference environment is defined, spatial characteristics may become easier to manage for an arbitrary fulfillment goal.

Spatial Management

Recently, the topic of managing the spatial characteristics of digital images, in particular, sharpness, has received increased attention. As with color management, several issues need to be addressed to fully enable an industry-wide infrastructure for the management of spatial image characteristics, including: a proper management architecture,[1] appropriate quantitative image quality metrics,[2-5] and a comprehensive model of spatial vision applicable to hybrid and digital imaging applications.[3-8] Each of these issues merits the attention of the scientific community. The scope of the current paper is limited to a discussion of architectural issues, specifically, to standards that may facilitate the interchange of digital images between systems.

A digital image may be spatially processed on multiple occasions, beginning with initial digitization and ending with fulfillment. Consider the case of a digital still camera (DSC) image that is spatially processed in the camera at the time of image capture, is subsequently manipulated through the use of an image-editing application — most likely one that is not intimately aware of the in-camera processing that was performed — and is submitted to a separate printing system for fulfillment. To manage spatial quality and characteristics, it is necessary for a fulfillment application to properly interpret the spatial content of the images it receives. The application must resolve the following questions:

- Did the picture capturer have a specific spatial (e.g., sharpness) preference in mind at the time of capture?

- Have the spatial characteristics been tailored for a particular application/use?

- What expectations does the fulfillment requestor have for the image, for example, *create facsimile of original scene structure*, *match to appearance on soft copy display*, *apply further spatial enhancements* (sharpen, mitigate noise, correct defects/artifacts, etc.)?

To unambiguously resolve these questions and properly manage the spatial characteristics, an interpretation of the spatial content must be associated with the image in some manner.

Explicit Interpretation of Spatial Content

An interpretation of spatial content may be associated with an image explicitly by the image file creator appending metadata (non-image data) to the image file. Embodiments in the open literature that follow this approach include the use of metadata fields available in standard file formats[9-10] and the passing of spatial transformation parameters or profiles.[1,11-13]

Associating information with an image file that explicitly describes the spatial content of the digital image has the benefit that images are not required to conform to specific exchange conditions. This may preserve the repurposability of a given image. However, management approaches that rely solely upon the transportation of metadata are subject to certain problems. The metadata may be corrupted or deleted from the image file at some point in its processing history or it may become out-of-sync with the image contents after image processing operations are applied.

To maintain open-system interoperability, it is important to avoid the use of proprietary metadata formats and/or values for the purpose of managing image characteristics. Otherwise, depending upon the system that receives the image, there is a potential for the metadata to be improperly interpreted or not to be used at all. This may lead to system-dependent results, thereby breaking the "what-you-see-is-what-you-get" (*WYSIWYG*) paradigm that consumers have come to expect. It is worth noting that some newer image file formats, such as the *JP2* file format (defined as part of the *JPEG 2000* standard[14]), strongly discourage (and in some cases disallow) the use of metadata that will cause interoperability problems between baseline and extended applications.

Implicit Interpretation of Spatial Content

An interpretation of spatial content may be associated with an image implicitly by establishing standard interchange conditions. For example, the image file creator could tailor the image's structure characteristics for some assumed, reference fulfillment purpose. This approach to image management has already achieved a significant level of industry adoption for tone/color image characteristics, as evidenced by the pervasive use of standard color encodings such as *sRGB*.[15-17]

The development of interchange standards for spatial image characteristics may simplify the problem of spatial management: a clearly defined set of exchange conditions could preserve system interoperability while not precluding opportunities for differentiation such as the support of proprietary spatial enhancement algorithms, the development of proprietary spatial transformation models, and the support of custom management aims, e.g., *optimal overall spatial quality*, *device-matched sharpness*, *minimal artifact visibility*, etc. Consider the case where a DSC-produced *EXIF*[9] image file is known to contain *sRGB* data whose spatial characteristics have been prepared to produce a 4 x 6-inch print on a reference printer/media combination, which will be viewed at a typical handheld distance by a standard human observer, under standard lighting conditions. Given the knowledge of its structure content, a system receiving this image may be able to more easily determine and perform the appropriate spatial-processing operations to prepare it for a different imaging goal, e.g., *soft copy display*, *hard copy enlargement*, *high-quality digital archival*, etc.

In the remaining sections of this paper, example components of such a reference fulfillment environment are discussed, and data that illustrates the importance of understanding this information is presented.

Reference Fulfillment Environments (RFEs)

An RFE defines a context for the interpretation of the pixel data contained in an image file. For spatial image characteristics, an RFE consists of two main components:

- **Fulfillment Channel:** the imaging components that are assumed will be used to convert the digital image to the desired (fulfilled) format
- **Evaluation Environment:** the assumed qualities of the observer of the fulfilled image, and the conditions under which it is assumed observation will occur

In an open-system environment, it would become the responsibility of an application that creates/releases the image to ensure its characteristics have been properly prepared for fulfillment through the specified RFE. In this way, the receiving (fulfillment) application's task of interpreting the image's structure content may be simplified.

Fulfillment Channel Considerations

A fulfillment channel must minimally consist of a display/writing device, along with any required media. Certain digital spatial processing operations may also be required as part of the channel.

The spatial characteristics of the fulfillment channel must be properly specified. As illustrated by the modulation transfer function (MTF) data in Figure 1, these characteristics can vary substantially between device-media combinations. For example, a typical CRT display is a significantly less-sharp fulfillment option than a high-quality silver halide (AgX) marking engine. The fulfillment hardware and media selected for use during spatial performance optimization of a digital capture device, such as a DSC, can have a significant influence on this process.

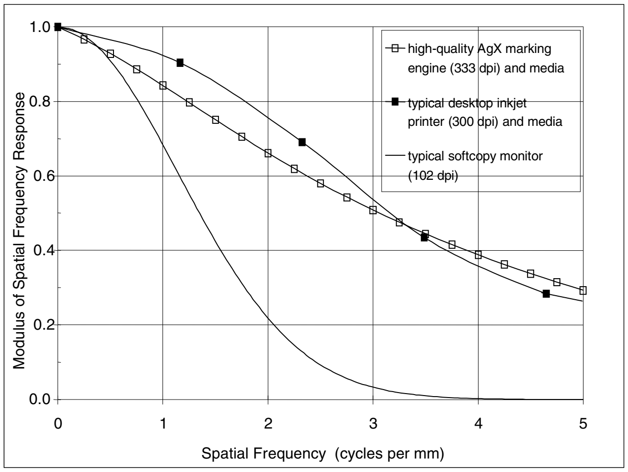

Figure 1. The MTFs of three device-media combinations.

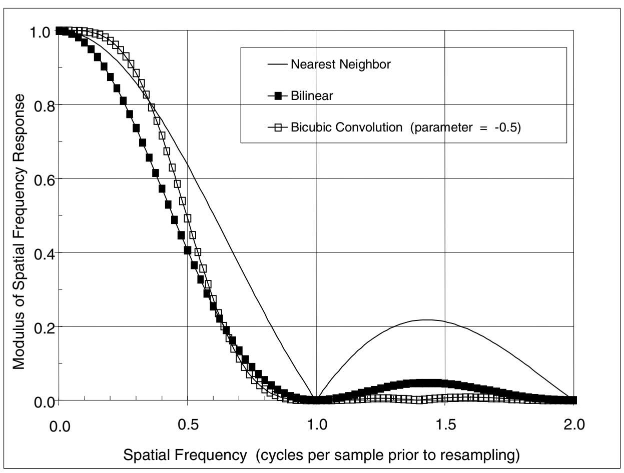

Figure 2. The phase-averaged MTFs of three common resampling techniques.[18]

To minimize the complexity of fulfillment-channel specifications, it may be advantageous to keep the inclusion of digital spatial processing operations to a minimum. However, failure to include specifications about certain critical operations can lead to ambiguity in the interpretation of the RFE. For example, consider digital resampling. As illustrated by the MTF data in Figure 2, the selected resampling technique may impact spatial characteristics like sharpness and (aliasing) artifacts. For situations in which downsampling is required, it may be considered necessary to apply an anti-alias filter to the image prior to resampling. The filter's design will depend on several factors, including the desired tradeoff between computational throughput, image sharpness, and aliasing. The overall impact of resampling on spatial quality may be significant, depending on the dimensions of the starting image, the resolution of the fulfillment hardware, and the evaluation environment. Specifying the details of resampling is, therefore, an important consideration when defining a complete fulfillment channel.

While certain fulfillment hardware choices may warrant the specification of additional digital processing details in order to remove ambiguity, for example, the halftoning algorithm employed by a particular inkjet marking engine, the inclusion of processing steps not commonly considered part of the fulfillment channel itself, e.g., preference-driven digital sharpening, is likely best avoided. Such operations, which may depend on scene content, user preferences, and other non-systemic factors, may overcomplicate the definition of an RFE.

Evaluation Environment Considerations

An evaluation environment must minimally describe the spatial traits of the image observer and the viewing geometry in which observation occurs.

The development of perceptual image quality models is a dynamic, evolving field.[3-8] At present, no universally accepted, comprehensive formulation of human vision has been established. For perceived sharpness alone, several acutance metrics and quality factors have been developed. Such acutance metrics and quality factors entail a slightly different formulation or weighting of the human visual system (HVS) contrast sensitivity function (CSF).[19-21] In practice, the appropriateness of a given model depends on several factors, including ambient light level.[22]

Models of perceptual image quality are increasingly being used to predict and optimize the performance of digital imaging devices such as DSCs. Changes in the HVS formulation used in a given model may drive the design toward a different solution point. An understanding of the formulation used is, therefore, an important consideration.

In addition to specifying a model for human vision, it is important to provide information about the intended viewing geometry when specifying a complete evaluation environment. Viewing distance is particularly important for spatial quality, and most quantitative psychophysical experiments tightly regulate this parameter.[3,23] Without knowledge of viewing distance, it is possible to make ambiguous predictions of spatial image quality.

RFE Justification and Component Selection

In this section, image quality simulation examples are presented, which illustrate the importance of the assumed fulfillment environment for an image.

At Eastman Kodak Company, full-system image quality simulations have been regularly used in formulating business strategies, guiding design decisions, establishing product aims, budgeting system tolerances, and benchmarking products. Development of a general image quality model includes the following stages: (1) linking psychophysical responses and objective measurements to create attribute-specific predictive equations; (2) creating a mathematical method for predicting the combined effects of multiple image quality attributes; (3) building a capability model that predicts the output of systems operating under ideal conditions; (4) building a performance model that generates the complete frequency distribution of final image quality, including contributions from manufacturing, environmental, and customer-induced variability sources; and where possible, (5) creating automated system design features that optimize the component specifications based on the predicted image quality. A detailed description of the method used to combine the effects of multiple-image, quality attributes, is contained in this volume under the title "Multivariate Image Quality from Individual Perceptual Attributes".

The RFE specifications in Table 1 and Table 2 are representative of common fulfillment tasks that an image fulfillment system might be expected to handle. These RFE examples have been used to create the simulation results summarized in this paper.

Table 1. The specifications for a representative hard copy reference fulfillment environment.

Fulfillment Channel	**Device/Media:** AgX marking engine, 333-dpi AgX reflective media **Fulfillment Format:** AgX reflective hard copy, 8 x 10-inch **Resampling:** cubic convolution interpolation
Evaluation Environment	**HVS formulation:** Kodak perceptual image quality model[3-5] **Viewing Geometry:** handheld viewing distance for specified fulfillment format (14 inches)

Table 2. The specifications for a representative soft copy reference fulfillment environment.

Fulfillment Channel	**Device/Media:** CRT monitor, 102-dpi **Fulfillment Format:** soft copy display, 4 x 6-inch **Resampling:** anti-alias filtration and decimation
Evaluation Environment	**HVS formulation:** Kodak perceptual image quality model[3-5] **Viewing Geometry:** typical computer monitor viewing distance (20 inches)

Figures 3 and 4 display just-noticeable-difference (JND) units of image quality as a function of spatial filter gain. A one-JND change corresponds to the smallest image quality difference that can be perceived by 50% of observers in critical paired-image comparisons. A difference of two JNDs can be seen by about 90% of observers, and a drop of six JNDs reflects about a full subjective quality category (e.g., excellent → very good) change in quality. The "0 JND" level is the point above which further improvements in image structure, such as acutance, fail to produce higher perceived image quality. Consequently, all attributes listed on the plots constitute degradations (negative JNDs) relative to that "ideal" image.

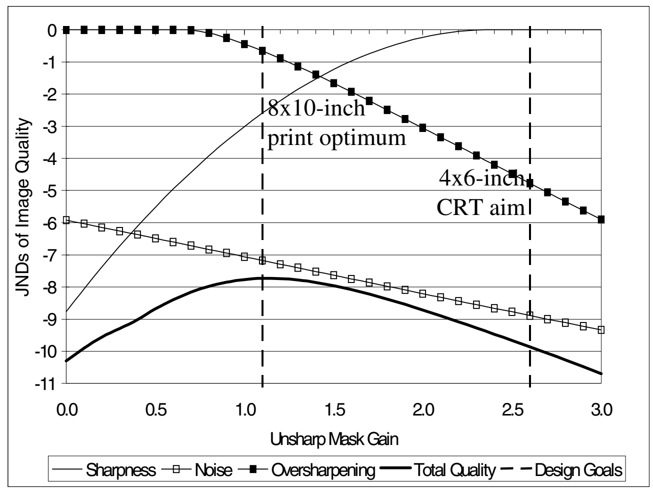

Figure 3. The effect of spatial filter gain level on the quality attributes of a particular 3.1-mega-pixel DSC capture written to 8 x 10-inch reflection media at 333-dpi.

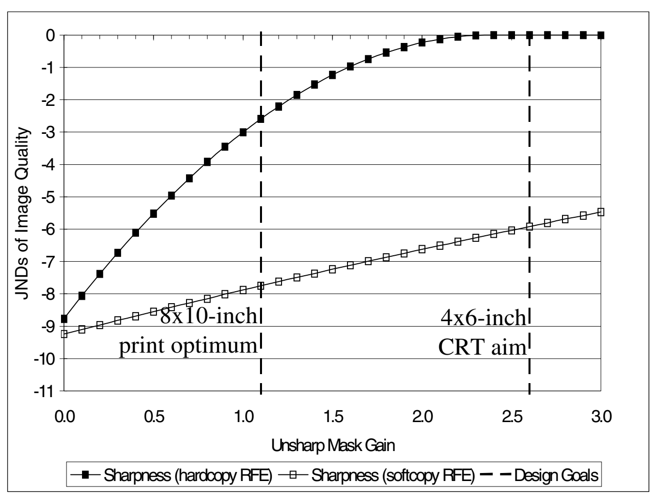

Figure 4. The effect of spatial filter gain level on the perceived sharpness of a particular 3.1-mega-pixel DSC capture written to 8 x 10-inch reflection media at 333-dpi and displayed at 4 x 6-inch size on an 102-dpi CRT monitor.

Figure 3 reveals the effect of the spatial filter gain, applied via a 5-by-5 unsharp masking operation, on the perception of noise, sharpness (acutance), oversharpening artifacts, and overall quality for captures from a particular 3.1-mega-pixel DSC written to 8 x 10-inch reflection media at 333-dpi, viewed at a distance of 14 inches. As the gain is increased, the sharpness improves, while the noise and artifacts become more visible, thereby decreasing quality. The optimum overall spatial quality (highest multivariate sum) is achieved at a spatial filter gain of about 1.2.

Figure 4 displays image quality with regard to sharpness only for the 8 x 10-inch print system described above and for a second system consisting of the same 3.1-mega-pixel DSC images displayed at 4 x 6-inch size on a 102-dpi CRT monitor, viewed from a distance of 20 inches. These two cases represent typical hard copy and soft copy fulfillment environments. In the case of the 4 x 6-inch CRT system, the spatial filter gain was selected to provide sharpness within one subjective quality category (-6 JNDs) of the "ideal" level, while still maintaining near-optimum overall spatial quality. The 2.6 gain level required to achieve the CRT design aim (-6 JNDs) fails to match the optimum sharpness of the 8 x 10-inch print system (-2 JNDs) at the 1.2 gain level. However, increasing the gain for the 4 x 6-inch CRT system above 2.6 leads to a less favorable multivariate quality position. Therefore, at a sharpness level of –6 JNDs, the 4 x 6-inch CRT gain is 2.6, while the 8 x 10-inch print gain is only 0.4. Returning to Figure 3, if the 4 x 6-inch CRT design aim gain (2.6) is applied in the 8 x 10-inch print system, the multivariate quality is reduced by two-JNDs, relative to the 8 x 10-inch print optimum gain (1.2), due to excessive noise and oversharpening artifacts. This example highlights problems, which might arise, if spatial processing aims are derived with different fulfillment environments and preferences in mind.

Conclusions and Recommendations

Standard interchange conditions for tone/color image characteristics have achieved a significant level of industry adoption. The development of analogous standards for spatial image characteristics may help to further simplify the exchange of digital images in an open-system environment. The adoption of standard RFE assumptions may encourage more consistency in the spatial performance of digital capture devices such as DSCs, by reducing the variability in design goal assumptions used during design and optimization.

Image quality simulation examples have been presented that illustrate the importance of the assumed fulfillment environment for an image. The development of standard fulfillment environment specifications, as part of a to-be-developed industry level, spatial management architecture, may encourage more consistency between vendors in their design aims. In the absence of this information, fulfillment applications may need to implement more intensive source-specific compensation schemes to manage the spatial characteristics of arbitrary images.

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Biography

Robert Parada received his B.S. degree in imaging science from RIT in 1992, his Ph.D. degree in Optical Sciences from the University of Arizona in 1997, and his Ph.D. degree in Optical Physics from the Université du Littoral (Dunkerque, France) in 1997. He has been with Eastman Kodak Company since 1997 where he is currently a Research Associate in the Imaging Science Division. His work has primarily focused on the development of consumer imaging products, with emphases on digital photofinishing, imaging architectures, spatial image processing, and Internet imaging.