Gamut Mapping for Motion Picture

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Abstract

New technologies in capturing and displaying images with extended color gamut and new standards for wide color gamut color encoding enable a new market of extended-color-gamut content (cinema, television, video on demand, games, electronic documents). This paper addresses the scenario of introducing extended-color-gamut motion picture production, post-production and distribution. One technical issue is the management and compatibility of different color gamuts. Manual (high-end) and automatic (consumer) color conversion tools are needed. For this purpose, we analyze in this paper different gamut mapping algorithms for motion picture type content. A psycho-physical evaluation framework is developed that is based on motion-picture related quality criteria aiming the preservation of the artistic intent and the optimal use of destination color gamut. We notably focus on gamut mapping algorithms that analyze geometrically both the source and the destination color gamut. A new method for automatic detection of the cusp of a color gamut is developed and used for cusp to cusp gamut mapping. The evaluation of several gamut mapping algorithms shows that best results are obtained for cusp to cusp mapping. According to the motion picture evaluation framework, the cusp to cusp gamut mapping algorithm performs significantly better, notably for night scenes and animated content.

Introduction

New technologies in capturing and displaying images (multiple exposure, LED backlighting, laser) with extended color gamut and new standards for wide gamut color encoding [7] and distribution [1] enable a new market of extended-color-gamut content (motion picture, sports, news, games, electronic documents).

This paper addresses the scenario of introducing a new extended-color-gamut video master format in motion picture production, post-production and distribution. Main obstacles for this scenario are cost of instruction of a new master format, standardization and compatibility to existing infrastructure. For cost reduction and compatibility, a technical issue is the conjoint management standard color gamut and extended color gamut. Manual (high-end) and automatic (consumer) color conversion tools for motion picture content are needed. However, color conversion changes the color of images and can be in conflict with film making as an artwork of the Director of Photography.

One important step in color conversion is gamut mapping. The task of gamut mapping is to map the colors belonging to a source color gamut (for example the extended color gamut of film) into a destination color gamut (for example the color gamut of a standard television monitor). Morovic and Luo [3] give a comprehensive overview on gamut mapping algorithms. Montag and Fairchild [8] as well as Zolliker [10] present comprehensive comparisons and evaluate different approaches to gamut mapping.

Gamut mapping always changes image colors since device constraints have to be met. There is no “zero error” or “no degradation” method. Gamut mapping always changes colors and impacts an image as artwork. Gamut mapping for automatic color conversion has therefore to be designed considering artistic requirements or it should be a tool used by the colorist among other.

In this paper, we first review several known gamut mapping algorithms. We then propose a new gamut mapping algorithm for motion picture that exploits the geometric shape of destination *and* source color gamuts. The algorithm requires gamut related metadata about the destination of the image (which is usually available) *and* about the source of the image (which needs to be made available). From a color gamut, the algorithm exploits cusp lightness. The cusp of a color gamut includes the most saturated colors. In order to reduce required metadata, a new method of automatic cusp extraction will be developed.

This paper presents also a psycho-physical quality evaluation framework based on motion-picture-related quality criteria that link the preservation of the artistic intent with the optimal use of destination color gamut. The framework allows to compare existing methods with the new method.

Review of existing gamut mapping methods

The first important choice for gamut mapping is the c**olor spaces** to be used. A series of algorithms use simply CIELAB color space. However, it is known to have uniformity problems in the blue section. The CIE [11] recommends therefore color spaces with better perceptual uniformity such as IPT [13] or hue-corrected color spaces [9, 13].

Gamut mapping usually requires a g**amut boundary description** (GBD) that defines the boundary of a color gamut. GBDs consist often in explicit, generic 3D representations such as triangle meshes or volume models.

There are three groups of methods for calculating a GBD. *Colorant space methods* require device dependent and device independent color coordinates as input. The GBD is calculated by using device dependent coordinates with either minimum or maximum values. *Convex methods* such as the **convex hull method** require as input a more or less exhaustive set of device independent colors belonging to the color gamut. The assumption is that a convex hull includes all these colors. *Non-convex methods* such as alpha shapes and discrete flow complex need the same input data but allow a degree of non-convexity.

The **cusp of a color gamut** is the set of colors, where each of these colors has a larger chroma compared to all other colors in the same constant hue leaf of the 3D color space.

Hue preserving minimum ΔE clipping [12] is a variation of *minimum ΔE clipping*. The basic idea is to map an original color onto the closest color of the gamut boundary of the destination color gamut. This method minimizes the three dimensional color differences between original and reproduction. Lightness, saturation and hue may be changed. *Hue preserving minimum ΔE clipping* is a variation [12] where the hue is kept constant. The closest color is searched within a leaf of constant hue in 3D color space.

The **CUSP clipping** is one of the so-called chroma clipping or chroma mapping methods, reviewed by Montag et al. in 1998 [6]. The basic method is *straight clipping* where hue and lightness are preserved and all out-of-gamut colors are mapped or clipped into the destination gamut using straight, horizontal mapping trajectories that all aim so-called anchor points lying on the lightness axis. *Straight clipping* reduces only the chroma of colors leading to reduced saturation in resulting images. In *node clipping*, the mapping trajectories do not exhibit constant lightness, but aim all a single anchor point lying on the lightness axis at L*=50. *Node clipping* reduces chroma and changes lightness of colors leading to reduced saturation and reduced contrast in resulting images. In *cusp clipping*, the anchor points are lying on the lightness axis but have the same lightness as the gamut cusp in the hue leaf of the color to be mapped.

The **GCUSP algorithm** is intended by Morovic J. and Luo M. R. [5] in 1997 as a direct implementation of former review results. It consists of an initial chroma-dependent lightness compression followed by CUSP mapping. The degree of lightness compression is high at the achromatic axis (C*=0) and is smoothly decreased as chroma increases.

The **SGCK algorithm** is one of the two methods recommended by CIE to be used as reference algorithm in psychophysical tests. The details of this algorithm are described in the CIE guidelines [11]. This algorithm is a combination of GCUSP, sigmoidal lightness mapping and cusp knee scaling proposed by Braun and Fairchild [4]. The algorithm has the following characteristics:

- Keeping hue constant;
- Compressing lightness by sigmoidal mapping using a discrete, cumulative normal function that is adapted and normalized to the destination gamut [11];
- Chroma-dependent lightness compression according to GCUSP algorithm [5];
- Defining an anchor point according to the cusp clipping method;
- Compressing colors into the outer 10% of the destination gamut if they are close or outside of the gamut boundary.

Gamut mapping for motion picture

The requirements for gamut mapping of motion picture content are:

- Preservation of color neighborhood and order;
- Continuity of color;
- Separate control for lightness, hue and saturation;
- Signaling.

Preservation of color neighborhood and order prevents from incoherent reproduction of grey and color ramps. Continuity of colors prevents from banding and false contours. Separate control for lightness, hue and saturation allow the formulation of a higher, semantic level of artistic intents. Signaling is the feedback of the method such as soft gamut alarm [2] to indicate to an operator or control mechanism what happened to the color.

A new gamut mapping framework

For motion picture content, we use the gamut mapping framework shown in Figure 1. It includes classical color management tools such as source and destination display models. New tools are the cusp estimation and the gamut mapping itself.

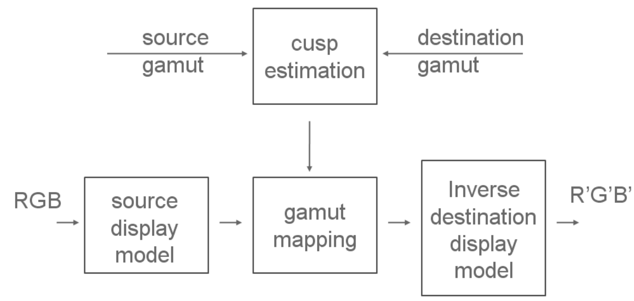

***Figure 1**. Framework of the new gamut mapping algorithm*

The algorithm requires metadata about the destination of the image (destination color gamut) and the source of the image (source color gamut). We represent this metadata explicitly using a 3D triangle mesh, each color is represented by a vertex *V*. The metadata is generated by a convex hull method in CIEXYZ color space but gamut mapping is carried out in CIELAB color space. The triangulation includes topological parameters on shape and size of triangles in order to run with same parameters on measured (noisy) as well as on synthetic, often collinear, color data.

For the estimation of the cusp of a color gamut, a new algorithm is developed and presented in the following sub section.

The cusp information is then used for gamut mapping. The GCUSP algorithm uses the destination color gamut cusp lightness to choose the anchor point, the ending point of a mapping trajectory. In opposite to GCUSP, so-called cusp to cusp mapping algorithms adapt the entire mapping trajectory in a way that source primary cusp colors are mapped to destination primary cusp colors. In opposite to known cusp-to cusp mapping, our method is based on the following characteristics:

- Keeping hue constant to preserve the artistic intent;
- Lightness compression towards the cusp lightness, the lightness compression using a chroma dependency factor;
- Classical chroma clipping, such as minimum ΔE clipping.

Estimation of the cusp of a color gamut

In order to estimate the cusp, a color gamut is analyzed using the following steps:

1. A current cusp vertex is detected being the vertex of the gamut boundary description having the highest saturation;
2. For all neighboring vertices in the neighborhood of the current cusp vertex, a quality criterion (definition see further down) is calculated; the neighborhood being all vertices that are linked to the current cusp vertex by an edge of a triangle;
3. A next cusp vertex is detected being the vertex of the neighborhood having the highest quality criterion;
4. If the next cusp vertex satisfies a stop criterion (definition see further down), the analysis is finished; if not, the next cusp vertex is overtaken as current cusp vertex and the procedure continues at step no. 2.

The mentioned quality criterion calculated for a neighboring vertex *V* is a combination of four sub criteria: a saturation criterion, an intensity similarity criterion, a hue angle increase criterion and a collinearity criterion.

The **saturation criterion** C_S aims to find most saturated cusp vertices. It is based on the saturation

$$C^* = \sqrt{a^{*2} + b^{*2}}$$

of the neighboring vertex that is identical to the chroma with a* and b* being the coordinates of the neighboring vertex in CIE 1976 L*a*b* color space:

$$V = \begin{pmatrix} L^* \\ a^* \\ b^* \end{pmatrix}.$$

In order to calculate the saturation criterion C_S, additionally the distance

$$D = V - \breve{V} = \sqrt{\left(L^* - \hat{L}^*\right)^2 + \left(a^* - \hat{a}^*\right)^2 + \left(b^* - \hat{b}^*\right)^2}$$

between the neighboring vertex V and the current vertex $\hat{V}$ is taken into account. The final saturation criterion is

$$C_S = \frac{C^*\left(1 + D/c_2\right)}{c_1}$$

with constant parameters c_1 and c_2.

The **intensity similarity criterion** C_I aims to cusp colors having a similar intensity along the cusp. It is based on the difference between the intensities of the neighboring vertex L^* and the current vertex $\hat{L}^*$ according to

$$C_I = 1 - \frac{\left(L^* - \hat{L}^*\right)^2}{\left(c_3\right)^2}\left(1 + D/c_2\right).$$

The **hue angle increase criterion** C_H aims to cusp colors that increase in hue in order to efficiently result in a closed and smooth cusp polygon. It is based on the hue angle α_H of the neighboring vertex. The hue angle α_H is the angle in degrees in the *L*=0* plane between the a* axis and the vector defined by the a*,b* coordinates of the neighboring vertex. In a corresponding manner, the hue angle $\hat{\alpha}_H$ of the current vertex is defined. The hue angle difference criterion C_H is calculated according to

$$C_H = \frac{\alpha_H - \hat{\alpha}_H}{c_4}$$

with c_4 a constant parameter.

The **collinearity criterion** C_D aims to cusp colors that build a smooth shaped cusp polygon. It is based on a polygon direction difference involving the neighboring vertex V, the current cusp vertex $\hat{V}$ and the previous cusp vertex V''' that has been detected before the current cusp vertex. Two direction vectors

$$d = V - \hat{V} \text{ and } \hat{d} = \hat{V} - V'''$$

are calculated and the polygon direction difference angle

$$\alpha_D = \angle\left\{d; \hat{d}\right\}$$

is calculated in degrees showing the change of direction in 3D color space of the cusp polygon. From this angle, the polygon direction difference criterion

$$C_D = 1 - \alpha_D / c_5$$

is calculated with c_5 a constant parameter.

The mentioned quality criterion is *C* calculated for a neighboring vertex *V* is finally calculated by a weighted sum according to

$$C = c_S C_S + c_H C_H + c_I C_I + c_D C_D$$

with weights c_S, c_H, c_I and c_D.

The above mentioned stop criterion evaluates two characteristics of the latest detected cusp vertex, each of them is sufficient to indicate the successful detection of the gamut cusp and the end of the algorithm:

- Either, the latest detected cusp vertex is identical with the first cusp vertex
- or the latest detected cusp vertex has an associated hue angle that is larger than the hue angle of the first cusp vertex augmented by 360 degrees.

Evaluation methods for gamut mapping

The performance of gamut mapping can be investigated using objective and/or subjective criteria.

Zolliker et al. [10] propose an objective test procedure to evaluate local color continuity of gamut mapping algorithms. The test procedure analyses statistically local geometrical features of color changes introduced by gamut mapping in order to detect local artifacts.

In 2005, the CIE [11] developed an evaluation framework for gamut mapping algorithms. The framework includes a set of test images, media, viewing conditions, measurement methodologies and benchmark algorithms. The framework requires the use of at least one specific test image ("Ski").

Viewing conditions exclude strongly colored objects in the field of view, walls, ceilings, floors and other surfaces are required to be matt grey. Borders and surrounds are specified for reflective prints, for color monitors and for transparencies. When color monitors are used, white temperature is D65, luminance is between 75cd/m2 and 100cd/m2, ambient light on the monitor should be less than 32 lx. For benchmarking, two reference algorithms are used: hue preserving minimum ΔE clipping [12] and SGCK [11].

Dugay et al. [14] followed the recommendation of the CIE to evaluate spatial gamut mapping algorithms compared to the reference methods recommended by the CIE (minimum ΔE clipping, SCGK). They observed a variability of performance of algorithms with respect to the test images. Furthermore, they report that the evaluation results are impacted by the percentage of out-of-gamut pixels as well as by the experience of the observers in color observation. They also state a poor performance of the minimum ΔE clipping.

Wide color gamut image corpus

We generated a test corpus of 13 images. Each test image has been color corrected for the Wide Color Gamut (WCG) display. In order to ensure natural looking colors, we generated several versions of each test image and selected one by a rapid subjective test among 5 test persons. We want to prevent from influence on the evaluation result by images showing unnatural colors on the WCG display. The test images shown on the WCG display should be accepted as reference by the observers.

The six chosen images are critical examples from motion picture production including the following scenes:

- Close-up of outdoor flowers
- Outdoor garden scene with colored toys
- Outdoor, downtown night scene
- Computer animated flowers
- Computer animated animal characters
- Modern painting

We added the well-known test image "Ski", such as recommended by the CIE [15].

Test method

We developed a test method different from the CIE [11] in order to address the following requirements:

- Minimize the bias in evaluation caused by color difference of color gamuts of displays;
- Evaluation of impact on different aspects of color.

Gamut mapping always degrades colors when the destination color gamut is smaller than the source color gamut. We want to design a test method that prevents from negative evaluation results only due to this. We also want to evaluate the impact on different aspects of color such as hue, saturation, contrast, white temperature and memory colors.

In order to satisfy the requirements, our test method is characterized by the following:

- Comparison to the original images;
- Comparison between different methods;
- Exclusion of display characterization errors;
- Absolute quality scale;
- Focus observation to specific objects in images;
- Focus on specific color aspects.

The characteristics of our test method are detailed in the following. All gamut mapped images are compared to the respective original, reference image in a side by side manner. In order to exclude display characterization errors, each gamut mapped image is presented in butterfly mode side by side with the original, reference image on a single Wide Color Gamut (WCG) display. Figure 2 shows an example for test image "Party".

***Figure 2**. Example of butterfly side-by-side presentation: The original Wide Color Gamut (WCG) image (right) and a gamut mapped image (left)*

Each gamut mapped image is judged using an absolute quality scale according to Figure 3. There is an issue when using an absolute quality scale for evaluation of a single gamut mapped image (in butterfly presentation together with the original image). The judgment will be biased due to the large degradation of colors of gamut mapping caused by the difference of color gamuts between source and destination display. This bias depends on the employed displays and will lower the generality of results. In order to focus the attention of the observer to the level of quality on the destination display, two butterfly images generated by two different gamut mapping methods are presented in temporal order according to Figure 4. As a consequence, the observer is aware of the difference of quality between different gamut mapping methods and is less biased by the difference between source and destination color gamuts.

***Figure 3**. Absolute quality scale*

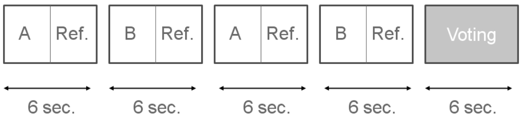

Figure 4. *One test cell*

We invited 7 persons to the test having general skills in image processing but no specific skills in color science. We conducted 120 pair comparisons for each person involving six test images. In order to be able to analyze the quality of the mapped color according to different aspects of color, we asked the test persons to judge the fidelity of either hue or saturation**.**

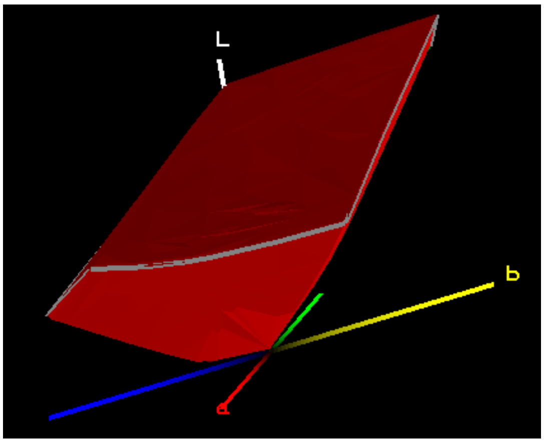

Figure 5.*.Estimated cusp (white line) for the color gamut of a standard Rec. 709 display.*

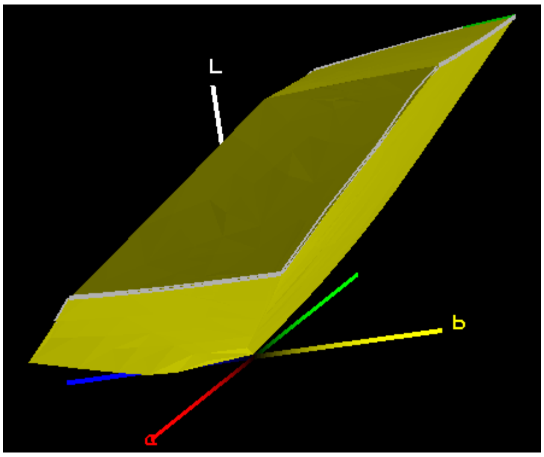

Figure 6. *Estimated cusp (white line) for the color gamut of an LCD LED backlight wide color gamut display.*

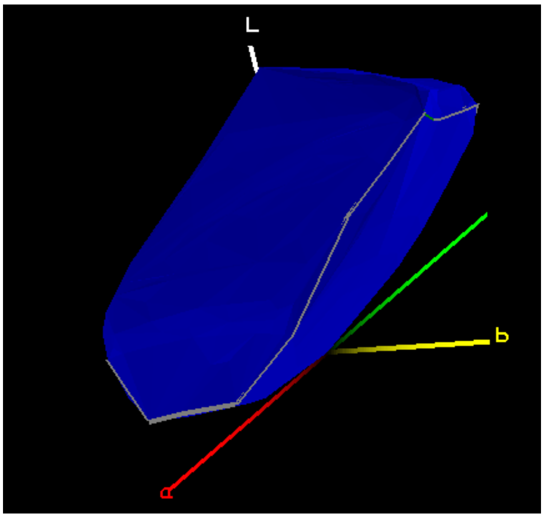

Figure 7.*. Estimated cusp (white line) for the color gamut of positive 35mm film printing and projection.*

Results

In this section, we present results of cusp estimation and evaluation results on gamut mapping algorithms.

Results of cusp estimation

The cusp estimation algorithm has been tested for a series of gamuts including imaging standards and measured displays. The weights for saturation estimation were chosen as follows for all experiments:

- Saturation criterion: c_S =0.5;
- Intensity similarity criterion: c_I =1.0;
- Hue angle increase criterion: $c_H = 0.7$;
- Collinearity criterion: c_D =0.4;

Figure 5, Figure 6 and Figure 7 show representative results. For the film gamut in Figure 7, the film gamut incorporates some noise and the estimated cusp is slightly below the true cusp in yellow tones.

Evaluation results on gamut mapping algorithms

In our experiments, a wide color gamut (WCG) display and a standard Rec. 709 display have been used. The WCG display is an HP 24" LCD display "Dreamcolor" with RGB LED backlight and 1920x1080 resolution (reference: LP2480), while the standard display is a Philips 37" LCD screen with CCFL backlight and 1920x1080 resolution (reference: 37PF9830). Very similar results can be obtained when replacing the HP display by the TVLogic 24" LCD monitor (reference XVM-245W).

In our experiments, three known methods and the new cusp-to-cusp mapping are compared. The four methods are summarized in Table 1 and have the following characteristics:

1. **Straight clipping**: nearly-straight CUSP clipping with anchor points being inside 10 to 90 lightness interval; we expect to better preserve hue with respect to RGB clipping.
2. **Straight linear scaling in source gamut:** Derived from straight clipping, but clipping is replaced by scaling. All colors inside the source color gamut are linearly scaled into the destination gamut instead of being clipped; we expect to better preserve image details with respect to straight clipping.
3. **Straight non-linear scaling in source gamut:** Same as the second method but compression is non-linear, better preserving colors with lower chroma; we expect to better preserve non-saturated colors such as skin tones compared to the fourth method.

4. **New cusp-to-cusp mapping:** Similar to the third method but using also lightness compression towards the cusp lightness, the lightness compression using a chroma dependency factor; we expect to preserve better most saturated colors compared to the third method.

Table 1: Tested gamut mapping methods

Charac-teristics of algorithm	Straight clipping	Straight linear scaling in source gamut	Straight non-linear scaling in source gamuts	New cusp to cusp mapping
Lightness compression towards the cusp lightness	no	no	no	yes
Color space for mapping	CIELAB	CIELAB	CIELAB	CIELAB
Straight mapping/clipping	yes	yes	yes	yes
Chroma compression	clipping	linear	non linear	non linear
Use of source gamut	no	yes	yes	yes

We do not use minimum ΔE clipping since this method has been proven to have poor performance [14]. We do not use SCGK method since sigmoidal lightness mapping makes no sense when display white luminance is constant.

Table 2: Psycho-physical evaluation results

Gamut mapping method	Straight clipping	Straight linear scaling in source gamuts	Straight non-linear scaling in source gamuts	New cusp to cusp mapping
Score	2.47	1.99	2.36	2.67
Std. dev.	0.64	0.40	0.62	0.33

Table 2 shows the mean scores and standard deviations obtained by the psycho-physical evaluations. It can be seen that linear scaling methods do not perform well. The reason is that there is too much loss of saturation. Clipping and non-linear scaling are close to each other and better preserve saturation. Additionally, non-linear scaling preserves image details with respect to clipping. Best method is clearly the new cusp-to-cusp mapping. It preserves saturation of most brilliant colors while lightness changes are tolerated. The standard deviation shows that results are clear (standard variation lower than 0.4) for straight linear scaling (bad score of 1.99) and the new cusp-to-cusp mapping (good score of 2.67). Less clear (standard deviations larger than 0.6) are the straight clipping and non-linear scaling that sometimes produce good and sometimes bad results. The individual scores with respect to hue and saturation are very close to each other. This shows that it is difficult to independently judge these color aspects in a test with limited observation time (6 seconds per comparison plus 6 seconds for voting).

Figure 8 shows a typical result for the "Ski" image where the preservation of saturations in the red tones is visible. Please note that the images in this paper are calculated in the RGB space of the HP WCG display. The color differences are distorted when reproduced on paper or on computer screens. However, we verified the visibility of most of shown color differences on Rec. 709 LCD displays and high quality sRGB computer LCD screens. Figure 9 shows an example of painting like or animated content. Since colors are often highly saturated, the benefits of the new cusp-to-cusp mapping are easily visible.

Figure **10** shows an example of a night scene in downtown where often highly saturated colors occur. For other test images with natural indoor and outdoor scenes, scores are still significantly better but the color difference are poorly visible when this paper is reproduced on a standard display.

Figure 8*. Close-up of test image "Ski" straight- clipping method (top) and for the new cusp-to-cusp mapping (bottom)*

Figure 9*. Close-up of test image "painting" for straight- clipping method (top) and for the new cusp-to-cusp mapping (bottom)*

Conclusions

We developed a new gamut mapping framework for motion picture using classical color management tools (source and destination display models) as well as new tools: color gamut cusp estimation and lightness mapping towards the cusp lightness. We also developed a psycho-physical evaluation framework having less bias caused by choice of used display gamuts and allowing evaluation of aspects of color such as hue, saturation, contrast, white temperature and memory colors.

In comparison to known methods (clipping, linear scaling and non-linear scaling), the new gamut mapping framework performed significantly better, notably for images with saturated colors such as outdoor night scenes and animated content.

Future work will include a validation of the framework for other color spaces than CIELAB.

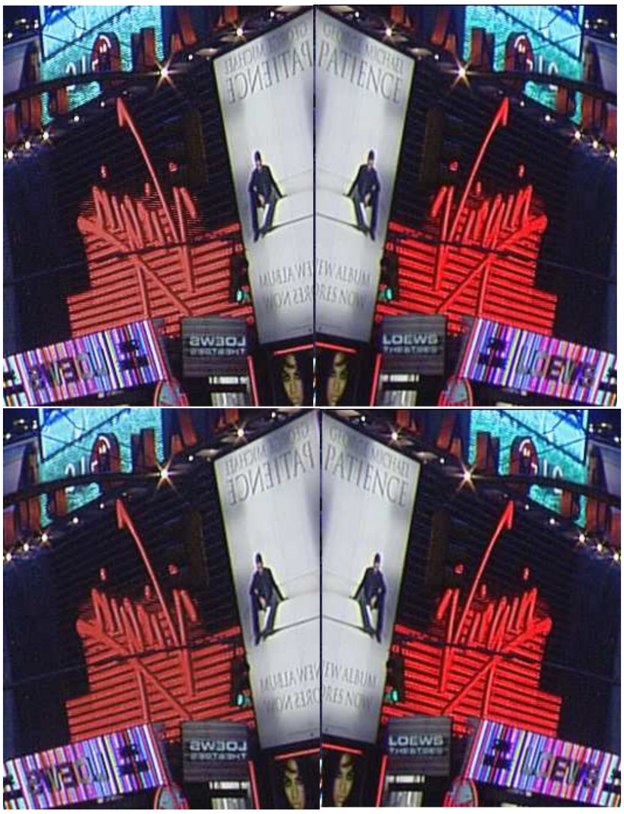

***Figure 10**. Close-up of test image "night in downtown" for straight- clipping method (top) and for the new cusp-to-cusp mapping (bottom)*

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Author Biography

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Corinne Porée received her DEA in Optics and "Magistère de physique" from University of Grenoble (USTMG) in 88 and her Master of Signal Processing from Supélec in 89. Since then she has worked in the Thomson Research Labs in Villingen (Germany) and now in Rennes (France). Her work at present focuses on Wide Color Gamut for the moving picture industry.

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Laurent Blondé is graduate engineer of the Institut d'Optique (1985). Hired as a research engineer at Thomson Research Labs, he participated in more than a few R&D projects including: Infrared Image Synthesis, Special Effects and Virtual Studio, Display processing, Anti-Camcorder and Color Management for Cinema applications, 3D Perception. Image, color and vision expert and multi-project Technical Advisor, he tries to be a creative technical leader enriching image processing with Physics and Perception