Quantifying Smoothness of the LUTs-based Color Transformations

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Abstract

The quality of reproduced images suffers from several limitations in a color management system, such as device profiling, color transformation, etc. one of the most accurate numerical models for device profiling is achieved by the measurement of a large number of colors which, in turn, can be used to develop multi-dimensional look-up-tables (LUTs) with interpolation for any intermediate colors. To achieve high quality on image reproduction and acceptable performance of a color management system, relative smooth color transformation using LUTs is demanded.

A research was carried out to explore the possibility to measure the smoothness of LUT transformation in the color management system based on ICC specifications. Psychophysical experiments were conducted to evaluate the smoothness of the reproduced images subjectively by using a number of ICC printer profiles. An image difference metric was designed and tested to quantify the experimental results objectively.

Introduction

The International Color Consortium (ICC) has introduced the role of ICC profile in a color management system. Due to the recent advances in color imaging science and technology, there have large progress been made in the field of color management. The lower cost color management system has been brought to the desktop users besides the graphic arts industry. One question of how to assess the quality of the profile has been widely discussed. The ICC white paper[1] raises several issues to determine the profile's quality including the accuracy of colorimetric profiles, assessing the quality of non-colorimetric profiles, and the smoothness of color transformation. The overall quality of ICC profiles has been investigated according to media and software by several researches [2-5]. In this study, we focus on the evaluation of the smoothness of color transformation.

A profile is a standard formatted file, which defines the relationship between a device's control signals and the actual color that those signals produce. The ICC profile often employs multi-dimensional LUTs to store the desired values for the purpose of accurate color transformation. A process known as device profiling serves for the purpose, which provides a reliable way for color communications between media, and it has been widely involved in commercial applications. With respect to the selection and calibration of instruments and well controlled measuring environment, the systematic measurement errors remain constant in time, while the random noise is somehow instantaneous and unavoidable due to unpredictable variations during the measurement, which is inherited in LUTs' transformation. Consequently, smoothness artifacts, such as bandings and contours etc. will be evoked in reproduced images.

Olson [6] analyzed smoothness artifacts in image reproductions and their originations in ICC profiles based color transformation. Several issues dominated in smoothness artifacts include luminance errors, size of LUTs' and influences of medium etc. Fig. 1 shows a comparison of an original test image (left) and its reproduction by using a printer profile which presents visually discernable contours.

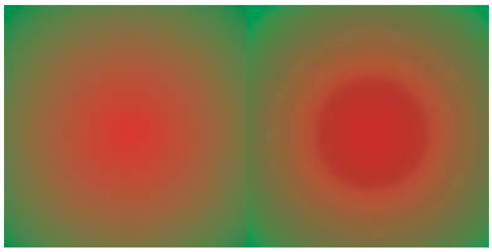

Figure 1 contours generated using a printer profile

Estimating the LUTs' smoothness directly might be a challenging because of the nonlinear color mapping and noise introduced by measurement. However, due to the visual artifacts brought by the unsmooth transformation makes it link to the image quality evaluation. The assessment of image quality and difference between original and reproduced images has been in the discussion for a number of years. Different algorithms have been proposed and tested for different applications. The motivation in this study is to apply an image difference metric to evaluate the smoothness of color transformation in profiles objectively. The context considered is printer profiles as the LUTs widely used and the variations of settings related. The visual judgments of smoothness of profiled images were collected by conducting a series of perceptual experiments. An adaptive bilateral filter[7] algorithm was investigated for the purpose of quantifying experimental results.

Color Measurement and Profile Generation

The ICC profile contains no codes and algorithms and is nothing more than to store the device characterization data which describes the color transformation from one medium to another. Although many of the factors should be considered in profiling, careful selection of the instrument can greatly reduce the variation from the measurement. Over the last few years, considerable progress has been made in instrument design and manufacture, which has led to more reliable instruments, stable readings and devices that are faster, lighter, and easier to use.

A GretagMacbeth Eye-One Pro was used in spectral reflectance scanning measurement mode. The Eye-one Pro employs diffuse illumination and normal viewing. An UV- cutoff filter at 400 nm has built in to provide high precision in printer profiling, which removes the UV part of spectrum of light reflected from papers and prevents it from disturbing measurement in visible spectrum part.

To generate printer profiles, we used a Xerox Phaser 7760 printer driving in RGB mode. TC9.18 RGB test chart was created using GretagMacbeth ProfileMaker5 based on the reference text associated with Eye-One Pro, which includes twenty-seven 9-step colour ramps covering the colour spectrum repeated three times used to be averaged in profiling software to produce a more accurate set of numbers, and seven 17-step narrow gamut and grayscale ramps for linearising. This chart was printed in the size of 27×21.5*cm* on normal office paper (each colour patch is 0.7×0.7*cm*). The printer resolution was set to 600×1200*dpi*.

The software ProfileMaker5 was used through the measurement and profiles generation. Two profile sizes are provided by the software, which correspond to the size of LUTs. In this study, profiles were generated in LUTs size of 33×33×33 which is interpolated from the measurement data of TC 9.18 RGB chart.

To investigate the variation of the LUTs transformation in profiles, a series of profiles were generated. A number of 20 profiles were generated by the 20 successive profiling using an identical paper. Five profiles were generated in a period of five hours with even interval. To further investigate the variability due to the different substrates, 20 profiles were generated by using 20 papers from the same batch. Totally, 45 profiles were prepared for evaluating the smoothness of LUTs transformation.

Figures 2 and 3 plot the average color difference in the 20 successive measurements and 20 measurements with different papers. The color difference is the average of all patches in the chart and calculated using the function provided by the ProfileMaker5. From Fig.2 and Fig.3, it might be concluded that the quality of different profiles is quite similar except the 14th item in Fig. 3.

Questions concerning the way of optimizing random noise suggested using the average of a number of repeated and consecutive measurements. However, the overall averaging also reduces differences between measurements and the variation in the LUTs transformation, which effect on the appearance of reproduced images.

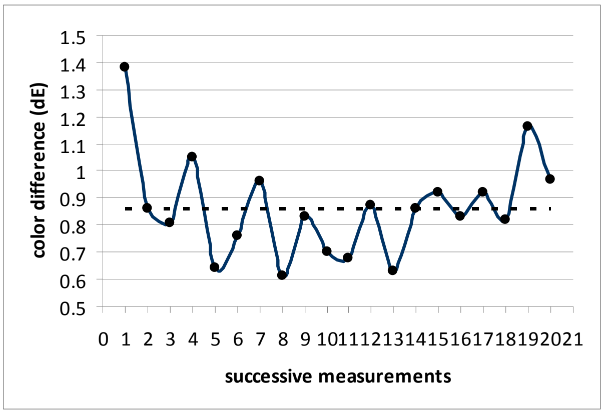

Figure 2 average color differences of 20 successive profiles.

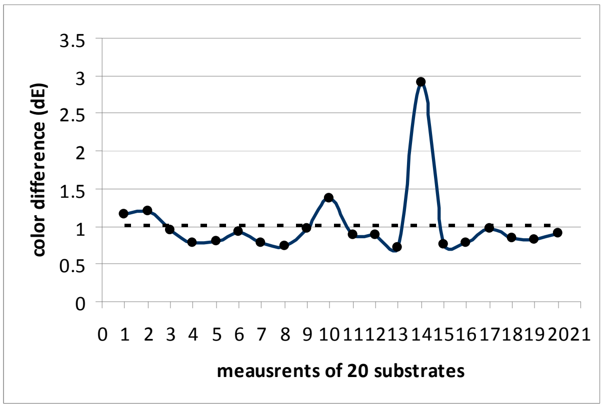

Figure 3 average color differences of 20 papers' profiles

Fig. 4 shows two images reproduced by two different profiles from 20 successive measurements. Different contouring effects can be seen clearly in these two images.

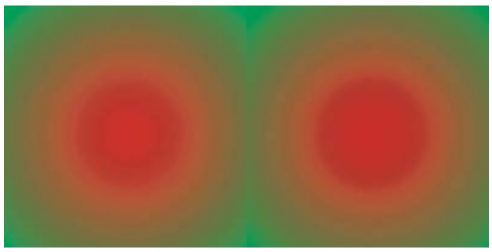

Figure 4 different contours artifacts by using different profiles

Due to the color reproduction ability of different profiles, two profiles involved in Fig. 4 could give quite similar artifacts as shown in Fig. 5.

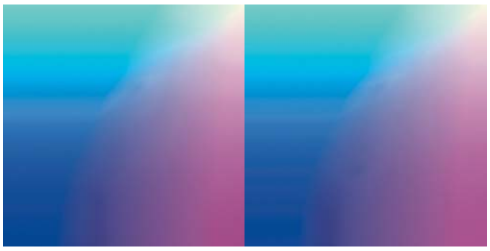

Figure 5 different bandings caused by different profiles

Thus, the overall average could not give us any idea about the quality and the smoothness. The study addresses the question to evaluate the smoothness of profiles by using the following experiments.

Experimental Evaluation

Four samples were selected to test the variations of appearance in terms of smoothness as shown in Fig. 6. These samples were processed with 45 printer profiles using Adobe Photoshop. The rendering intent chosen was Perceptual to preserve the overall image appearance. A number of 180(=4×45) test images were reproduced in total.

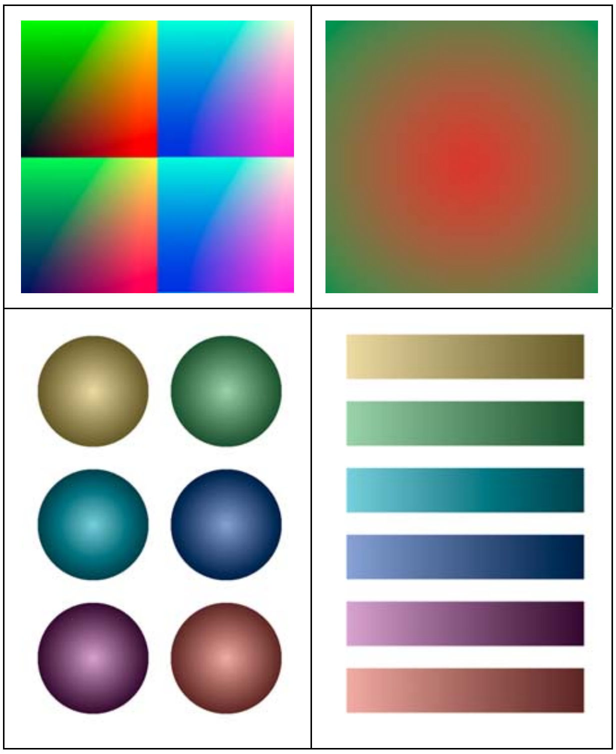

Figure 6 testing samples (image courtesy of [8])

Perceptual experiments were conducted in a dark room using a Dell 21-inch LCD display. The display was calibrated and characterized according to ISO3664[9], which gave a predictive error with a median ΔE_{ab} of 0.43 for the forward characterization and a median ΔE_{ab} of 0.97 for the inverse characterization. The original images were provided and compared with the reproduced images on screen to give observers clear conception how smoothness an image could be. Because the gamuts of the printer and the display are quite different especially at L*=50 as shown in Fig. 7, all reproduced images need to be converted back to sRGB space using Adobe Photoshop as well.

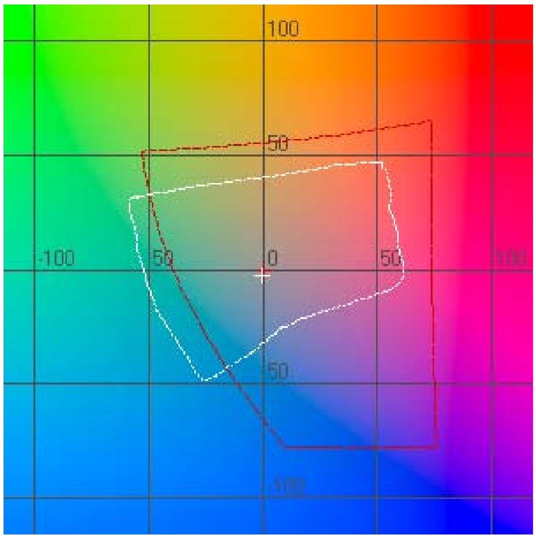

Figure 7 the gamut differences (L=50) between the printer (white) and the display (red) used in experiments.*

Four normal color vision observers participated in experiments to evaluate the smoothness level of reproduced images using category judgment method. The smoothness categories are defined from 1 to 5 corresponding to the smoothness level from perfect smooth to extreme unsmooth. Totally, 720 (=4×180) visual judgments were collected. Inter-observers' variation was examined by means of CV [10] measurement which arrived at an better agreement with an average of 23 and 95% significant level of 25 comparing with that of the previous research [7]. The visual judgments were converted to z-scores according to Torgerson's Law of Categorical Judgment.

The adaptive bilateral filter [7] reacts to the corresponding viewing conditions and the quantity and homogeneity of information contained in an image. Two parameters dominate the behavior of the filter, which remove the imperceptible information based on contrast sensitivity functions and keep the discernable edge based on the average of perceptually similar colors. The experimental images were filtered in CIELAB space and the average pixelwise color difference between each original and reproduced image pair were calculated using CIELAB color difference formulae.

Pearson's correlation was employed to test the performance of the image difference metric, which indicates the degree of linear relationship between two variables and ranges from -1 to 1. The closer Pearson's correlation value is to +/- 1, the higher the performance. The error bars indicate 95% confidence interval (CI) which is calculated by 95% $CI = 1.96/\sqrt{2N} = 0.05$, where N represents the number of 720 overall observations.

Considering the testing samples as shown in Figure 6, these are somewhat non-uniform color patches and not complex images. Figure 10 shows the performances compared between the adaptive bilateral filter and the conventional color difference formulae – CIELAB. It shows the performances of both metrics are similar in each scale. The advantage of the adaptive filter is the effect of edges preserving which is not benefited from these testing samples. The image entropies, which is used to determine how edges are preserved in images, are not considerably different between reproduced images as shown in Fig. 9. A future study need to be considered using complex images.

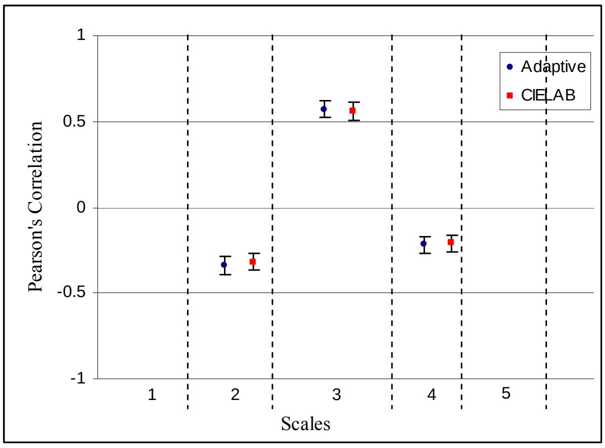

Figure 8 Performance comparison of Adaptive Bilateral Filter and CIELAB in terms of Pearson's Correlation

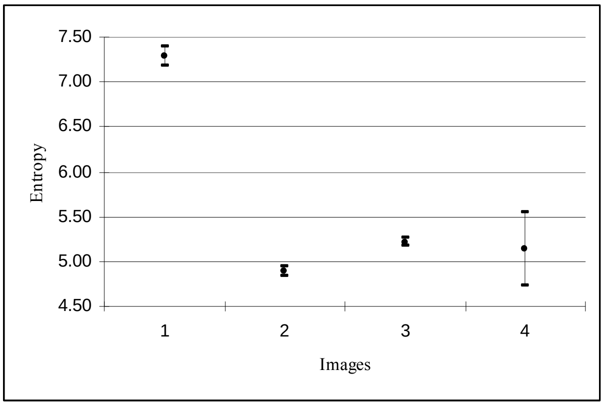

Figure 9 Entropies of reproduced images

Conclusion

In summary, we conducted psychophysical experiments to address the smoothness measurement of LUTs' color transformation in ICC profiles. The performance of an adaptive bilateral filter was tested using smooth testing samples and compared with that of CIELAB. Complex images are considered to be used in the future study to gain the advantage of this spatial filtering algorithm.

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Biography

Zhaohui Wang received his Msc in color imaging science from the Color & Imaging Institute at the University of Derby (2004) and his PhD in color imaging science from the Department of Color Science at the University of Leeds (2008). Currently, he is a postdoctoral researcher in the Norwegian Color Research Laboratory at Gjøvik University College. His work has focused on the development of a perceptual image difference metrics, and is sponsored by the Research Council of Norway.