# Problems in Publishing Accurate Color in IEEE Journals

Michael J. Vrhel, *Member, IEEE,* and H. J. Trussell, *Fellow, IEEE*

***Abstract*—To demonstrate the performance of color image processing algorithms, it is desirable to be able to accurately display color images in archival publications. In poster presentations, the authors have substantial control of the printing process, although little control of the illumination. For journal publication, the authors must rely on professional intermediaries (printers) to accurately reproduce their results. 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.**

***Index Terms*—Color reproduction, display and printing.**

## I. 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. This was also the premise in Stone's paper dealing with the problem of printing of color images for a special issue of *Color Research and Application* [2], [3]. In practice, most authors publishing in journals have very little control over the final color printing process. Typically, the process of demonstrating results of color image processing algorithms in an archived journal is as follows:

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

Manuscript received April 3, 2000; revised January 23, 2002. The associate editor coordinating the review of this manuscript and approving it for publication was Prof. Robert L. Stevenson.

M. J. Vrhel is with Color Savvy Systems, Ltd., Springboro, OH 45066 USA (mvrhel@colorsavvy.com).

H. J. Trussell is with the Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27695-7911 USA.

Publisher Item Identifier S 1057-7149(02)03976-3.

In the end, it is possible that the final published image will not match the proof selected by the author. This process and the uncertainty in the final output makes it difficult to accurately display color images in an archived journal.

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 publication 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.

The definitions of device independent and dependent color spaces (DICS and DDCS) as well as device gamuts are outlined in [1]. Some DDCSs will be described as *pseudo-device dependent color spaces* (PDDCSs). PDDCSs are designed such that there will exist mappings between a number of DDCSs *into* the PDDCS. In this way, such a color space becomes a standard space through which to translate device dependent values. There are a number of color spaces that have been suggested as standard spaces [6]. The term *pseudo* is used for this color space since the device dependent values of the PDDCS are not necessarily directly related to a physical device.

## II. An Example

In [1], a comparison was made between the commonly used digital color Lena image (the RGB data is available at several sites), a rescanned version of Lena (recorded with our scanner), and a color corrected version of the rescanned version of Lena. 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 in the original are shown in Table I for CIE D50 illumination, in the columns labeled $L^*$, $a^*$, and $b^*$. These printed images were provided to the publisher for reproduction in the journal.

In the publication process, a first proof of the Lena images was obtained from the publisher and, based on visual inspection, judged unacceptable. In this case, the differences were

TABLE I
CIELAB VALUES OF ORIGINAL SAMPLES

| Sample | $L^*$ | $a^*$ | $b^*$ |
|---|---|---|---|
| Bright Yellow | 90.95 | -9.33 | 101 |
| Bright Green | 44.77 | -74.98 | 28.67 |
| Black Point | 9.59 | -9.87 | -0.9 |
| Pale Green | 49.01 | -41.7 | 14.4 |
| Orange | 66.75 | 23.44 | 50.26 |
| White Point | 95.1 | -0.02 | -0.95 |
| Bright Red | 37.33 | 69.37 | 52.11 |
| Bright Magenta | 38.88 | 78.84 | -12.55 |
| Pale Blue | 51.3 | -19.96 | -32.58 |
| Pale Pink | 67.26 | 28.98 | 10.7 |
| Purple | 11.8 | 23.52 | -48.15 |
| Bright Cyan | 48.53 | -45.41 | -36.05 |

TABLE II
$\Delta E_{ab}$ COMPARISON BETWEEN PRINTS

| | $\Delta E^*_{ab}$ | | | | |
|---|---|---|---|---|---|
| Sample | Orig-P1 | Orig-P2 | Orig-Final | P1-Final | P2-Final |
| Bright Yellow | 13.01 | 8.55 | 18.80 | 10.24 | 12.31 |
| Bright Green | 32.73 | 18.80 | 32.30 | 15.44 | 14.23 |
| Black Point | 9.56 | 7.85 | 14.43 | 7.13 | 8.86 |
| Pale Green | 31.43 | 17.01 | 22.96 | 16.17 | 11.29 |
| Orange | 5.79 | 2.60 | 11.34 | 10.86 | 9.01 |
| White Point | 3.52 | 3.03 | 3.34 | 2.63 | 1.24 |
| Bright Red | 27.55 | 24.24 | 30.77 | 5.29 | 6.79 |
| Bright Magenta | 22.28 | 17.31 | 20.74 | 9.18 | 3.81 |
| Pale Blue | 12.03 | 3.35 | 11.52 | 10.34 | 9.44 |
| Pale Pink | 8.09 | 1.89 | 8.0 | 15.19 | 6.17 |
| Purple | 13.23 | 10.95 | 16.75 | 6.40 | 13.54 |
| Bright Cyan | 21.38 | 12.07 | 20.55 | 15.67 | 10.89 |
| Average | 16.72 | 10.64 | 17.63 | 10.38 | 8.97 |

very large and no measurements were needed. A second proof was obtained and judged sufficiently improved that the authors agreed to publish the images as given in this second proof. Unfortunately, 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 $\Delta E^*_{ab}$ differences in CIELAB between the original image, the two different proofs, and the final image were computed and are shown in Table II. Specifically, the column labeled, Orig-P1, is the $\Delta E^*_{ab}$ between the original image and the first proof; Orig-P2, is the $\Delta E^*_{ab}$ between the original image and the second proof; and Orig-Final, is the $\Delta E^*_{ab}$ between the original image and the published image. The $\Delta E^*_{ab}$ difference between two CIELAB values is simply the Euclidean distance between the two three-element vectors. A value $\Delta E^*_{ab} > 3$ would be noticeable to the standard human observer [9]. 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. Recall that the original Lena is a hardcopy produced by a high quality four-color printing process. The differences in the printing processes should be relatively small. The last two columns of Table II provide the $\Delta E^*_{ab}$ difference between the proofs and the final print. Note that proof 2 should have been a very close match to the final print but was not (this is assuming that the proofing process was a reasonable match to the actual printing process, which of course is the point of proofing).

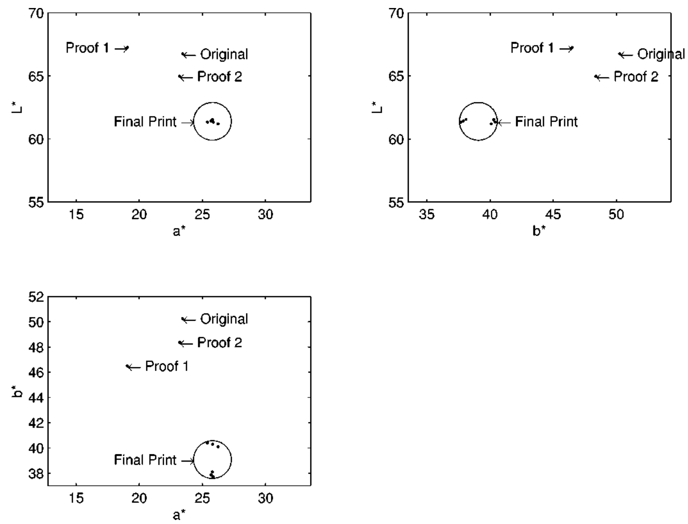


Fig. 1. CIELAB comparison of orange sample.

The Lena image itself has an orange cast to it 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 square, the difference between proof 2 and the original is quite small at only 2.60 $\Delta E^*_{ab}$. 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 $\Delta E^*_{ab}$, which is an indication of the error seen in the final Lena print. This example demonstrates the difficulty in obtaining accurate color results in an archived journal.

To obtain information about the variation in the printing process, six copies of the published squares were measured. Fig. 1 provides a graphical view of this variation and its relationship to the errors in Table I for the Orange sample. In the figure, a view along each axis in CIELAB space is shown. The points in the circle labeled Final Print are the six Orange samples measured in the six journal copies. Note that the differences between the journal copies is very small relative to the difference to the proofs and the original. Also note the large difference between Proof2 and the final print.

## III. PUBLISHING SOLUTIONS

One approach for accurately displaying color image results is to publish the color images in only the electronic version of a journal. 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.

If hard copy images are critical, then it may be possible to achieve some degree of success by displaying color samples with the color image. Any recording, processing, or reproduction that is performed on the data would be performed on the color samples. To remove the necessity of having the original image to compare, the device independent (DI) values of these samples could be indicated in the image. This is similar to the process used in [1]. These color values would be carefully selected to be within the gamut of most color reproduction devices and include saturated and neutral colors. It would be up to the printer to ensure that the best match was obtained.

The international color consortium (ICC) has provided a standard for describing mappings between DDCSs and the CIELab color space using multidimensional lookup tables (MLUTs) [4]. In the electronic approach, one method for conveying accurate color information is to use an electronic format that allows 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 Adobe's Portable Document Format (PDF). For the example discussed in Section II, 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 display such an image properly 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) 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. There are several makers of software and/or hardware for computing monitor ICC profiles, including Praxisoft, GretagMacbeth, Datacolor, ProfileCity, and Monaco Systems. Given the proper ICC profile, the mapping that is performed on the image RGB values is given by $\mathcal{F}_{display}^{-1}(\mathcal{D}(F_{printer}(\cdot)))$, where $\mathcal{F}_{printer}(\cdot)$ is the mapping from RGB values to CIELAB values for the dye-sublimation printer, $\mathcal{D}$ is the gamut mapping operation for the display device and $\mathcal{F}_{display}^{-1}$ is the mapping to the device dependent (DD) values of the display device.

Note that an ICC approach could also be used by the publisher/printer to obtain improved control of the color reproduction process. If the printer has characterized their printing process, (i.e., created an ICC profile) and this profile was made available to the author, then it would be possible for the author to transform his color image data to obtain an improved final print. There are standard web offset printing ICC profiles readily available. Due to the current lack of control, it is unclear if handing the publisher CMYK standard web offset digital data using a generic SWOP ICC profile would improve the printing process.

Another solution to the electronic approach is to use a color space such as sRGB [5]–[7] to describe the color data. As mentioned, the sRGB color space is a *pseudo-device dependent color space* (PDDCS). If the gamuts of the devices (e.g., the monitor and the printer) are within the gamut of the PDDCS, then it is possible to communicate the necessary color information in the PDDCS. If the devices have color values outside of the PDDCS, then information will be lost. This problem is illustrated in Fig. 2. In this figure, the sRGB gamut is shown along with the gamut of a three-color dye sublimation printer

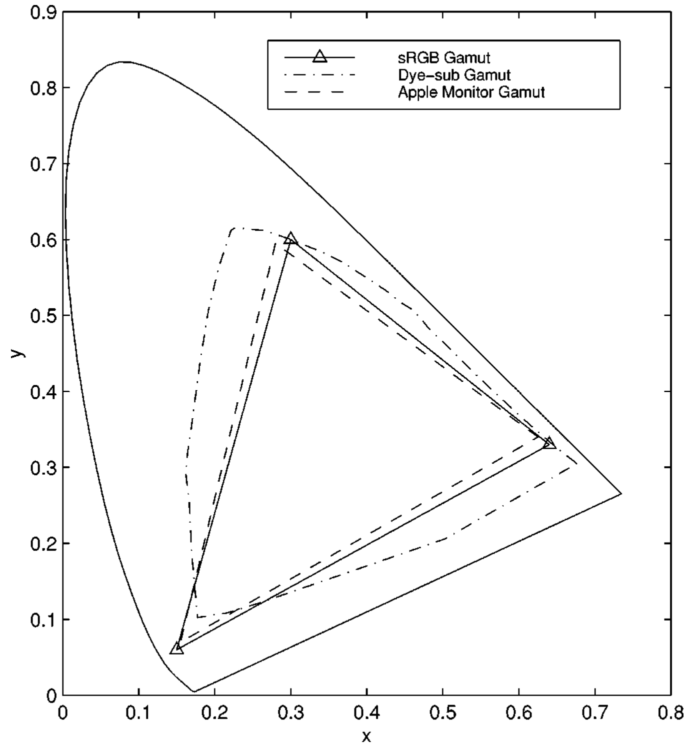


Fig. 2. Two device gamuts and a PDDCS. Device gamuts have values outside the allowable range of values in the PDDCS.

and an Apple Multiple-Scan monitor. The sRGB color space is limited in its gamut due to the fact that only nonnegative values are defined. The proposed sRGB64 color space removes this restriction by allowing the encoding (as a signed 16 bit value) of negative RGB values [8].

It should be noted that in these transformations, compensations are usually made to correct for perceptual effects, most notably the problem of white point adaptation. For example, often a CIELAB value of [100,0,0] is mapped to the white point of a monitor and the white point of the printer even if neither the paper or monitor white have a CIELAB value of [100,0,0]. If this matching of white points is not performed, then the printed image may have an undesired color cast compared to the monitor, or vice versa.

## IV. Conclusion

A real example of the difficulty of accurately printing color in an archival journal was described. Various approaches to solving this problem were briefly discussed. Many of the solutions rely upon the electronic form of the publication.

## References

[1] M. J. Vrhel and H. J. Trussell, "Color device calibration: A mathematical formulation," *IEEE Trans. Image Processing*, vol. 8, pp. 1796–1806, Dec. 1999.

[2] M. C. Stone, W. B. Cowan, and J. C. Beatty, "Color gamut mapping and the printing of digital color images," *ACM Trans. Graph.*, vol. 7, no. 3, pp. 249–292, Oct. 1988.

[3] ——, "A description of the reproduction methods used for color pictures," *Color Res. Applicat.*, vol. 11, pp. S83–S88, June 1986.

[4] Int. Color Consort. Profile Format Ver. 3.4. International Color Consortium. [Online]. Available: http://www.color.org/

[5] M. Anderson, R. Motta, S. Chandrasekar, and M. Stokes, "Proposal for a standard default color space for the internet-sRGB," in *Proc. 4th Color Imaging Conf.: Color Science, Systems, and Applications*, Nov. 1996, pp. 238–246.

[6] S. Susstrunk, R. Buckley, and S. Swen, "Standard RGB color spaces," in *Proc. 7th Color Imaging Conf.: Color Science, Systems, and Applications*, Nov, 1999, pp. 127–134.

[7] "Multimedia Systems and Equipment—Color Measurement and Management—Part 2–1: Color Management—Default RGB Color Space sRGB,", IEC 61 966-2-1, 1999.

[8] "Multimedia Systems and Equipment—Color Measurement and Management—Part 2–2: Color Management—Extended RGB Color Space sRGB64,", IEC 61 966-2-2, 1999.

[9] M. Stokes, M. D. Fairchild, and R. S. Berns, "Precision requirements for digital color reproduction," *ACM Trans. Graph.*, vol. 11, no. 4, pp. 406–422, October 1992.

**Michael J. Vrhel** (S'87–M'87) was born in St. Joseph, MI, in 1964. He received the B.S. degree in electrical engineering from Michigan Technological University, Houghton, in 1987 and the M.S. and Ph.D. degrees in electrical engineering from North Carolina State University, Raleigh, in 1989 and 1993, respectively.

From 1993 to 1996, he was a National Research Council Associate with the National Institutes of Health, Biomedical Engineering and Instrumentation Program. Currently, he is the Senior Scientist at Color Savvy Systems Limited, Springboro, OH. His research interests include color reproduction, signal restoration/reconstruction, and wavelets.

**H. J. Trussell** (S'75–M'76–SM'91–F'94) received the B.S. degree from the Georgia Institute of Technology, Atlanta, in 1967, the M.S. degree from Florida State University, Tallahassee, in 1968, and the Ph.D. degree from the University of New Mexico, Albuquerque, in 1976.

He joined the Los Alamos Scientific Laboratory, Los Alamos, NM, in 1969 where he began working in image and signal processing in 1971. During 1978-1979, he was a Visiting Professor at Heriot-Watt University, Edinburgh, U.K., where he worked with both the university and with industry on image processing problems. In 1980, he joined the Electrical and Computer Engineering Department, North Carolina State University, Raleigh. During 1988–1989, he was a Visiting Scientist at the Eastman Kodak Company, Rochester, NY.

Dr. Trussell is a past Associate Editor for the IEEE Transactions on ACOUSTICS, SPEECH, AND SIGNAL PROCESSING and is currently an Associate Editor for the IEEE SIGNAL PROCESSING LETTERS. He is a member and past chairman of the Image and Multidimensional Digital Signal Processing Committee of the IEEE Signal Processing Society. He founded and edited the electronic newsletter published by this committee. He received the the IEEE Acoustics, Speech, and Signal Processing Society Senior Paper Award (with M. R. Civanlar) in 1986 and the IEEE Signal Processing Society Paper Award (with P.L. Combettes) in 1993.