Framework for an Image Sharpness Management System

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Abstract

A new framework for image sharpness management is proposed, analogous to the existing framework for color management systems. Knowledge of both the human visual contrast sensitivity function (CSF) and of device spatial resolution, characterized via the modulation transfer function (MTF), can be used to determine the optimum correction to be made to the sharpness of an image for specified viewing conditions, via parametric image processing techniques. The proposed framework includes profiles for spatial input and output device characteristics, connected via a profile connection space with the facility for the operator to specify a sharpness rendering intent.

Automation of Color Image Processing

The development of color management systems during the past decade has been driven by the following factors:

Cost and productivity – When image production systems need to be automated for commercial production of images of acceptable quality, it is not cost-effective to employ a skilled person to make visual judgements for each image. Batch processing and lower skill levels are essential;

Device independence – It should be possible to reproduce an image on multiple devices with the same color appearance, i.e. independent of the device or process characteristics;

Inter-operability – It should be possible to preserve the color appearance of an image when transferring it from one system to another. The destination system should be able to interpret the colors in the image to produce an equivalent visual representation of the source.

The same arguments justified the development of negative film printing systems in the past. More recently they have applied to desktop publishing in the graphic arts, and now they are driving the development of industry standards in digital video editing and broadcasting.

All the attention so far has been on color and tonal fidelity, and standards such as those of the International Color Consortium (ICC) reflect this focus.[1] Yet color and tone are not the only visual dimensions of images. Sharpness and noise are arguably of equal importance in determining the overall appearance of an image, but these have received little attention from the color imaging community. In this paper is proposed a new framework for image sharpness, which the author believes will enable new levels of image quality to be achieved economically through embedded processing within imaging systems, with a minimum of operator intervention.

Visual Contrast Sensitivity

The ability of the human eye to resolve fine spatial detail is expressed by its spatial *contrast sensitivity function* (CSF), or relative visual response as a function of spatial frequency. Spatial contrast sensitivity depends on the scene luminance level, as shown in Figure 1 in which the retinal illuminance varies from 0.0009 trolands up to 900 trolands. The greatest sensitivity is achieved at about 8 cycles per degree, i.e. about 1 line pair per mm at 48 cm viewing distance. At lower levels of illumination (mesopic and scotopic) the sensitivity is reduced and peaks at a lower spatial frequency, becoming a low-pass instead of band-pass characteristic. The drop in photopic contrast sensitivity at low spatial frequencies can be explained by the field size exceeding the effective diameter of the center-surround receptive fields produced by the post-receptoral neural interconnections in the retina and visual cortex.[2]

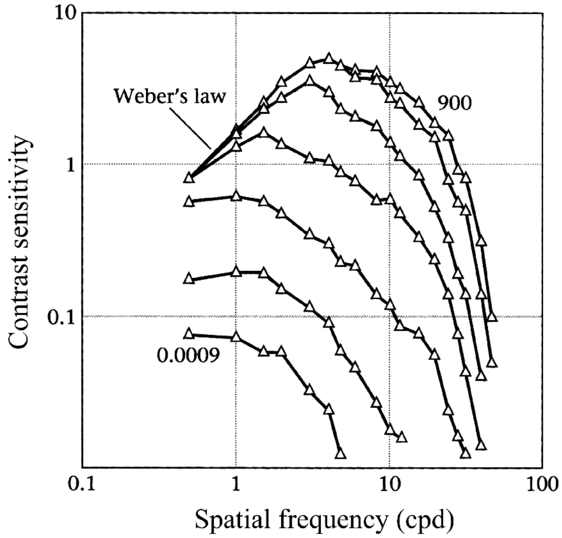

Figure 1 Contrast sensitivity as a function of spatial frequency, with retinal illuminance as a parameter (Reproduced by courtesy of Brian Wandell)

Within the retina there can be identified at least four separate receptive fields, each of which operates at a different spatial scale. These fields peak at spatial frequencies of about 1, 5, 9 and 12 cycles per degree (cpd), and combine to produce the composite contrast sensitivity function.[3] The lower two have relatively sustained temporal properties, whereas the higher two are more transient. The spatial receptive field of each region can be approximated by a difference of two Gaussian (DOG) functions.[4] Recent developments in color appearance models make use of multi-resolution processing – simulating the neural channels – filtering the image array generated by the photoreceptors into a pyramid of image components at different spatial frequencies, resulting in better predictions of induction, crispening and spreading effects than conventional models.[5]

Typical spatial CSFs for luminance contrast (black-white) and chromatic contrast (red-green and yellow-blue at constant luminance) are shown in Figure 2. The luminance CSF is band-pass in nature, approaching zero at both very low (less than 0.1 cpd) and very high (greater than 50 cpd) spatial frequencies. The chrominance CSFs have a low-pass shape, with a lower peak sensitivity and lower cut-off frequencies than the luminance CSF.[6] Only spatial patterns with frequencies less than about 5 cpd can excite the L-M (‘red-green’) opponent neural pathway, and only spatial patterns with frequencies less than about 2 cpd can excite the S-(L+M) (‘blue-yellow’) opponent neural pathway. [7]

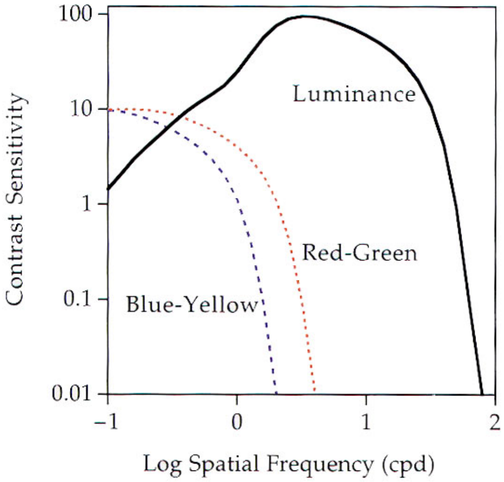

Figure 2 Contrast sensitivity functions for spatial luminance and chromatic contrast. (Reproduced by courtesy of Mark Fairchild)

Spatial interactions within the visual system lead to interactions between perceived color and sharpness. Cornsweet demonstrated that perceived brightness depends not only on the intensity of an object or region in the visual field, but also on its edge contour. By applying a localized change in intensity on either side of the edge of a region of a spinning disc, he created the illusion of a region of different lightness.[8] The effect works best when the region subtends a large visual angle (2 degrees or more), so that its spatial frequency at a normal viewing distance is low (less than 1 cpd) and hence the visual CSF is low. The effect can only be seen in luminance, not chrominance, because the opponent color channels are band-pass and do not have lower response at low spatial frequencies.

Studies have shown that spatial frequency has a strong effect on chromatic induction.[9] Changes in the spatial frequency of test stimuli caused a transition in observers’ colour perception from contrast (below 1 cpd) to assimilation (at 9 cpd). In general, the spatial structure of an image must be taken into account in formulating a complete model of color appearance.[10]

Device Resolution

All imaging devices have spatial structures in their construction and therefore impose spatial characteristics on the images they capture or produce. These characteristics, combined with the point-spread effects of optical or electrical transfer functions, result in limitations on the spatial frequencies the devices can produce. One must distinguish, moreover, between *addressed resolution* and *achieved resolution*. The former is the limit of control available from the host computer, usually represented by the addressable pixel array in an image, whereas the latter is determined by the actual spatial frequency response of the device or medium, characterized in terms of its *modulation transfer function* (MTF). Achieved resolution can be defined by the spatial frequency at which the MTF has decreased to a given percentage of its peak value, typically 10%.

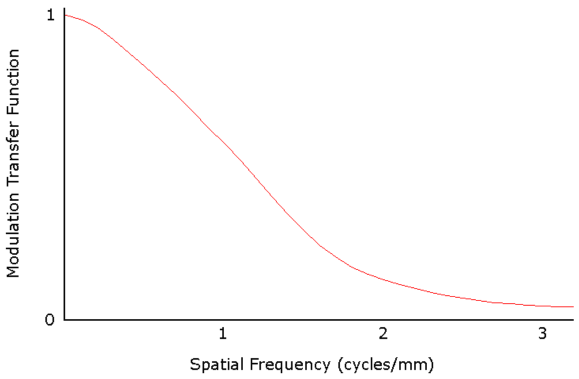

Figure 3 Modulation transfer function (MTF) of a typical desktop CRT display

MTF is a measure of how well an imaging device or system can reproduce a scene. Ideally the MTF should be high over the full range of frequencies of interest, which for human viewing means the full range of spatial frequencies to which the human visual system is sensitive under the prevailing viewing conditions. The MTF of most imaging systems is limited by the display device.[11] For cathode ray tube (CRT) displays, the MTF is determined primarily by the point-spread function of the electron beam and secondarily by bandwidth limitations in the electronics,[12] of the overall contribution of all discernible spatial frequencies, and hence the contrast sensitivity function (CSF) of the eye must be taken into account in formulating a useful metric for image sharpness.[13,14,15]

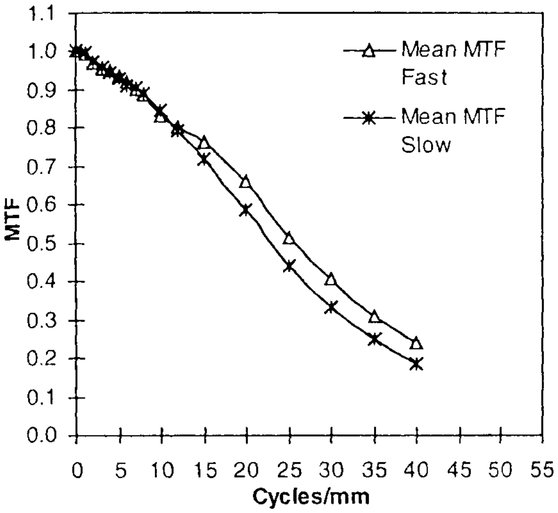

Figure 4 MTF characteristics of a 35mm film scanner for the fast and slow scanning directions (Reproduced by courtesy of Ralph Jacobson).

Different techniques may be used to determine the MTF characteristics of imaging devices. For film scanners and digital cameras, typical targets are sine wave charts with patches of different frequencies and specified modulation depth. Other techniques involve the scanning and Fourier transform of photographic grain noise patterns, and the analysis of the spatial frequency response of slanted edges.[16] Line-array scanners may exhibit different MTF characteristics in the two scanning directions, parallel and perpendicular to the CCD array, as shown in Figure 4. For displays a modulated pattern may be generated, and photographed on film or via a digital camera for analysis. The resulting system MTF is the cascaded combination of both camera and display characteristics, from which the display's MTF can be extracted.[17] Printing devices and processes are characterized by their dot size and/or halftone frequency, and can be measured via micro-line resolution targets or via photographic analysis, as for displays.[18]

Dealing with Sharpness in Image Reproduction

Sharpness can be regarded as a separate dimension of image appearance, independent of lightness, hue and chroma, as shown in Figure 5. When an image is sharp, more detail can be discerned – sharp edges permit the observer to discriminate objects more clearly, and sharp details permit the observer to recognize surface characteristics more accurately. Sharpness is lost in image capture through optical and physical limitations of the scanner or digital camera, such as aperture size, lens aberration and sampling interval. Sharpness is also lost through subsequent digital quantisation, compression and transformations such as geometric manipulation and color space conversion. Finally sharpness is lost through rendering of an image for output, for example in halftones or error diffusion for printing, or in the spatial microstructure of a display or film recorder.

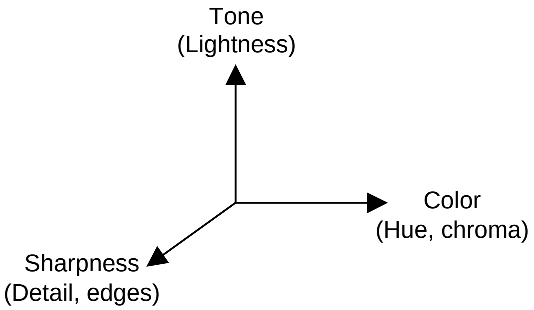

Figure 5 Three dimensions of image reproduction

Substantial improvements in image appearance can be achieved through applying the optimum amount of sharpening. For some types of image, sharpness can be argued to be a more important factor than color, in the sense that degradation of sharpness will make the image less acceptable than degradation of color. Yet sharpness is frequently overlooked as a factor in image reproduction, the assumption being that either it has been dealt with elsewhere in the system or that it is outside the control of the processing software. Certainly sharpness has received very much less attention than color for image enhancement and/or correction.

It would be possible, of course, for a user of an image reproduction system to adjust the degree of sharpness of individual images, using the editing tools provided in Adobe *Photoshop* or in other similar software. But for reasons of cost and productivity it would be highly desirable to be able to offer facilities within the computer operating system to support the semi-automated sharpness enhancement of images from any source device *en route* to any destination device. The key benefits to the customer of this approach would be as follows:

1. Enhance the visual quality of images derived from consumer digital input devices, such as digital cameras and desktop photo scanners, and also images obtained from image libraries or the Internet;
2. Support automated processing in workflows involving large numbers of images for print and multimedia applications;
3. Obtain image reproductions, in display or print, that are optimized for the viewing conditions in which they will be viewed.

Many image processing techniques, such as 'edge crispening' convolution filters and Fourier domain filters, exist for sharpness enhancement.[19] Image reproduction systems, such as television, have built-in sharpness enhancement to compensate for MTF losses in both source (camera) and destination (display) devices. In the graphic arts industry the unsharp mask (USM) filter is well known as a means of applying sharpness enhancement to images and has been widely implemented in both scanner hardware and workstation software.[20] Most of these techniques have been developed empirically, however, with little or no sound theoretical basis, and they are usually applied to all device color channels (RGB or CMYK) simultaneously.

Because the achromatic channel of vision carries most of the sharpness information, it follows for an image encoded into separate luminance and chrominance components that the chrominance data can be sampled at lower spatial frequency without significant loss of image quality. This principle is used in the reduction of bandwidth requirements for color television broadcast systems (NTSC and PAL) and in color image compression algorithms (JPEG and MPEG).[21]

The enhancement of image sharpness should therefore be performed optimally by processing an image separately in its luminance and chrominance components, or to a good approximation by processing the luminance channel alone. This suggests that an efficient implementation of image sharpening could be achieved by processing only the lightness (L*) component of an image encoded in a uniform color space such as CIELAB or CIELUV. The sharpening filter should be designed to enhance the appropriate spatial frequencies of the image in two ways: (1) those lost because of device MTF characteristics; and (2) those required to render the image most effectively for the needs of the human visual system under the viewing conditions in which it will be seen.

Framework for Image Sharpness Management

A framework for an image sharpness management system is proposed, as shown in Figure 6, analogous to the ICC framework for color management.[1] This goes beyond previously proposed systems[22] by defining a generic structure for separately characterizing the spatial characteristics of input and output imaging devices, and a standard connection mechanism for image processing.

The spatial characteristics of the input device, including MTF and enlargement factor, would be stored in an *input profile*. These data would be used by the input transform to convert the input image into a device independent form, representing the appearance of the ideal image when viewed by an observer of standard visual acuity in a standard viewing environment at a standard viewing distance. The image in this *profile connection space* (PCS) would be perfectly corrected for the losses of sharpness caused by the optics and sampling process of the input device. In similar fashion, the spatial characteristics of the output device, including MTF and enlargement factor, would be stored in an *output profile*. These would be used by the output transform to convert the image from the PCS into the output format. This transform could optionally include characteristics of the environment under which the final image should be viewed, such as luminance level and viewing distance.

The operator of the system would also have the possibility of making editorial corrections to an image, such as sharpness enhancement, either by processing the image data directly in the profile connection space, or by adjusting the parameters of the input or output profiles. As with the practical implementation of color management systems, the source and destination profiles could be compounded into a single transform for more efficient processing of images.[23]

The concept of *rendering intent* can also be applied to sharpness. Plausible rendering intents could include:

Maximize sharpness
Enhance edges
Minimize noise (grain)
Facsimile of original
Soft focus
Pleasing portrait

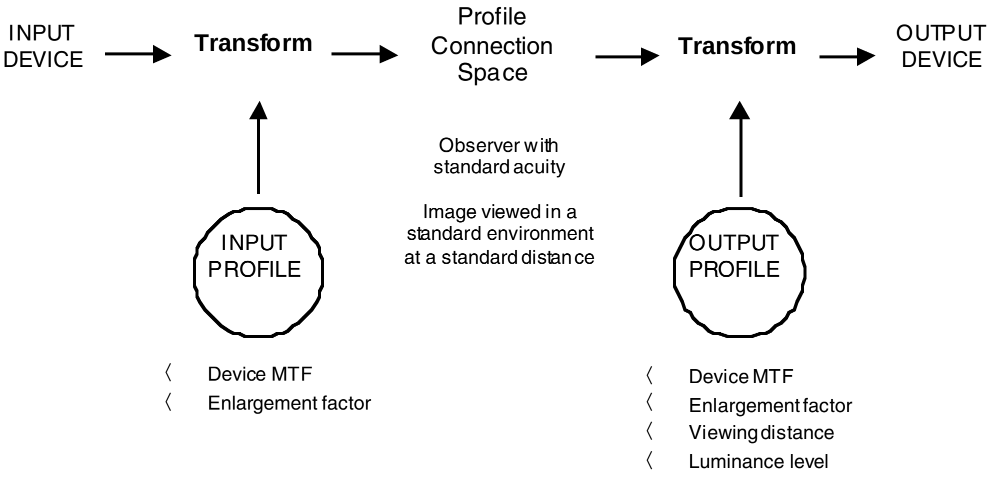

Figure 6 Framework for an image sharpness management system

More sophisticated rendering intents may apply differing degrees of sharpness enhancement in different colour components or different regions of an image. Studies of photographic color prints have shown that the subjective preference for sharpness can be enhanced through suitable filtering of the green component of the image, thereby smoothing the magenta dye component of the print.[24] A critical case is the rendering of facial portraits, in which the hair, eyebrows and lips may benefit from increased sharpness whereas skin tones may benefit from softening (reduced sharpness) in order to disguise skin pores and blemishes.[25] Such rendering may be achieved through the use of a colour-selective sharpening/softening algorithm.

The nature of the input and output media and the user’s viewing task (scanning and fixation patterns, attention span, motivation, etc.) can also affect the appearance of sharpness in images. A more complete framework would therefore include corrections for the media types and the intended viewing task, such as ‘at a glance’, protracted examination, legibility of text, discriminability of information, conspicuity of status warnings, continuity of moving images, etc.

Conclusions

Although it is arguable that sharpness is more important than color rendering in image reproduction, sharpness has not yet been properly addressed in desktop imaging systems. Sharpness losses due to the spatial sampling characteristics of imaging devices should be compensated to achieve more pleasing reproduction of images. Because human vision has much higher contrast sensitivity for achromatic luminance information, processing efficiency could be achieved by sharpening images in the luminance component alone. Sharpness management systems with architectures analogous to existing color management systems should in future fulfil this need. One way to achieve this would be to extend the ICC framework to include the additional spatial data in device profile definitions and to add sharpness enhancement to CMM processing.

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