Gjøvik University College,
Faculty of Informatic and Media Technology,
Master in Media Technology

Master thesis:

Smoothness of color transforms

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June, 2010
Introduction

• Color image quality is an important factor in variety media such as digital cameras, displays and printing systems.

• The different type of digital color devices reproduce color differently.

• Many manufactories try to achieve successful cross-media color reproduction.

• The image reproduction in cross-media depends mostly on some limitations of processes in a device characterization.
Introduction

• Three main processes which influence on reproduced and transmitted color between devices:

• **Device calibration** guarantees that device conform to an established state or condition;

• **Characterization** is a way of determining the output of the device in response of known input (input and output are defined colors or device’ signals);

• **Color conversion** defines translating color one from device color space to device-independent coordinates.
Introduction

• The one of the widely used empirical approaches for device characterization is multidimensional LUTs (Look up tables) color transformations which are basis for ICC profiles.
• International Color Consortium (ICC) profiles allows to manage color from one device to another for obtaining consistent and predictable result.
• The idea of ICC is based on color communication of devices throughout a reference color space or profile connection space to which every input and output device can be related. (CIEL*a*b* and XYZ)
Introduction

- The consistent transformation color from device color space to PCS and from PCS to color space of other device is important for achieving high image color quality reproduction.

- The smoothness is also a desirable property of color transforms often given ranking in visual evaluations of color reproductions (Phil Green).

- Smooth transitions of colors are often presented on natural and business graphic images (Blue sky, Skin tones, Green grass, color ramps). The visually smooth ramp contains no discernible steps (T.Olsen).

- **Smooth color transform is transform which provide output smooth color transition without artifacts (bounding, gains, stripes, color shift, contours)**
Problem statement

• The limitations of device characterization such as unavoidable noise in measurements, interpolation methods, LUTs size, precision errors during computation leads to not consistent and not smooth color transformation and affect on quality of output result.
• How to objectively quantify that one or another transform gives smooth or not smooth results?
• Which factors are mainly influence on smoothess of color transforms?
The goal of the project and motivation

• The aim of this project is to quantify smoothness of color transformation throughout analysis of 3DLUTs based device characterization process (profiling) and the factors which affect on it and test different smoothness and image quality metrics.

Motivation:

• Prediction and prevention of not smooth results during process of device characterization;
• Finding objective way for evaluating smoothness of color transformation which will be closed to visual perceived evaluation of smoothness
• Testing profiles on smoothness
Background

• There are many studies have been done in this area:

• **T.Oslon(1999)** considered causes of smoothness artifacts (countours and banding) on color ramps. He investigated that countours appear when step size between luminance of adjusted points in ramp is too large. Olson found that luminance step size should be limited to $\Delta L^* \leq 0.25$ for guarantee smooth grading colors of color ramp. He found that smooth ramps cannot be generated using 8-bit precision profiles.

• **Phil Green(2008)** proposed 2 ways of evaluating smoothness of output color transform:
  • Second derivative of transform;
  • Difference between smooth original gradient and output of color trasnformations gradient
Background

- Phil Green method have been shown high correlation with visual judgments
- **Drawbacks:**
  - The experiment were carefully designed: ICC profiles were from synthetically generated data with different level of noise (Gaussian random noise).
  - The metric was tested only on color ramps.
  - The metric suppose to predict smoothness of color transforms only using 1 ramp

Phil Green’ metric workflow
(Second derivative of transform)
Background

- **Drawbacks:**
  - method did not involved real ICC profiles color transforms;
  - metric was tested on color ramps with natural colors;
  - requires weights for tone-clipping estimation

![Kim et al. Metric workflow diagram]

10
## Background

### Image difference and quality metrics:

<table>
<thead>
<tr>
<th>Metric</th>
<th>Formula</th>
<th>Description</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E^{*ab}$</td>
<td>$\Delta E^{<em>ab} = \sqrt{(\Delta L^</em>)^2 + (\Delta a^<em>)^2 + (\Delta b^</em>)^2}$</td>
<td>Metric for predicting color difference between 2 images in uniform color space</td>
<td>The common and widely used metric</td>
</tr>
<tr>
<td>SSIM</td>
<td>$SSIM(x, y) = [l(x, y)]^\alpha [c(x, y)]^\beta [s(x, y)]^\gamma$</td>
<td>Structural similarity metric is based on measure structure changes between two images</td>
<td>Smoothness distortions are often presented as changes in images structural information (contours, banding)</td>
</tr>
<tr>
<td>GSSIM Chen et al.</td>
<td>Almost same as SSIM (structure and contrast functions are computed for images’ gradient maps)</td>
<td>Extension of SSIM for blurred images</td>
<td>Changes in smoothness are related to gradient changes</td>
</tr>
<tr>
<td>sCIELAB X.Zhang, B.A.Wandel</td>
<td>Color separation (opponent color space) and spatial filtering are applied to reference and source images. Color difference is computed for them.</td>
<td>Extension of $\Delta E^{*ab}$ aimed to imitate ability of human visual system blurring images (example, halftoning images)</td>
<td>Widely used metric for predicting image difference</td>
</tr>
<tr>
<td>Adaptive bilateral filter Z.Wang</td>
<td>Based on improvements of bilateral filter metric (range and domain filters are combined together)</td>
<td>Extension of bilateral filter for adaptation of predicted result to corresponding viewing conditions and homogeneity of image</td>
<td>This metric is aimed to in good way simulate human visual system (blurring image with preserving structural information)</td>
</tr>
</tbody>
</table>
## Background

<table>
<thead>
<tr>
<th>Metric</th>
<th>Formula</th>
<th>Description</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural content</td>
<td>$SC = \frac{\sum_{i=1}^{M} \sum_{j=1}^{N}</td>
<td>F(i,j)</td>
<td>^2}{\sum_{i=1}^{M} \sum_{j=1}^{N}</td>
</tr>
<tr>
<td>E. Silva T. Kratochvil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge Similarity</td>
<td>$\text{MINK}(x, y) = (</td>
<td>x_1 - y_1</td>
<td>^k +</td>
</tr>
</tbody>
</table>
Proposed method

- 3D LUT (3 dimensional look up table) is typically presented as a table or matrix of \( n^3 \) color values at the lattice points of the source space (device-dependent) and corresponding to them measured color specifications of output color space (device-independent).

- 3DLUT \( L^*a^*b^* \) is included in ICC profile in AToB# (Device coordinates to PCS) tables.
Proposed method

- 3DLUT can be presented as 3D grid (cube) contained color primaries in particular color space.
- Color planes are presented by grid points lied through interval with same coordinates along 1 dimension.
Proposed method

- Color plane of 3DLUT\(L^*a^*b^*\) (33x33x33 grid points)

- For each horizontal and vertical ramp \(\Delta L^* \Delta a^* \Delta b^*\) and second derivative are calculated. The 95 percentile is derived as tone-jumpping factor.
Proposed method

- Mean of values in horizontal direction – $\alpha$
- Mean of values in vertical direction – $\beta$
- For $N$ color planes final value of metric can be found as average of sum horizontal and vertical components:

$$PM = \frac{\sum_{j=1}^{N} \alpha_j \cdot \beta_j}{N}.$$ 

PM L*a*b* - color plane metric
Project workflow

- **I stage** - The sources of errors during device characterization we studied and analyzed.
- **II stage** – Printer characterization. Profile generation.
- **III stage** – Psychophysical experiment for evaluating smoothness of images reproduction (profiled images). Metrics’ computation.
- **IV stage** – Analysis of results.
Experimental methods

• **Printer profiling:**
  • **Spectrophometer:** Eye One Pro i1-iO with UV cutoff filter and robotic automatic chart reading system
  • **Printer:** Color Laser Office printer Xerox Phaser 7760/GX
  • **Chart:** Color target TC 9 18 RGB i1-iO (936 color patches)
  • **Software:** Measure Tool 5.0.10 (Part of ProfileMaker 5.0.10 Pro solution)
  • **Measure mode:** Stripe
  • **Printer quality mode:** Standard
  • **Paper:** Multicopy office paper (A4)

### Measurements repeatability for printer profiling

<table>
<thead>
<tr>
<th>Interval</th>
<th>Number</th>
<th>Paper-target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consecutive &lt;=1 min</td>
<td>20</td>
<td>Same paper-target</td>
</tr>
<tr>
<td>30 min</td>
<td>20</td>
<td>Same paper-target</td>
</tr>
<tr>
<td>1 hour</td>
<td>10</td>
<td>Same paper-target</td>
</tr>
<tr>
<td>Consecutive &lt;=1 min</td>
<td>20</td>
<td>Several copies of target on same paper type</td>
</tr>
</tbody>
</table>
Profile selection

• 20 successive measurements of one chart

20 successive measurements

Spectral reflectance's of red color patch for 20 successive measurements (period \( \leq 1 \) min)

• The measurements were averaged. Color difference between average and each measurement was found.
• The measurements provide profiles with similar quality except 1\(^{st}\), 19\(^{th}\).
Profile selection

- Measurements of 20 substrates (one color chart was printed on 20 papers of same type)

- The measurements were averaged. Color difference between average and each measurement was found.
- The measurements provide profiles with similar quality except 14th and 10th item.
Profile selection

- Measurements of color chart with 1 hour repeatability

The measurements were averaged. Color difference between average and each measurement was found.

The measurements provide profiles with similar quality except 6th item.
Profile selection

- Measurements of color chart with 30 min repeatability

- The measurements were averaged. Color difference between average and each measurement was found.
- Few measurements shows high difference with others.
Profile selection

- 45 measurements were chosen for generating profiles:
- 20 successive measurements;
- 20 measurements of substrates;
- 3 profiles: 6, 7, 9 items for repeatability 1 hour;
- 2 profiles: 16, 17 items for repeatability 30 min.
- The variability of color measurements is presented in these profiles.
- The profiles were generated by Profile Maker 5.0.10
- 4 images x 45 profiles = 180 reproductions were used in experiment
Images data set

- 4 images have been chosen for experiment. They contain different smooth color gradation and transition. These images were converted to profiles (to printer RGB color space).

- The algorithm for generating images were proposed by Eric Garcia
Images data set

- 4 images have been chosen for experiment.

Images were converted to printer RGB(AtoB0) and to sRGB for displaying them.
Psychophysical experiment

- Dark room
- 180 images
- 20 observers with normal color vision
- LCD display DELL 21-inch were calibrated and characterized according to ISO3664 which gave a predictive error with a median $\Delta E_{ab}=0.43$ for the forward characterization and a median $\Delta E_{ab}=0.97$ for inverse characterization.
- The observers were asked to compare the difference in smoothness between the original image and the image reproduction using a category scale from 1 (perfect match in smoothness) to 5 (worse match in smoothness).

<table>
<thead>
<tr>
<th>Category</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Perfect match in smoothness</td>
<td>There is no difference in smoothness</td>
</tr>
<tr>
<td>2</td>
<td>Slightly different in smoothness</td>
<td>Noticeable difference in smoothness</td>
</tr>
<tr>
<td>3</td>
<td>Acceptable match in smoothness</td>
<td>Tolerable differences in smoothness</td>
</tr>
<tr>
<td>4</td>
<td>Moderate match in smoothness</td>
<td>Quite essential difference in smoothness</td>
</tr>
<tr>
<td>5</td>
<td>Worse match in smoothness</td>
<td>Large difference in smoothness</td>
</tr>
</tbody>
</table>
Visual judgments analysis

• Mean opinion scores for images reproductions

- Image 3 and Image 4 estimates do not show explicit differences for groups of profiles.
Visual judgments analysis

• According to Torgerson’s law of categorical judgements, results of psychophysical experiments were converted to z-score.

• The z-score scale was computed.
• z-score is inverse-proportional to mean opinion score.
• Higher z-score presents corresponds to increasing level of smoothness.
Visual judgments analysis

- According to Torgerson’s law of categorical judgements, results of psychophysical experiments were converted to z-score.
- The z-score scale was computed.
- z-score is inverse-proportional to mean opinion score.
- Higher z-score presents corresponds to increasing level of smoothness.
Visual judgments analysis

- Total z-score was computed for profiles using Torgerson’s law
- Profiles were placed into categories

Chi-square Pearson criterion for first 5 observers:

<table>
<thead>
<tr>
<th>Observer</th>
<th>Chi-square</th>
<th>dF</th>
<th>Probability</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>169.3355</td>
<td>176</td>
<td>0.62701</td>
<td>( \chi^2 &lt; \chi^2_{mp} ) H0 is rejected</td>
</tr>
<tr>
<td>2</td>
<td>176.3118</td>
<td>176</td>
<td>0.4799</td>
<td>( \chi^2 &lt; \chi^2_{mp} ) H0 is rejected</td>
</tr>
<tr>
<td>3</td>
<td>199.5038</td>
<td>176</td>
<td>0.3245</td>
<td>( \chi^2 &lt; \chi^2_{mp} ) H0 is rejected</td>
</tr>
<tr>
<td>4</td>
<td>123.0876</td>
<td>88</td>
<td>0.4234</td>
<td>( \chi^2 &lt; \chi^2_{mp} ) H0 is rejected</td>
</tr>
<tr>
<td>5</td>
<td>185.8632</td>
<td>176</td>
<td>0.4234</td>
<td>( \chi^2 &lt; \chi^2_{mp} ) H0 is rejected</td>
</tr>
</tbody>
</table>

H0 is that there is no dependency between observer’s visual judgment of image and profile

For 90% of observers H0 was rejected
Visual judgments analysis

- Image 3 and Image 2 z-scores curve closely to total z-score curve. For Image 1 and Image 4 visual data is variable.
- From plots obviously
Analysis of experimental results

- Phil Green metric (PG), Kim et. al. metric (KM) and Color planes’ metric (PM) were calculated for 45 profiles.
- Pearson correlation between z-scores for profiles and metrics’ performance were calculated.
- Pearson correlation is defined on interval [-1,0] and [0,1] where 0 means that there is no correlation; 1 means absolute correlation.
Analysis of experimental results

Outliers for PG metric are 41st profile, 20th profile

41st profile is 6th item of measurements with repeatability 1 hour
20th profile is 20th item of 20 successive measurements
Analysis of experimental results

Metric performs average correlation, and values of metric are dispersed.
Analysis of experimental results

3 outliers are distinguished from scatter plot: 30, 34 profiles
30 profile corresponds to 10th item of substrates measurements;
34 corresponds to 14th item of substrates measurements
Analysis of experimental results

- Outliers shows high level of distortions (colors are totally wrong) but reproductions are smooth
Analysis of experimental results

- PM metric easily identifies problems with profiles (30, 14, 6)
- PM predicts possible non-smooth better than other existed methods

![Distribution of PM and z-score function](image)

Original image 1

Image 1 – 15th (35) item of 20 substrates measurements
PM = 0.9020

Image 1 – 12th (12) item of 20 successive measurements
PM = 3.6376

Image 1 – 10th (30) item of 20 substrates measurements
PM = 7.9096
Analysis of experimental results

- Image difference metrics performance for images
- Pearson correlation between different metrics’ values and
- z-score for 45 reproduction of each image

<table>
<thead>
<tr>
<th>Metric</th>
<th>Image 1</th>
<th>Image 2</th>
<th>Image 3</th>
<th>Image 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E_{ab}$</td>
<td>-0.3854</td>
<td>-0.7324</td>
<td>-0.5822</td>
<td>-0.1542</td>
</tr>
<tr>
<td>Adaptive bilateral filter(ABF)</td>
<td>-0.3839</td>
<td>-0.6929</td>
<td>-0.5729</td>
<td>-0.1418</td>
</tr>
<tr>
<td>GSSIM</td>
<td>0.4561</td>
<td>0.7040</td>
<td>0.5346</td>
<td>0.2538</td>
</tr>
<tr>
<td>SSIM</td>
<td>0.4471</td>
<td>0.4918</td>
<td>0.2260</td>
<td>0.3538</td>
</tr>
<tr>
<td>sCIELAB</td>
<td>-0.3809</td>
<td>-0.7801</td>
<td>-0.6461</td>
<td>-0.1200</td>
</tr>
<tr>
<td>EdgeSim</td>
<td>-0.2925</td>
<td>-0.4518</td>
<td>-0.5437</td>
<td>-0.1503</td>
</tr>
<tr>
<td>SC</td>
<td>0.4056</td>
<td>0.7773</td>
<td>0.6477</td>
<td>0.3075</td>
</tr>
</tbody>
</table>
Analysis of experimental results

- Structural content shows high performance Pearson correlation with visual data

Pearson correlation 0.7773

Image 2

Pearson correlation 0.6477

Image 3
Analysis of experimental results

- GSSIM shows high correlation with visual z-score for Image 2 but relatively average and low correlation for others images.

Pearson correlation 0.7040

Pearson correlation 0.5346
Analysis of experimental results

- sCIELAB shows high correlation with visual z-score for Image 2 and Image 3, but low correlation for others images.

Pearson correlation:
- Image 2: -0.7801
- Image 3: -0.6461
Analysis of experimental results

Original image

6th (26) item of 20 substrates measurements
GSSIM= 0.9804;
SC= 0.9853;
sCIELAB= 0.6715.

12th (12) item of 20 successive measurements
GSSIM= 0.9537;
SC= 0.9725;
sCIELAB= 0.9185.

10th (30) item of 20 substrates measurements
GSSIM= 0.9483;
SC= 0.9666;
sCIELAB= 1.0709.
Analysis of experimental results

- Distribution of SC values for Image 2
- Distribution of z-score values for Image 2
Analysis of experimental results

- Distribution of SC values for Image 3
- Distribution of z-score values for Image 3
Analysis of experimental results

- Distribution of GSSIM values for Image 2
- Distribution of z-score values for Image 2
Analysis of experimental results

- Distribution of GSSIM values for Image 3
- Distribution of z-score values for Image 3
Analysis of experimental results

- Distribution of sCIELAB values for Image 2
- Distribution of z-score values for Image 2
Analysis of experimental results

- Distribution of sCIELAB values for Image 3
- Distribution of z-score values for Image 3
Conclusions and future work

• Proposed method of color planes for evaluating smoothness of transform through profile have been shown high performance compare with others existed metrics

• GSSIM and Structural content image quality metric shows best results for evaluating smoothness of color transformation in case if reference image is available for comparison

• These metric can be used for predicting not smooth transformation or evaluating smoothness of output image compared with reference image

• **Future work:**
  • extension of Color Plane Metric in 3 dimensions;
  • testing metric on complex and natural images.
Thanks for attention!

Questions