Journal of Imaging Science and Technology® 51(3): 243–247, 2007.

New Set of RGB Primaries for Display Covering Full Range of Real World Object Colors

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Abstract. *It is inevitable that there are some colors that cannot be reproduced with three primaries even in the case of a laser display. The purpose of this study is to define a new set of RGB primaries for display that can reproduce all real world object colors. At the first step, the region of real world object colors was estimated from the comparison between the measurement data of 453 object colors and the 1294 standard data of Munsell colors. Through the second step, the region boundary of real world object colors was optimized as a triangle according to two rules. Accordingly the wavelengths of RGB primaries were defined as 630, 532, and 468 nm, respectively. At the third step, with the help of 53,361 SOCS data, the tolerance limit of B primary was also defined as the range of 463–468 nm. Finally, the color reproducibility of commercial laser display systems was evaluated using the optimum gamut as a criterion.* **© 2007 Society for Imaging Science and Technology.**
[DOI: 10.2352/J.ImagingSci.Technol.(2007)51:3(243)]

INTRODUCTION

The prime function of a display is to show accurate representation of real objects. Therefore, a display has to distinctively reproduce a large fraction of colors that exist in the real world. It basically produces colors by means of combining a number of primary colors but only the three-primary case is addressed in this research. A color gamut is defined as a range of colors achievable on a display under a given set of viewing conditions[1] and can be described as a three-dimensional volume in color space. However, in the display manufacturing industry, it is usually described and communicated as a ratio of the area of a triangle, which is comprised of three primary color points, to that of the NTSC triangle[2] on the CIE x, y diagram. The size of the triangle depends on the purity of three primary colors of a display.

With new development in display technologies in the past few years, the size of the gamut has increased.[3–5] The Organic Light Emitting Diode (OLED) display showed a large gamut comparable to CRT displays. The RGB LED backlight extended the gamut of LCD display to more than that of the NTSC standard. Laser display also has been increasingly developed in the last few years and it is known as one of the next generation displays. The color reproducibility of laser display shows much better performance than any other displays, because laser can produce monochromatic light located on the spectral locus of the CIE chromaticity diagram. Considering the laser display's gamut, we find that the size of the triangle is no longer the only issue. Another important issue is the specific choice of wavelengths of three primary colors. The region of colors possible for a given laser is determined by wavelengths of the three primary colors.

In the previous paper,[6] the measured x, y chromaticity coordinates of 453 objects were reported, and thus the wavelengths of RGB primaries of the optimum gamut were defined. However, there was a lack of objectivity in determining the location of the G primary. In this present paper, the wavelength of the G primary is redefined and the tolerance limit of the B primary is also defined. Furthermore, a relationship between the wavelength of B primary and the number of out-of-gamut SOCS data is derived. Practically, four commercial laser display systems are evaluated using the new set of RGB primaries as a criterion.

MEASUREMENT

To figure out the region of real world object colors, 453 objects were selected in two categories: Artificial objects and natural objects. For artificial objects, we selected garments and electronic devices because of their frequent appearance in TV dramas or movies. The garments consisted of 112 casual garments and 156 Tibetan traditional garments. All garments displayed in a casual clothing shop were measured. The Tibetan traditional garments, displayed in the 2005 World Museum Culture Expo, which was held in Korea, were measured. The measured electronic devices consisted of 99 products such as washing machines, refrigerators, hair dryers, etc. All products displayed in a shop were measured. For the natural objects, 50 flowers and 36 leaves, which were available during July and September in Korea, were measured. As the reference, the 1294 standard data of Munsell colors were considered. Since Munsell colors[7] are originally defined under the CIE standard illuminant C with a 2° viewing angle, they are converted into the viewing condition under a standard illuminant, D65, using the CAT02 chromatic adaptation transformation.[8]

A portable type of spectrometer (Eye-one Photo, SN/0121018, GretagMacbeth) was used to perform all measurements in the field. The spectral reflectance data, from 380 to 730 nm with a 10 nm interval, were measured and used to calculate CIE x, y chromaticity coordinates, which

Received Sep. 6, 2006; accepted for publication Jan. 11, 2007.
1062-3701/2007/51(3)/243/5/$20.00.

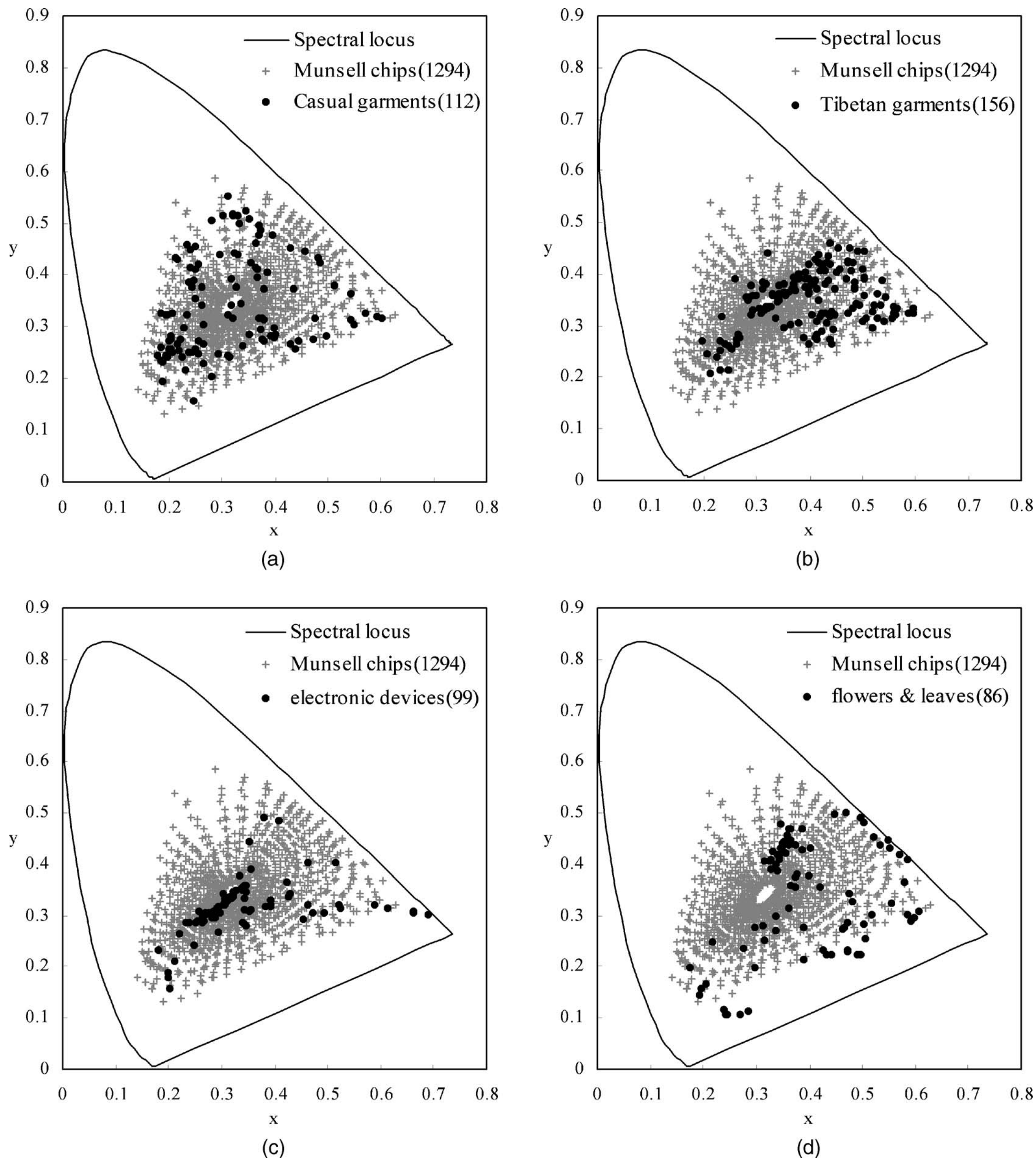

Figure 1. Measured data for (a) 112 casual garments, (b) 156 Tibetan traditional garments, (c) 99 electronic devices, and (d) 86 flowers and leaves compared with the standard data of Munsell colors.

were obtained by calculating XYZ under the CIE standard illuminant, D65.

RESULTS AND DISCUSSION

Estimation of the Region of Real World Object Colors

Figure 1 shows the measurement data plotted on the x, y chromaticity diagram for (a) casual garments, (b) Tibetan traditional garments, (c) electronic devices, and (d) flowers and leaves. The 1294 standard data of Munsell colors are also plotted together in each figure. The measured data are represented by the black circle symbols, and the Munsell data are represented by the x symbols. It is interesting that the Munsell data are partially distributed on the x, y chromaticity diagram. Obviously, no colors are around the lobe of the spectral locus at all.

Figure 1(a) shows that the casual garments, which were produced by synthetic dyes, are distributed evenly within the Munsell color region. Tibetan traditional garments, which were produced by natural dyes, are distributed locally as shown in Fig. 1(b). Figure 1(c) shows that the electronic devices are concentrated in several specific hue locations. From Fig. 1(a)–1(c), it can be assumed that any artificial object's color would be located within the Munsell color region. Meanwhile, Fig. 1(d) shows that some natural object's colors are distributed up to and beyond the Munsell color region. Some are located very near to the right-side spectral locus, and some are closer to the purple line.

With these experimental results, we assumed that any object color, including artificial and natural, should be located within the region consisting of the 1294 Munsell standard colors and 86 measured natural colors, which are presented by the hollow circle symbol in Figure 2. Figure 2 also shows the comparison with the two internationally stan-

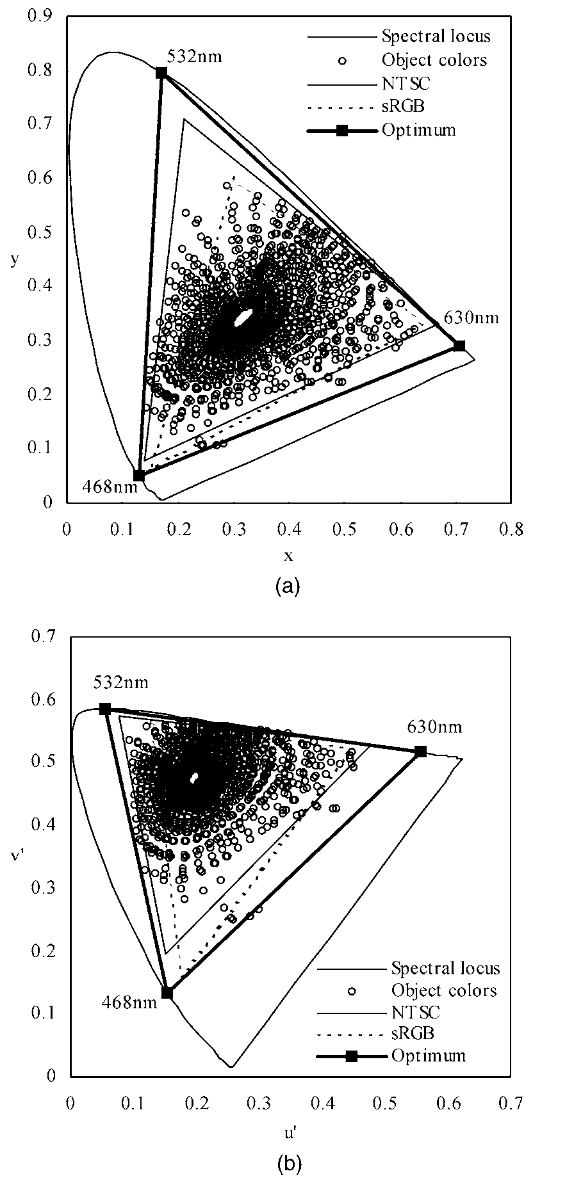

Figure 2. The optimum gamut of real world object colors compared with the standard gamuts on the CIE chromaticity diagram with (a) x, y coordinates and (b) u', v' coordinates.

dardized color spaces; the NTSC gamut and the sRGB gamut.[9] The given object color data are not covered by either of the two standard gamuts.

Wavelengths of RGB Primary Colors

In Fig. 2, the region boundary of real world object colors is shown as a thick lined triangle. Figure 2(a) illustrates the x, y coordinates, and Fig. 2(b) illustrates the u', v' coordinates. There are two rules in determining three vertices of the thick lined triangle. The first rule is that both the sRGB gamut and the NTSC gamut should be included, and the other rule is to comprise the object color data as much as possible. The three vertices positioned on the spectral locus were determined as follows.

First, the position of the left vertex plays a key role to covering left corners of the two standard gamuts. If the left vertex is positioned at a relatively long wavelength in the blue region, the bottom boundary of the thick lined triangle, which connects the left vertex and the outmost data near the purple line, cuts some part of the NTSC gamut as well as the sRGB gamut. Meanwhile, if the left vertex is positioned at a relatively short wavelength, the left boundary of the thick lined triangle cuts some part of them. Thus, the left vertex was optimally determined as the cross point of the left-side spectral locus and the extension of the sRGB bottom line so that the sRGB gamut is just included within the thick lined triangle.

Next, the right vertex of the thick lined triangle was simply determined as the crossing point of the line, which connects the left vertex and the outmost data near the purple line, with the right-side spectral locus.

Last, the position of the top vertex is also critical to covering object color data located both very near to the right-side spectral locus and around the left-side spectral locus. So, the top vertex was determined as the crossing point of the upper-side spectral locus and the extension of the right vertex and the R primary of NTSC gamut so that the NTSC gamut is just included in the thick lined triangle.

Figures 2(a) and 2(b) showed the same result. Accordingly RGB primary colors of the optimum gamut were defined as the monochromatic wavelengths of three vertices of the thick lined triangle: 630 nm (R), 532 nm (G), and 468 nm (B).

Sensitivity of Color Reproduction to B Primary

It is necessary to test the optimum gamut against other object color data not included in Fig. 2. The Standard Object Color Spectra (SOCS) database in the ISO TR 16066 standard was developed for proper evaluation of the color sensor quality of image input devices.[10–12] The spectra of 53,361 objects were collected from 9 categories, which cover practically all object colors. These are photographic materials (Transparencies/Reflection prints), graphic prints (Offset/Gravure), computer color prints (dye sublimation/electrostatic/ink-jet), paint (not for art), paints (oil paints/water colors), textiles (synthetic dyes/plant dyes), flowers and leaves, outdoor scenes (Krinov data except for flowers and leaves), and human skin. The SOCS data was converted to CIE x, y chromaticity coordinates under a standard illuminant, D65, and tested as to how many SOCS data are out of the optimum gamut. It had been reported that there is no great difference between the gamut of SOCS and Pointer's gamut.[13,14]

Figure 3 shows the number of SOSC data out-of-gamut varies with the shift of B primary from 443 to 478 nm with a 5 nm interval when R and G primaries are fixed to 630 and 532 nm, respectively. The gray bar illustrates the number of out-of-left boundary SOCS data, and the black bar illustrates the number of out-of-bottom boundary SOCS data. As the wavelength of B primary gets shorter, the height of the gray bar rapidly increases while the height of black bar increases as the wavelength of B primary becomes longer than 463 nm. So the accumulated heights, which mean the numbers of out-of-gamut SOSC data, form a parabolic figure having the minimum number of 125 at the wavelength of 463 nm. For the total SOCS data of 53,361, the failure

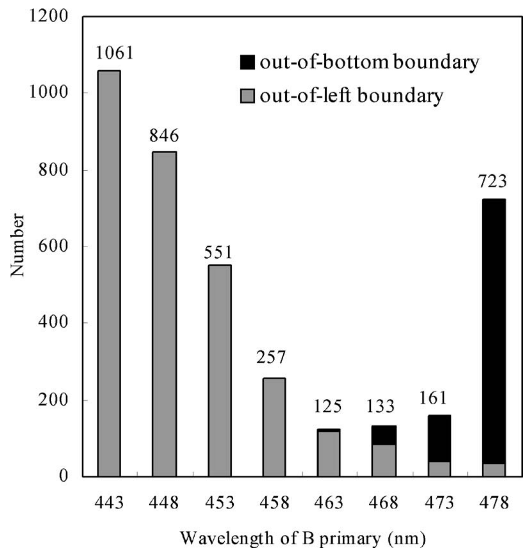

Figure 3. The numbers of out-of-left boundary SOSC data and out-of-bottom boundary SOSC data varies with the shift of B primary.

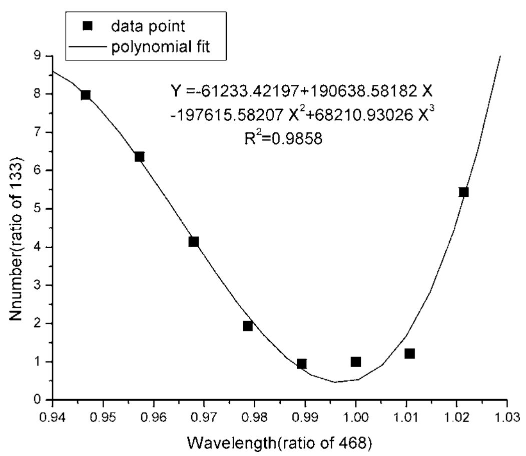

Figure 4. The numbers of out-of-gamut SOSC data and their polynomial fit.

percentage was 0.23%. These out-of-gamut data occurred all out of the computer color print category, especially of the dye sublimation type. Anyway, Figure 4 shows relatively small numbers of out-of-gamut data points for the wavelengths 463, 468, and 473 nm. However, the wavelength of B primary must be below 468 nm so that the sRGB gamut can be included in the optimum gamut. Consequently, the range of 463–468 nm can be defined as the tolerance limit of the B primary.

In Fig. 4, the numbers of SOSC data out-of-gamut were plotted as square symbols against the wavelength of B primary. Each unit of the y axis corresponds to 133 SOSC data points out-of-optimum gamut, and the x axis represents the wavelengths of the B primary normalisms to 468 nm. The third order polynomial function obtained using data analysis software ORIGIN 6.1 (OriginLab Co., Northampton, MA) is also shown. The coefficient of determination (R^2) of 0.9858 indicates that the relationship between wavelength of B primary and the number of out-of-gamut SOCS data is well described by a third order polynomial function. However, this function shows a little discrepancy near to the tolerance limit of the B primary.

Table I. The wavelengths of the RGB primaries for four commercial laser display systems.

Company	R primary	G primary	B primary
Symbol	635 nm	532 nm	440 nm
COLOR	628 nm	532 nm	447 nm
SONY	642 nm	532 nm	457 nm
ILP	630 nm	532 nm	473 nm
Optimum RGB	630 nm	532 nm	468 nm

Evaluation of Commercial Laser Display Systems

With the help of the SLM (Spatial Light Modulation) technology and diode laser, various types of laser display systems have been developed. In Table I, the RGB primaries for four laser display systems from different companies are compared. Symbol Technologies has developed a micro laser projection display engine, which employs red and blue semiconductor lasers and a green diode-pumped solid-state (DPSS) laser[15] to produce full color images. The Corporation for Laser Optics Research (COLOR) develops and manufactures high-powered RGB DPSS laser systems[16] for video projection and other industrial and scientific applications. Sony Corp. has developed a prototype front-projection display system based on grating-light-valve (GLV) devices.[17] This system uses a red semiconductor laser and DPSS lasers. International Laser Productions (ILP) markets RGB DPSS Laser Systems[18] for laser show entertainment in a variety of environments.

For the G primary, all laser display systems use the DPSS laser of 532 nm, the same as the optimum G primary. For the R primary, only the ILP system uses 630 nm, the same as the optimum R primary. The other systems use different wavelengths of 628, 635, or 642 nm. For the B primary, however, all systems use wavelengths different from the optimum B primary. Symbol, COLOR, and SONY use 440, 447, and 457 nm, respectively, which are shorter than the optimum B primary. ILP uses 473 nm, longer than the optimum B primary.

Figure 5 shows the comparison of these four laser display systems' gamut and the optimum gamut on the CIE chromaticity diagram. Figure 5(a) illustrates the x, y coordinates, and Fig. 5(b) illustrates the u', v' coordinates. Because the color of lasers is so pure, different B primaries slide the gamut along the spectral locus. Figure 5(b) shows the gamut difference in a more uniform scale. The wavelengths of the G primary for all laser systems are consistent at 532 nm, so the number of out-of-gamut SOCS data can be estimated using the third order polynomial function obtained from Fig. 4.

Table II shows this estimated number, the actually counted number, and their relative error. The estimated or counted numbers of four systems are in the order of wavelength of B primary. The Symbol system, for which wavelength is the shortest, shows the largest number, and the ILP

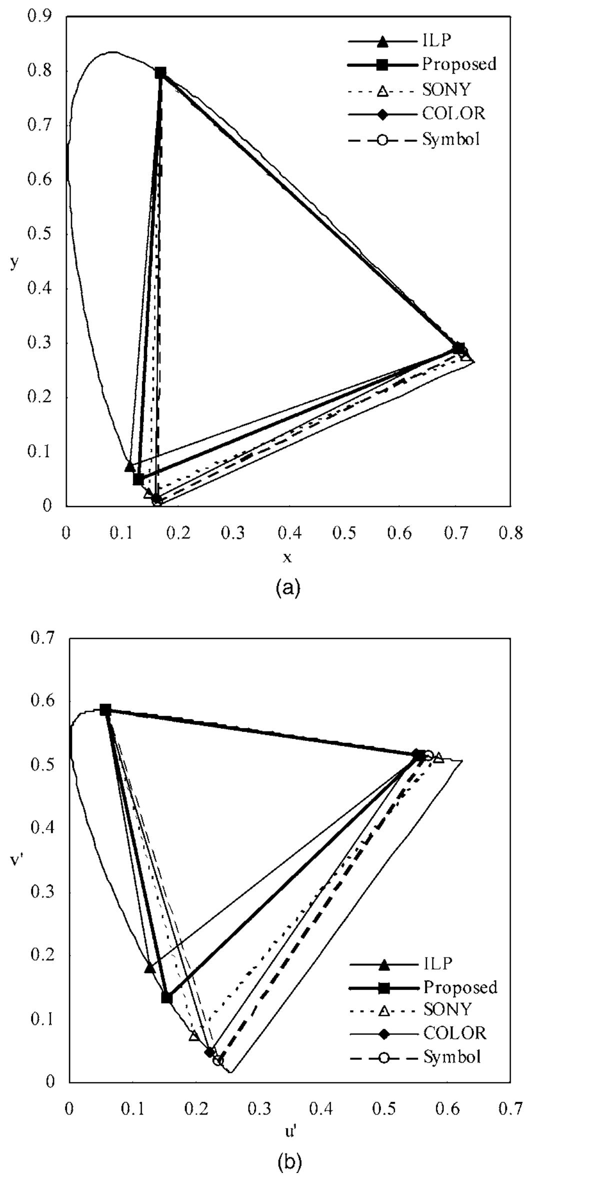

Figure 5. Comparison of four laser display systems' gamut and the optimum gamut on the CIE chromaticity diagram with (a) x, y coordinates and (b) u', v' coordinates.

Table II. Comparison of estimated and counted results for commercial laser display systems.

Company	Estimated No. Out-of gamut	Counted No. Out-of-right boundary	Out-of-bottom boundary	Out-of-gamut	Relative error (%)
Symbol	1146	1181	0	1181	−3.0
COLOR	887	910	0	910	−2.5
SONY	338	299	0	299	13.0
ILP	241	86	47	164	47.0

system shows the smallest number due to the location of B primary, which is closest to the tolerance limit. The relative error increases as the wavelength of B primary becomes closer to the tolerance limit, as shown in Fig. 4. For Symbol, COLOR, and SONY, the counted numbers for out-of-bottom boundary SOCS data are all zero. This shows that the wavelength of the R primary has little influence on the color reproduction, and the wavelength of the B primary is the key issue to achieve full color reproduction in a laser display system. In addition, for the R primary, from the viewpoint of visibility,[19] a shorter wavelength is better.

CONCLUSION

The region of real world object colors was described approximately with the 1294 standard data of Munsell colors and some measured data of natural objects. The three vertices of the optimum gamut triangle were determined in order to cover the two standard gamuts as well as the object color region. Accordingly RGB primary colors of the optimum gamut were defined as the monochromatic wavelengths of three vertices of the inclusive triangle: 630 nm (R), 532 nm (G), and 468 nm (B). The tolerance limit of the B primary was also defined as the range of 463–468 nm, using the SOCS data. The relationship between wavelength of the B primary and the number of out-of-gamut SOCS data was adequating described by a third order polynomial function.

REFERENCES

[1] J. Morovic, Ph.D. thesis, University of Derby, UK, 1998.

[2] C. Poynton, *Digital Video and HDTV Algorithms and Interfaces* (Morgan Kaufmann Publishers, New York, 2003).

[3] P. Strohriegl, M. Bäte, C. Neuber, K. Kreger, H. Schmidt, and M. Sonntag, "Novel aromatic amines for photoconductor and organic electronic application", *Proc. IS&T's NIP22* (IS&T, Springfield, VA 2006) pp. 21–24.

[4] W. Folkerts, "LED backlighting concepts with high flux LEDs", SID Int. Symp. Digest Tech. Papers 1126–1129 (2004).

[5] C. Deter and W. Biehlig, "Scanning laser projection display and the possibilities of an extended color space", *CGIV 2004-Second European Conference on Color in Graphics, Imaging and Vision* (IS&T, Springfield, VA, 2004) pp. 531–535.

[6] S. O. Park, H. S. Kim, and Y. J. Kwon, "Guideline on designing laser display primary for reproducing real world object colors", *CGIV 2006-Third European Conference on Color in Graphics, Imaging and Vision* (IS&T, Springfield, VA, 2006) pp. 216–219.

[7] http://www.cis.rit.edu/mcs/online/munsell.php

[8] R. S. Berns, *Principles of Color Technology* (John Wiley & Sons, New York, 2000).

[9] IEC 61966-2-1 Part 2–1: Colour management-Default RGB colour space—sRGB.

[10] J. Tajima, M. Tsukada, Y. Miyake, H. Haneishi, N. Tsumura, M. Nakajima, Y. Azuma, T. Iga, M. Inui, N. Ohta, N. Ojima, and S. Sanada, "Development and standardization of a spectral characteristics data base for evaluating color reproduction in image input devices", Proc. SPIE **3409**, 42–50 (1998).

[11] J. Tajima, Hideaki Haneishi, Nobutoshi Ojima, and Masato Tsukada, "Representative data selection for standard object colour spectra database (SOCS)", *Proc. IS&T/STD 10th Color Imaging Conference* (IS&T, Springfield, VA, 2002) pp. 155–160.

[12] ISO TR 16066-2003, Graphic Technology-Standard object color spectra database for colour reproduction evaluation.

[13] M. Inui, T. Hirokawa, Y. Azuma, and J. Tajima, "Color gamut of SOCS and its comparison to Pointer's gamut", *Proc. IS&T's NIP20* (IS&T, Springfield, VA, 2004) pp. 410–415.

[14] M. R. Pointer, "The gamut of real surface colours", Color Res. Appl. **5**, 145–155 (1980).

[15] http://www.symbol.com/assets/files/WP-LPD.pdf

[16] http://www.colorvision-lasers.com/displays.aspx#

[17] http://www.eetimes.com/story/OEG20020614S0126

[18] http://www.internatlaser.com/laser_systems/DPSS_laser_systems.html

[19] R. W. G. Hunt, *Measuring Color* (Ellis Horwood Ltd., London, UK, 1987).