Colour Image Quality Metric S-CIELAB and Its Application on Cross-Media Colour Conversions via LUTs with Interpolation

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ABSTRACT

Approaches of multi-dimensional look-up table (LUT) with interpolation have often been practically applied to perform colour conversions in colour management systems. Therefore, it is appropriately needed to preliminarily investigate the colour rendering performance of the LUT approaches, used for colour transformations from device-dependent colour space to device-independent colour space. In this paper, the recently recommended S-CIELAB model, as suggested by Zhang and Wandell, was used to evaluate colour-rendition performances of diverse developed cross-media LUT approaches with tetrahedral interpolation, applied in a scanner-to-printer transformation in terms of colour complex-images. Those LUTs considered were generated by well-performing mathematical device characterisation models (DCMs), derived previously for the CMS application. Also, a set of psychological experiments were conducted to cross verify the prediction performances of LUT approaches in question.

1. INTRODUCTION

Colour conversion is a key part of colour management systems (CMS), and often multi-dimensional look-up table (LUT) with interpolation makes an appropriate solution to many kinds of colour space transformations when converting images. The ICC (International Colour Consortium) profile format also allows for colour transformations from device-dependent colour space to device-independent colour space using LUT and interpolation. Furthermore, it is often desired to measure colour reproduction errors of complex colour images in digital colour imaging applications.

This paper considers both techniques of LUT models and a complex colour image-quality metric in the application of cross-media colour transformation. Based on the recently recommended CIEDE2000 combined with spatial filtering, as suggested by Zhang and Wandell [1], a spatial extension version of S-CIELAB metric was derived. The S-CIELAB metric model then carried out the investigation of colour-rendition performances of diverse LUT approaches using tetrahedral interpolation applied in the conversion of colour images in scanner-to-printer processes. The lattice-sample points of LUT of interest, in which the domain of the input or the output space, is populated by well-performing mathematically physical device characterisation models (DCMs), previously derived in earlier works. Finally a set of psychological experiments was conducted to cross verify the prediction performances of cross-media LUT models in question.

2. METHOD

Three well-characterised imaging media were used in this study. They included a sRGB format of Barco monitor, a RGB format of Acer 620PT scanner and a CMYK format of Epson 9000 printer. The PLCC model[2], the 3rd-order SVD approach (singular value decomposition) with a lightness-division strategy and the 2nd-ord SVD algorithm with a GCR (Gray component replacement) technique characterised the monitor, the scanner and the printer in question respectively[3]. Prediction performances of scanner, printer and monitor physical characterisation models of interest were 1.17, 1.58, and 0.62 respectively in terms of mean ΔE_{94}. To examine performances of mathematical packed LUT models, five sets of cross-media LUT image processing algorithms in the scanner-to-printer colour transformation process (as illustrated in Figure 1) were implemented. Table 1 tabulates lattice points along each corresponding axis of the colour space considered in each of the input and the output device for every cross-media LUT model. To specify the S-CIELAB error measure, a set of image processing algorithm was directly derived using the above mentioned mathematical device characterisation models (DCMs), combined with an S-type of gamut mapping to carry out cross-media colour transformations[3]. Then, every LUT (shown in Table 1) used in the cross-media colour transformation was packed using its corresponding well-behaved mathematical DCMs mentioned above. Images produced using both direct mathematical DCMs and LUT methods were representations of both originals and reproductions respectively.

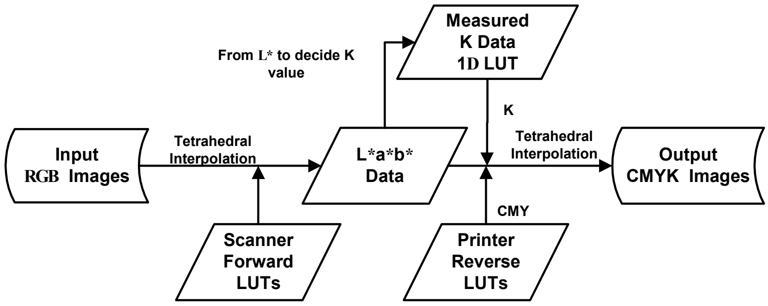

Figure 1: Cross-media colour transformation process for scanner-to-printer using LUTs approach with tetrahedral interpolation.

Three sets of cross-media LUT image processing algorithms were carried out using regular-grid (i.e. even-space); and the other two dynamic-grid (i.e. irregular-space) LUTs respectively, all with tetrahedral interpolation approaches[4]. To optimise the calculation of K-value in GCR process, as shown in Figure 1, a 15-step sampling of K scale in the IT8/7.3 test target printed by the printer of interest was measured to build a 1D LUT of K's FDAs (fractional dot areas) to their corresponding ***log***(L_o^*/L^*) values (L_o^* =100 is the lightness of white point considered, i.e. D_{65} in this study). Regular-Ia, Regular-Ib, and Dynamic-I had larger grid sizes populated than those in LUTs of Dynamic-II and Regular-II. Both Regular models had the same grid-interval distribution of LUTs in the scanner RGB colour space, but the Regular-Ia generated smaller grid intervals in the printer CMY domain than those in Regular-Ib (but with the same step sampling along K axis of the CMYK space). Additionally, both Dynamic models had smaller grid-interval between lattice points in highlight to mid-tone areas than those in shadow areas.

Table 1: Grid sizes along each corresponding axis of the colour space considered for each of the input and the output LUT space generated in the scanner-to-printer colour transformation.

Colour space	Regular-Ia	Regular-Ib	Regular-II	Dynamic-1	Dynamic-2
RGB	52 [Interval 5]	52 [Interval 5]	52 [Interval 5]	37	28
K*	15	15	15	15	15
CMY	26 [Interval 4]	21 [Interval 5]	26 [Interval 4]	21	15
L*	21 [Interval 5]	21 [Interval 5]	21 [Interval 5]	19	16
a*b*	65 [Interval 4]	65 [Interval 4]	33 [Interval 8]	65 [Interval 4]	65 [Interval 4]

Table 2: Prediction performances of LUT models generated for each device considered in every scanner-to-printer colour transformation in terms of ΔE_{94}.

Device	Regular-Ia	Regular-Ib	Regular-II	Dynamic-1	Dynamic-2
Scanner (RGB to L*a*b*)	2.19	2.19	2.18	2.18	2.22
Printer (L*a*b* to CMYK)	3.54	3.53	3.94	5.61	5.53

Five images were tested for every set of 5 LUT approaches (Figure 2). The Barco monitor was used as the soft proofing for printed reproductions to determine the perceived colour difference between image pairs. Therefore, CMYK format of every digital image produced in the scanner-to-printer process was firstly transformed into XYZ format via the printer forward mathematical DCM mentioned above. Then those colorimetric image data were both 1) converted to RGB format of images (which can be displayed on the Barco monitor) via PLCC model, and 2) input in the calculation of S-CIELAB representation of perceived colour differences for both originals and corresponding reproduction images tested. The newly recommended CIEDE2000 colour difference formula (ΔE_{00}) was utilized in the S-CIELAB model.

Table 3: Rendition performances of each image produced using each of cross-media LUTs models in the scanner-to-printer colour transformation using S-CIELAB error measure.

Image	Regular-Ia	Regular-Ib	Regular-II	Dynamic-1	Dynamic-2
Ski	3.50	3.33	2.61	5.31	5.41
Colour Rendition Chart	2.28	2.16	1.74	3.95	3.86
Bride	3.60	3.54	2.67	6.75	6.76
Fruits	3.51	3.20	2.38	4.88	4.83
Shoot	2.73	2.64	2.10	5.05	5.00

A set of psychophysical experiment was carried out to make comparisons of colour appearance matching between the original images (produced using mathematical DCMs)) and the reproduction images (reproduced using LUT approaches). The visual results were used to cross verify the prediction performances of those implemented LUT approaches, found in terms of S-CIELAB colour-fidelity metrics. A forced-choice paired comparison method[5], with simultaneously binocular viewing technique, was employed. It was based on the judgments made for the colour-fidelity quality of test images reproduced by 5 various LUT approaches. A panel of 10 observers, repeatedly twice in one week, viewed a paired of reproductions randomly presented, and judged which of the two gave a better match (i.e. colour fidelity) to an original tested

Figure 2: Image used in cross-media colour transformation process for scanner-to-printer using LUTs approach with tetrahedral interpolation.

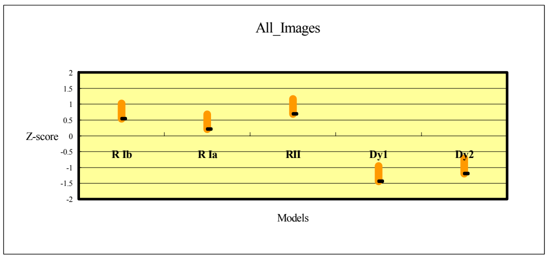

Figure 3: Different cross-media LUT models' performance for the overall colour-fidelity accuracy of all 5 tested images (including 95% confidence limit=0.2399).

3. RESULTS

The predication performances of the 5 LUT models, generated for each device considered in every scanner-to-printer colour transformation, are summarised in Table 2 in terms of mean ΔE_{94}. The overall results showed that three models of Regular-Ia, Regular-Ib, and Regular-II, gave better prediction results than those of both models of Dynamic-I and Dynamic-II. Two Regular-I models performed slightly better than, but very similar to, Regular-II models. There was also insignificant difference of prediction performances between both Regular models. However the Regular-Ib yielded much fewer calculations than those of the Regular-Ia due to less grid points of CMYK domain. As for the test of LUT approaches using complex images, both Table 3 and Figure 2 summarise results, respectively in terms of mean Z-score and S-CIELAB error measure. Clearly, the results obtained using S-CIELAB difference metrics were closely in accordance with those obtained from psychological experiments. The Regular-II gave the best performance for all test images. Both of the Regular-I models, with very similar performance, gave better results than those of both Dynamic models.

From further visually evaluating colour-rendition of CMYK reproduction images, the appearance of false contours apparently existed in some areas of images for both Dynamic models. It was found, from both careful investigation of built LUTs and track of interpolation results, these false contours were due to both 1) very similar luminance levels in some face's colour vertices; and 2) abrupt changes in luminance variance in others, especially when crossing highlight boundaries of tetrahedra of the CMYK LUTs. Particularly for the image of Bride that originally has large highlight areas of smooth and low-chroma (near-neutral) colours, visible false contours produced on some image areas for both Dynamic models; and Regular-II model visually gave the most satisfactory appearance of image results.

4. CONCLUSIONS

The paper considered both usability of the mathematically packed cross-media LUT models and the S-CIELAB representation of complex colour image quality metric that are of great interest in the cross-media colour transformation applications. The overall results show that smaller grid-size LUT with regularly-even spaced points would still visually satisfactorily produce better colour-rendition and smoothness appearance of images than those of larger grid-size LUT with regularly-even or irregularly-dynamic spaced points. It was clearly proved that, to provide a halftone without false contours (i.e. without abrupt screen frequency amplitude variations) the luminance of each of the face's colour vertices should differ from each other as much as possible. Also tetrahedrisation would yield visually poor results of false contours if there were transitions between tetrahedra with vertices having high luminance differences (CIELAB L*) and tetrahedra with vertices having low luminance differences. Therefore care must be taken to approximate and construct tetrahedrisations to minimise the appearance of false contours. Also from comparison results of both psychological experiments and S-CIELAB error measures, it clearly suggested that the S-CIELAB model could optimally simulate the sensitivity function of human vision system to determine the perceived image colour-quality metrics.

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