Quantitative Error Analysis of Color in IEEE Publications

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Abstract

To demonstrate the performance of color image processing algorithms, it is desirable to be able to accurately display color images in archival publications. Our previous work [1], describes requirements for accurately rendering images using your own equipment. This paper discusses the problems of dealing with intermediaries and offers suggestions for improved communication and rendering.

1 Introduction

As digital color printing has become more prevalent, more papers that deal with color image processing algorithms are being published. While numerical tables and various error metrics are used to present the results, the ultimate proof of the effectiveness of an algorithm or theory is a visual comparison of images. Our first paper was intended to describe methods for generating images that can be accurately compared [1]. The premise of that paper was that the user has control over all aspects of the image scanning and reproduction process. In the case of the publication of images in journals, this is not true. Typically, the process of demonstrating results of color image processing algorithms in an archived journal is as follows:

- The author prints the images on a high quality color printer and sends them to the publisher.
- The author obtains proofs of scans of these images from the publisher.
- The author has the opportunity to comment on the quality of the proofs.
- Iteration on the proofs is often required to assure accurate reproduction.
- The published images are created based upon the proof that appears best to the author.
- The author pays a large sum of money.

In the end, it is possible that the final published image will not match the proof selected by the author.

In this paper, we examine our recent attempt to produce accurate color images in the IEEE Transactions on Image Processing [1]. The results were sufficiently poor to warrant this follow-up paper to quantify the accuracy of the reproduction process and to suggest possible solutions that may make the demonstration of color image processing results easier for future authors. Differences in the processing of the images in that paper were large and significant. Even with poor color accuracy, the reader can see the large differences caused by the various methods. However, as methods become more sophisticated, the differences in algorithms for coding, restoration and reconstruction become smaller numerically and more subtle visually. Because of this, the subject of accurate reproduction using third parties and the precise communication of color information is very important.

2 Color Management

It will be assumed that the reader is familiar with the definition of a *device independent color space* (DICS), a *device dependent color space* (DDCS), and the gamut of a color display device. Figure 1 illustrates the color recording and reproduction process in a device independent color framework. In creating such a system, several transformations are determined. These transformation are

- $\mathcal{F}_{record}$, which maps the recorded data to a DICS.
- $\mathcal{D}$, which maps from a DICS into the gamut of the display device
- $\mathcal{F}^{-1}_{display}$, which maps from the gamut of the display device to the display device dependent (DD) values

The international color consortium (ICC) has provided a standard for describing these mappings using

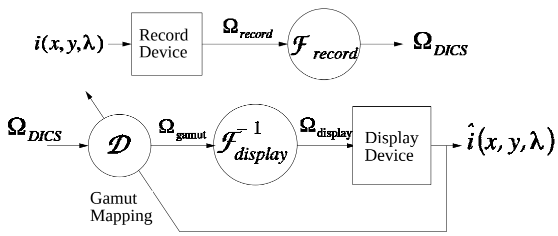

Figure 1: Color Management Block Diagram

multidimensional look-up tables (MLUTs) [2]. To reduce the effect of noise, the systems rarely map the image data to the DICS. Instead, all the operations to be performed are linked into a new MLUT that transforms the image data directly to the output device control values.

3 An Example

In [1], a comparison was made between the commonly used digital color Lena image (the RGB data is available from several sites), a rescanned version of Lena (recorded with our scanner), and a color corrected version of the rescanned version of Lena. To illustrate where the problems of reproduction arise, we will describe the process of reproducing the images accurately using our equipment and the process of reproducing the images for the journal.

The first step in performing the comparison was the scanning of an original published version of the Lena image with a desk-top scanner. The scanner was profiled, which is to say that $\mathcal{F}_{record}$ was determined. An RGB dye-sublimation printer was also profiled, which provided the mapping $\mathcal{F}_{display}^{-1}$. A gamut mapping algorithm $\mathcal{D}$, which mapped along lines of constant hue was used [4, 5]. The commonly used digital color Lena image, the rescanned image, and the rescanned image transformed through $\mathcal{F}_{display}^{-1}(\mathcal{D}(\mathcal{F}_{record}(.)))$ were each printed using the dye-sublimation printer.

To quantify the transformations that occurred in the proofing and final printing process, a series of color squares were included with the Lena images. The publisher was instructed to make sure that the same operations were performed on the Lena image data and the color square data. The CIELab values of these squares are given in [1].

In the publication process, a first proof of the Lena images was obtained from the publisher and, based on visual inspection, judged unacceptable. A second proof was obtained and judged sufficiently improved that the authors agreed to publish the images as given in this second proof. No physical measurements were made for the comparisons since the large differences were readily visible. The end result printed in the issue was noticeably different from the original image and from the second proof, which greatly reduced the usefulness of the printed images.

The ΔE differences in CIELab between the original image, the two different proofs, and the final image were computed and are shown in Table 1. For the standard observer, a $\Delta E > 3$ will be noticeable. Note that there are significant differences between many of the colors. While some of these differences could be caused by gamut limitations, most of the colors should be reproducible by the printing process.

The Lena image itself has a natural orange cast and the error on the Orange square is a rough quantification of the differences between the Lena image original, proofs, and final print. Note that for this Orange sample, the difference between proof 2 and the original is quite small at only 2.60 ΔE. This is the proof the authors agreed to use based upon a visual comparison between the proof and a copy of the original images. The difference is quite large however between the final print and the original for this color at 11.34 ΔE, which is an indication of the error seen in the final Lena print.

Table 1: Delta E errors between original samples and proofs plus original samples and final print

Sample	Proof1	Proof2	Final
Bright Yellow	13.01	8.55	18.80
Bright Green	32.73	18.80	32.30
Black Point	9.56	7.85	14.43
Pale Green	31.43	17.01	22.96
Orange	5.79	2.60	11.34
White Point	3.52	3.03	3.34
Bright Red	27.55	24.24	30.77
Bright Magenta	22.28	17.31	20.74
Pale Blue	12.03	3.35	11.52
Pale Pink	8.09	1.89	8.06
Purple	13.23	10.95	16.75
Bright Cyan	21.38	12.07	20.55
Average	16.72	10.64	17.63

4 Publishing Solutions

From the above results it is clear that the current process used in publishing color images in archival publications is insufficient to display subtle differences in color images. With the growth of digital color imaging and the exposure of printers and press operators to the methods of digital color management this situation will eventually change.

For now however, it may make more sense to spend extra time making sure that the electronic version accurately conveys the desired information. A clear downside of this approach is that those readers with nonelectronic subscriptions will be unable to view the proper images. In addition, there may be some work required by the reader of the electronic version to obtain the proper color on their display device.

4.1 The ICC Approach

One approach to provide a means of conveying accurate color information is to use an electronic format that allows for the embedding of ICC information into the image. While we do not wish to endorse any particular format, a format that currently supports the embedding of ICC information and is often used for electronic publishing of conference proceedings and journal papers is Version 4.05 of Adobe's Portable Document Format (PDF). For the example discussed in Section 3, the embedded profile would be the mapping from RGB to CIELab for the dye-sublimation printer that was used to print the RGB images, which were sent to the publisher in [1].

To properly display the image on a monitor or printer, it is necessary to know the ICC profile for the particular output device. This destination profile can be determined using some of the methods discussed in [1] or is often available from device manufacturers. Once the correct destination profile is known, proper display is achieved using an application (e.g. Adobe Photoshop/Acrobat 4.05) or system (e.g. Apple ColorSync) that properly handles ICC profiles. Displaying the image properly with this approach requires the user to have an accurate ICC profile for their display device in its current state. Note that changing the contrast or brightness controls on a monitor may require the recomputation of an ICC profile for the display device. Given the proper ICC profile, the mapping that is performed on the image RGB values is given by

$$\mathcal{F}_{display}^{-1}(\mathcal{D}(\mathcal{F}_{printer}(.))) \quad (1)$$

where $\mathcal{F}_{printer}(.)$ is the mapping from RGB values to CIELab values for the printer used to create the images, $\mathcal{D}$ is the gamut mapping operation for the display device, and $\mathcal{F}_{display}^{-1}$ is the mapping to the DD values of the display device.

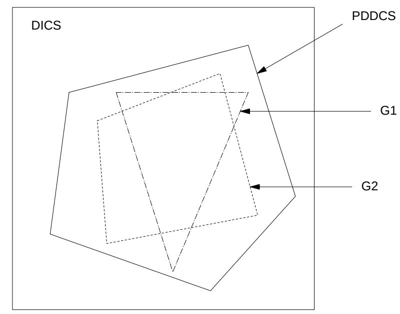

Figure 2: Conceptual 2-D drawing of two device gamuts and a PDDCS

4.2 The sRGB Approach

Another solution to this problem is to use a color space such as sRGB to describe the color data. The sRGB color space is a *pseudo-device dependent color space* (PDDCS). The term *pseudo* is used since the DD values are not directly related to a physical device. The 2-D graphical representation in Figure 2 illustrates how a PDDCS could be effectively used to communicate color information between devices. In this figure, the gamuts of two devices are denoted by G_1 and G_2. Since the gamuts of the two devices are completely inside the gamut of the PDDCS, the DD data from one device could be colorimetrically communicated to the other device without ever having to transfer data to the DICS. An advantage of using a PDDCS to communicate color as opposed to a DICS is that there may be lower quantization error introduced if a PDDCS is used since a smaller volume of the DICS needs to be sampled to represent the data. One obvious problem with using a PDDCS is what happens when two devices are used with gamuts that are outside the gamut of the PDDCS. In this case, color information that could be communicated using a DICS is lost since it must be gamut mapped into the gamut of the PDDCS.

An additional problem with using a PDDCS is that the space may not be well suited for gamut mapping. Unlike CIELab, the Euclidean difference between two nearby points in the space does not relate to any notion of perceptual difference. In addition, a common practice for gamut mapping is to preserve the hue at the expense of lightness and chroma. For CIELab, lines of constant hue have been empirically determined [6]. For many PDDCSs, it is unclear how to map along lines of constant hue, and such a mapping may be very complex. One approach would be to convert the data to a DDCS such as CIELab, but this negates one of the often proclaimed advantages of a space such as sRGB by introducing additional computations.

The use of sRGB for accurate display of published color data requires the author to map the images to the sRGB colorspace from a DICS. This mapping is well defined [3], but as mentioned, there may be a loss of information due to a gamut mismatch. For the Lena images, the following operations are necessary to prepare the data:

- Perform a mapping from the dye-sub DD RGB color space to a DICS via $\mathcal{F}_{printer}$.
- Map the colors in the DICS so that they are inside the sRGB gamut. [4, 5]
- Transform the gamut mapped image to sRGB.

To properly display the resulting sRGB color images, the images could be mapped to a DICS via an ICC profile and then mapped to the DD values of the reproduction device. Alternatively, there are many devices (both monitors and printers), which assume that the image data is in the sRGB color space. When sRGB data is sent directly to such a device, the device will internally perform the mapping $\mathcal{F}^{-1}_{display}(\mathcal{D}(\mathcal{F}_{sRGB}(.)))$ on the data where $\mathcal{F}_{sRGB}$ represents the mapping from sRGB to a DICS. This situation is probably the easiest for the reader, since no special operations are required. Note however, as with the ICC approach, adjustments to controls such as contrast or brightness will affect the final results. For completeness, the Lena color images from [1] were transformed to sRGB and are shown in Figure 3 (see the electronic version for color images). Image (a) is the commonly used digital color Lena image, (b) is a rescanned version of Lena (recorded with our scanner), and (c) is a color corrected version of the rescanned version of Lena.

5 Conclusion

In this paper, we demonstrated the difficulty of achieving accurate color reproduction in archival journal publications. A solution was proposed, which made use of the electronic form of the journal. The solution has the disadvantage of being unavailable to those without electronic subscriptions but has the advantage of providing accurate color with no additional cost to the authors.

Figure 3: sRGB Lena color images. See text for description

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